Eradicating European carp from Tasmania and implications for national European carp eradication.

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CONTENTS

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Objectives:

1. Use existing Lake Crescent data to develop a risk assessment model (based on characteristics of recorded catches) that will determine the number of male fish to leave in Lake Crescent while fishing down the females, and the period of fishing required to ensure that the Lake is free of female carp at a level of risk required by managers
2. Conduct the first three years of a strategic fishing plan to eradicate carp from Lake Crescent.
3. Interpret catch per unit effort and mark and recapture data collected since the start of the fishdown (1995) to develop a population model and determine the population characteristics of the Lake Crescent and Lake Sorell carp populations.
4. Use the models developed in steps 1 and 3 to determine the number of male carp to add to Lake Sorell as female aggregators, and the strategic fishing plan necessary to achieve eradication of females from this lake at the level of risk required by managers.
5. Monitor the results of selective fishdown of male carp. Determine the extent to which they validate the model predictions and any problems or concerns in using selective removal of males to eradicate the population.
6. Ensure that the successful results get distributed widely to promote mindset that feral fish can be eradicated and provide the techniques for that eradication.

NON-TECHNICAL SUMMARY:

Carp is a major feral pest in Australia. Development of control options has consistently been identified as a high priority research item. When carp were identified in lakes Crescent (2365 ha) and Sorell (4770 ha) in 1995, the Inland Fisheries Service (IFS) decided to eradicate – both populations. These represent the only extant carp populations in Tasmania and threaten the State's premier trout fishery that attracts 30,000 anglers per year. The presence of an endemic galaxiid in Lakes Crescent and Sorell prevented the use of poisons; draining the lakes was not possible; and the IFS decided on a campaign of containment, and eradication through fishing.

Effective containment was achieved rapidly and effectively by placing a weir with a series of mesh screens at the outlet of Lake Crescent, the downstream lake. Mesh sizes were small enough to prevent eggs and juveniles leaving the lake. In addition the two lakes were closed to anglers to reduce the risks of further translocations.

Eradication through fishing in medium to large lakes is not an instantaneous process and in lakes Crescent and Sorell it became a race to fish down the population rapidly before they had the chance to spawn and add further juveniles to the lakes. Temperatures in these two lakes are at the minimum end of those required for spawning by carp, so spawning is typically restricted to shallow margins of the lake in the summer, preferably during periods of stable or rising water levels. At the start of this eradication, Lake Crescent has very low water levels, and water levels were manipulated to maintain low and falling water levels during the spawning period and thus reduce the risk of additional spawning events. Similar manipulation was not possible for Lake Sorell, where input cannot be controlled and where there is a much wider range of marsh habitat available. More recently, the IFS has started to fence off marsh areas in Lake Sorell to restrict access to these spawning sites. Restriction of spawning has not been entirely successful. While some spawning in Lake Crescent was stimulated to catch the remaining females (eggs were removed after the females were caught), uncontrolled spawning also occurred in 2000 and these juveniles are now being caught. Uncontrolled spawning events took place in Lake Sorell in 1995/96, 1997/98 and 2000. Juveniles from the most recent spawning have been fished intensively. As in the past it has proven more difficult to target adult carp in Lake Sorell.

The effectiveness of the fishing operations in the two lakes was increased by using a variety of gears - fyke nets, seine nets, gillnets, traps, backpack electrofishing, boat electrofishing and combinations of these. Initially the fishing gear types were used somewhat randomly. Later, the IFS started targeting habitat favoured by carp and adapted fishing techniques based on previous catch rates and experience. In 1997, radio tagged male fish were first used as tracker or "Judas" fish to identify aggregations and to help understand carp habitat preference and behaviour. Detected aggregations were targeted using fishing techniques most applicable to the situation. The goal of total eradication was further refined to the eradication of female carp because females are highly fecund (up to 1.5 million eggs for a 6 kg fish) and this intermediate goal was thought to be more readily achievable. From December 1999, male fish were routinely tagged and returned to the lakes with the hope of promoting mixed aggregations of female and male fish. Release of tagged male carp back into the lake also made it possible to estimate the remaining population size, especially of female fish.

An important part of this project has been to monitor the success of the fishdown using a mark and recapture program. Initial population estimates were developed by IFS using standard Peterson estimates. This approach had the difficulty of deciding which data sets to use and could not be used to estimate tag loss and natural mortality. A daily mark and recapture model was developed to use all the mark and recapture information, which enabled the continual marking and release of fish. Tag loss was estimated using double-tagged fish and found to vary between small and large tags. Difficulties in estimating tag loss led to the recommendation that in future all tagged fish be double tagged with large tags (Traditionally you tag with one tag of each type – but we know the small tags are shed more readily!). Natural mortality was estimated but found to be negligible. The population size in Lake Crescent was estimated at 32 fish in November 2003. No mark and recapture population estimate was possible for Lake Sorell as to date the fish have been too small to sex and therefore all fish captured in this lake have been killed. A major constraint on the use of the model was inconsistency in data collection over the years. An ACCESS database was developed to assist consistent data entry, including the cross-validation of biological and catch data.

The use of radio tracked fish increased the effectiveness of the fishing by signalling when an aggregation was occurring. Differing behaviours of radio tracked fish suggests that carp in the lakes can adopt resident or mobile behaviours. While mobile fish can be caught in any aggregation, resident fish rarely move from their habitat unless a spawning aggregation is developing. Mark and recapture data also indicate that there is a larger than expected proportion of fish that are not recaptured after initial tagging. While this may be partly explained by the loss of tags before they become securely embedded in the flesh, there is also the suggestion that the tagged carp have varying degrees of vulnerability to recapture. Interestingly, there also seems to be a group of fish that are consistently caught at above the expected rate, leading to a larger number of high multiple recaptures than expected. This varying vulnerability could have serious implications for removing the final fish from the lake. Radio tracking resident and mobile fish may be necessary to target these last few fish.

Returning male fish to the lake to serve as a focus for aggregations that would attract female fish met with varying success. It is recommended that male fish be returned to the lake only in the numbers necessary to have radio tracked fish covering all behaviour types and for population estimates.

Trends in catch data suggest that the probability of catching a fish per days fishing effort has declined since 1998. If this decline continues then it is estimated that 213-435 fishing days would be required to remove the remaining 32 fish from Lake Crescent. However, data from the first half of 2003 suggests that the decline in capture probability has levelled off, in which case 140 days of fishing effort would be required to remove the last adults. However, at the moment the days of fishing required to eradicate carp from these two lakes will not be dictated by removal of the last current adult, but by removal of the last of the juveniles spawned in 2000/01 that are now evident in the population. Continued improvements in fishing effectiveness will be required to eradicate carp from Lake Sorell. Exclusion fences restricting access to the marshes used as spawning sites are now being used along with specifically designed traps. Ongoing development of carp attractants and repellents in the US may provide an additional option in the future, with the possible use of pheromones to attract fish into traps.

OUTCOMES ACHIEVED:

A daily mark and recapture model was developed for the ongoing carp eradication in lakes Sorell and Crescent and used to estimate the current population size. The model can be generalised to other lakes. An associated database was developed to reduce errors in data recording and transcription. Analysis of catch and effort data and the data on carp tagged and recaptured multiple times has shown the variability of behaviours in the carp populations that has important implications for the ongoing eradication. Observations on the effectiveness of different approaches to carp eradication have been documented to assist other groups considering eradicating carp through fishing.

KEYWORDS:

Carp, Eradication, Control, Radio tracking, Mark and Recapture, Population Estimation

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1. Background

Carp is a major feral pest in Australia. It has the largest biomass of any fish species in inland river reaches of the Murray-Darling below 600m altitude and constitute over 80 percent of the total fish biomass in the Murray-Darling Basin (MDBC 2000). Through habitat destruction and competition it strikes at the very heart of river health, biodiversity, and their use by recreational and commercial fishers. In May 1998, a strategic planning workshop was held at the Fisheries Research and Development Corporation's (FRDC) request to identify research that would best benefit carp management decisions. Development of new control techniques was considered high priority. In 1998 and 1999 the Carp Control Coordination Group (CCCG) met to determine the best approach to manage carp in Australia. Again, development of control techniques was identified as high priority research (MDBC 2000b).

Lakes Sorell and Crescent are examples of larger water bodies where poisons are too expensive and potentially too environmentally compromising to use. Carp were identified there in 1995 and since that time control has been based on targeted fishing and control of lake levels. This has had good success and has: a) confined the carp to these water bodies; b) reduced the population in Lake Crescent by removing around 7700 fish with an estimated 30 untagged fish remaining and; c) reduced the frequency of successful spawnings in Lake Crescent. Continued control will be required over the next decade. The cost to Tasmania's economy is substantial – carp control costs the State government, $400,000 per annum. In addition, Lakes Sorell and Crescent, two of Tasmania's premium trout lakes for recreational anglers and commercial guides, have had to remain closed or restricted to anglers, increasing pressure on the remaining productive fisheries.

One suggested approach to increasing the effectiveness of fishing as a control method is to release males to aggregate the females. Radio tagged male fish are used to detect aggregations containing untagged female fish. If the last females aggregate and are caught with the released males, female carp could be eradicated from these lakes. This would have obvious benefits to the trout industry and the State, which would assist in rehabilitating these lakes that were once prime locations in Tasmania's trout fisheries. This would benefit the 30,000 licensed recreational anglers in (or visiting) Tasmania and in turn release pressure from other trout fisheries that are showing signs of overuse. More importantly, if carp can be eradicated from these waters using targeted fishing, we will have provided a new weapon to eradicate carp from Australia and help change the perception that carp eradication is just too difficult.

2. Need

Development of control techniques for carp was given high priority in FRDC and CCCG reviews of Australia's carp problem. Carp control is hampered by a lack of effective techniques. Eradication is considered to be feasible only in small water bodies that can be poisoned or drained. Genetic and physiologically-based tools may be developed over time to control, and perhaps eradicate, carp from larger water bodies. However, this technology will be expensive to develop and public safety concerns may have to be addressed. What is lacking from carp control are techniques that can be used now in larger water bodies. In this study we have modified a standard control technique (physical removal through fishing) so that it can be used to eradicate carp from larger water bodies.

Eradicating carp from Tasmania will provide the basis to rehabilitate what were once two of Tasmania's finest trout fishing lakes forming an integral part of a $30 million fishery comprised of a mix of recreational fishers, commercial fishing guides, tourism operators, and equipment manufacturers. At the same time we will remove the risk of carp escaping from these lakes and causing extensive environmental and habitat damage to lowland rivers, lakes and reservoirs with the resulting loss of freshwater habitat and water quality.

3. Objectives

1 Use existing Lake Crescent data to develop a risk assessment model (based on characteristics of recorded catches) that will determine the number of male fish to leave in Lake Crescent while fishing down the females, and the period of fishing required to ensure that the Lake is free of female carp at a level of risk required by managers

2 Conduct the first three years of a strategic fishing plan to eradicate carp from Lake Crescent.

3 Interpret catch per unit effort and mark and recapture data collected since the start of the fishdown (1995) to develop a population model and determine the population characteristics of the Lake Crescent and Lake Sorell carp populations.

4 Use the models developed in steps 1 and 3 to determine the number of male carp to add to Lake Sorell as female aggregators, and the strategic fishing plan necessary to achieve eradication of females from this lake at the level of risk required by managers.

5 Monitor the results of selective fishdown of male carp. Determine the extent to which they validate the model predictions and any problems or concerns in using selective removal of males to eradicate the population.

6 Ensure that the successful results get distributed widely to promote mindset that feral fish can be eradicated and provide the techniques for that eradication.

4. Methods

Since the discovery of the introduced fish species, European carp (*Cyprinus carpio*), in two lakes in Tasmania, Australia, the Tasmanian Inland Fisheries Service (IFS) has been attempting to eradicate the population. There are four main elements of the eradication:

a. Quarantine the lakes to prevent escape of carp eggs, juveniles or adults to additional water bodies;
b. Manipulate water levels in the lakes to reduce the risks of additional spawning events;
c. Population reduction through a variety of fishing methods; and
d. Monitoring the success of the fishdown using a mark and recapture program.

4.1. Quarantine

When European Carp were discovered in lakes Crescent and Sorell (Full supply elevation Lake Crescent 803.8 AHD and Lake Sorell 804.36 AHD; Figure 4.1.1) in 1995, there was immediate concern about their potential impact on endemic fish and more desirable fishing species, through habitat degradation and competitive displacement. Other downstream lakes and rivers in the Derwent watershed could provide more suitable habitat for carp, due to their lower elevations and higher water temperatures, allowing the population to expand. Therefore these two popular fishing lakes (Crescent=2365 Ha and Sorell=4770 Ha) were immediately closed to the public to reduce the risk of further intentional spread of carp. Screening facilities were installed in the 1km canal which joins the lakes, to separate the populations of the two lakes, and a weir with a series of mesh screens was installed at the outlet of Lake Crescent to reduce the risk of adults, juveniles or eggs escaping downstream into the Clyde River (Figure 4.1.2).

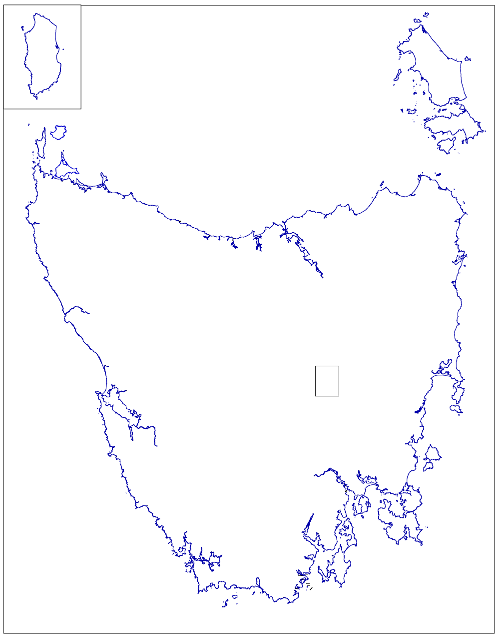


Figure 4.1.1: Location map indicating the position of Lakes Crescent and Sorell. These lakes appear in a direct line between Hobart and Launceston in the central highlands of Tasmania, Australia.

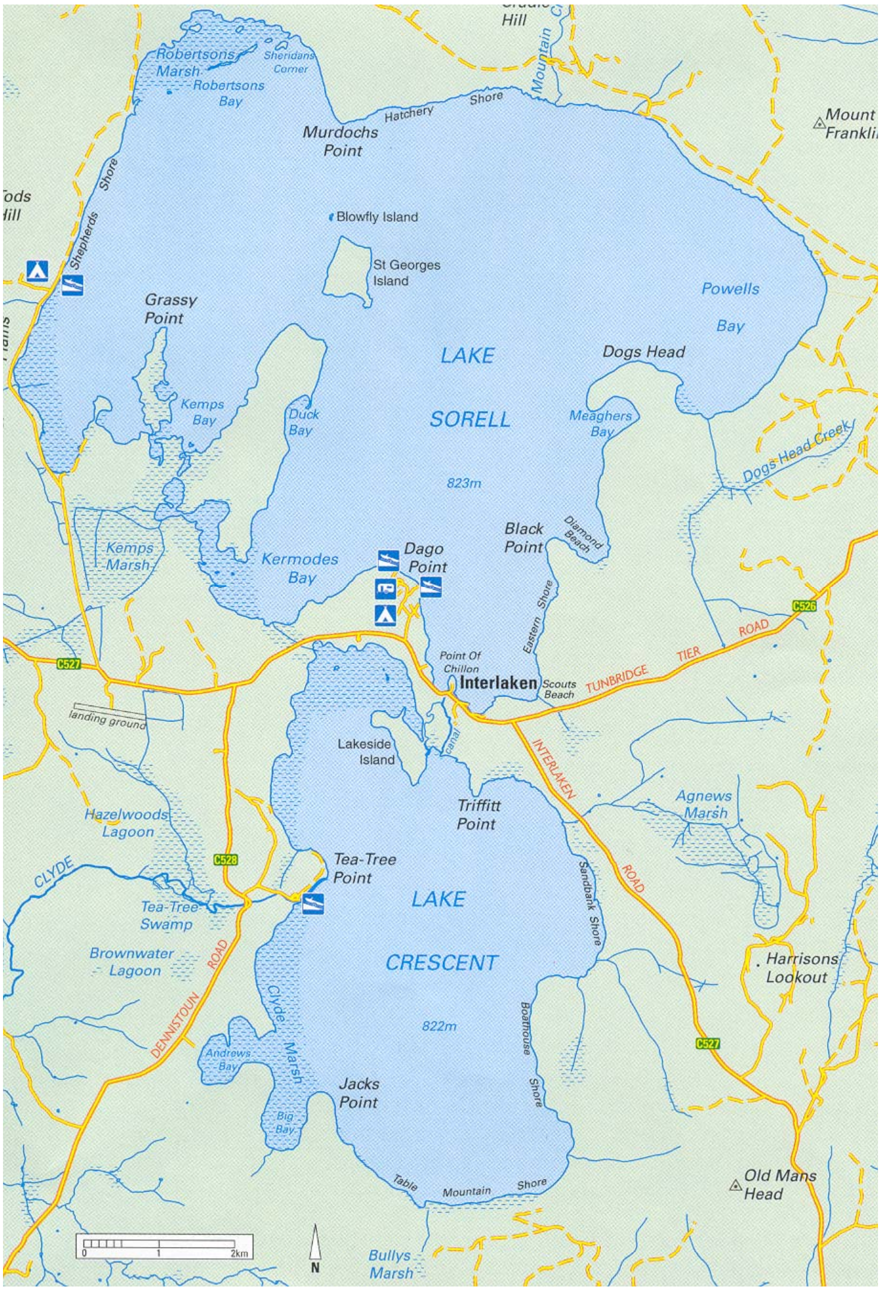


Figure 4.1.2: Detailed map showing relative size and position of Lakes Crescent and Sorell. The only outflow from Lake Crescent is the River Clyde on the western shore of Lake Crescent. The canal linking the two lakes is at Interlaken.

4.2. Spawning manipulation

Carp spawning is triggered by temperature cues and by the presence of newly inundated shallows (Koehn et al., 1999). The water temperature in Lake Crescent typically reaches the preferred range (17-24°C) for carp to spawn during the period from November to March. Since these optimal spawning conditions and habitat have been identified, the water level at Lake Crescent has been managed, to the extent possible, to maintain low and falling water levels during the peak summer spawning periods, thus restricting the availability of preferred spawning habitat. Management of static and falling water levels in Lake Crescent has been easier in recent years due to several years of below average rainfall while downstream demand for irrigation remained high. Water levels in Lake Sorell have been more difficult to manipulate due to its position above Lake Crescent, uncontrolled inflows and the greater availability of suitable spawning habitat at a wide range of lake levels.

4.3. Population reduction

The IFS began fishing down carp in February 1995. Eradication rather than just control was considered feasible because the species was contained, and the relatively low water temperatures and low availability of spawning habitat limit new recruitment. Physical removal of fish was selected as the only environmentally acceptable eradication strategy for carp in Lake Crescent. The combination of high cost and the ecological risks associated with chemical poisoning (Barnham 1998) or viral control were considered too great, in part due to the presence of a threatened endemic species of fish, *Galaxias auratus*. De-watering was also ruled out due to environmental and domestic water supply issues.

Physical removal has been a successful eradication method elsewhere, however only when used in conjunction with chemical control (Meronek et al., 1996); it is not generally considered a suitable eradication method for fish by itself (McClay, 2000). If physical removal were to be successful in these lakes, then novel strategies were required, especially to remove the last few fish. Several strategies have been used by IFS to increase the effectiveness of physical removal:

a. Radio-tagged male fish have been released into the lakes to act as ‘Judas’ fish. Typically when 3 or more radio tagged fish are in the same location it signifies an aggregation of carp. These aggregations are targeted during subsequent fishing.
b. The goal of total eradication was further refined to the eradication of female carp because females are highly fecund (up to 1.5 million eggs for a 6 kg fish) and this intermediate goal was thought to be more readily achievable. At any one spawning a single male can fertilise eggs from many females. In contrast, reproduction from a single female and multiple male fish is limited by the number of eggs the female can produce. From December 1999, male fish were routinely tagged and returned to the lakes with the hope of promoting mixed aggregations of female and male fish. Release of tagged male carp back into the lake also made it possible to estimate the remaining population size, especially of female fish.

A number of methods have been used to fish carp in both lakes since 1995 and both the methods and their application have developed over time. Gear types have included fyke nets, seine nets, gillnets, traps, backpack electrofishing and boat electrofishing. Initially the fishing gear types were used somewhat randomly. Later, the IFS started targeting habitat favoured by carp and adapted fishing techniques based on previous catch rates and experience. Catch rates typically increase following the introduction of new gear types or techniques and then subsequently fall as their effectiveness declines. In March 1997, radio tagged male fish were first used as tracker or “Judas” fish to identify aggregations and to help understand carp habitat preference and behaviour. Detected aggregations were targeted using fishing techniques most applicable to the situation.

4.4. Monitoring

Male fish were tagged and released to monitor the success of the eradication programme. The Lake Crescent population was selected for the two mark-recapture studies because this carp population was thought to be larger than the population in Lake Sorell (based on catch rate data). In addition water levels could be controlled, and fishing was easier. In the first mark-recapture study, 366 fish (males and juveniles) were tagged and released over a period of 17 days in November and December 1998. This initial study was designed to enable a Petersen estimate of the population (Seber 1982), with a distinct recapture period. The Petersen population estimate involves finding the tag ratio of captured individuals over a short time period, following the release of a known number of tagged individuals. Assuming that tagged and untagged individuals are equally catchable, the untagged population size can be estimated directly from this tag ratio.

In December 1999, a second ongoing mark-recapture-re-release study was initiated and an additional 313 tagged fish (males only) were either released or re-released between December 1999 and November 2003. Following recapture some tagged male fish were re-released to help maintain the number of male fish in the lake and possibly promote aggregations of male fish, while also maintaining tagged fish for population estimates. This second study required a more complex analysis than the Petersen estimate and allowed successive population estimates to be made.

The IFS has collected biological information for most of the fish caught since 1995. Data collected include length, weight, sex and gonad indices of individual fish. Data on fishing effort were also collected, including length of fishing operation, location and gear type used, as well as the number of fish caught.

4.5. Age composition of catches (From CAF 2002)

Carp samples were collected from Lakes Crescent and Sorell (Tasmania) between 1995 and 2001. A sample of carp otoliths were sent to the Central Ageing Facility (CAF) for age estimation. A total of 957 age estimates were determined from lapillus otoliths. This report details methodology and results.

4.5.1. Preparation of otoliths

Lapillus otoliths were embedded in rows of five in blocks of polyester resin and three or four sections approximately 0.3 mm thick were transversely cut through their centres with a modified gem-cutting saw. Sections were mounted on microscope slides under cover slips with further polyester resin. Sections were then viewed with transmitted light at 15.75 times magnification (1 x primary objective, 25 x magnification and 0.63 x secondary magnification). Each of the otolith sections were examined on the same magnification for ageing. All sections of each row of otoliths were inspected and the section closest to the primordium was used for subsequent ageing.

Lapilli were ground in a plane of maximum cross-sectional area. Otoliths were attached to a heated glass slide using Crystal Bond. Emery paper (1200 grit) was used to grind the lapilli until the otolith was at a stage where a daily age estimate could readily be determined. Increments were counted using a compound microscope at 400x magnification.

4.5.2. Counts and measurements

A customised image analysis system was used to view the sections, count marked increments, and measure their positions. A frame grabber in a personal computer captured an image from a video camera mounted on the dissecting microscope, and displayed it on the computer monitor. Using the screen cursor, a transect was drawn on the otolith image from the primordium to the edge of the section. The positions of increments along this transect, and of the otolith edge, were then marked with the cursor. The customised image analysis system then recorded the number of increments marked, and the distances from the primordium to each of the increments and to the edge of the otolith. These data were transferred automatically to an Excel spreadsheet linked to the image analysis system via dynamic data exchange.

All counts were initially made without knowledge of fish size, sex, or location or date of capture, to avoid the potential for biasing age estimates.

Once age estimates were completed, the ageing data were combined with information on fish length and sex, location and date of capture, and otolith weight, for subsequent analyses.

4.5.3. Otolith weights

Otolith weight is a useful diagnostic tool in assessing potential errors in age estimates and for examining patterns of otolith growth. Otoliths tend to grow linearly in length and width with increasing fish size, and to grow linearly in thickness and weight with increasing fish age. In long-lived species, plots of otolith weight against estimated age will therefore show an increasing slope at older ages if the ages have been underestimated. Such underestimation has often occurred for species when whole otoliths have been used, when it was necessary to section otoliths to reveal all the annual increments. Also a large variation about the relationship may indicate of a lack of precision in the estimates.

All otoliths were weighed to the nearest 0.001 g on an electronic balance.

4.5.4. Precision of the age estimates

Repeated readings of the same otoliths provide a measure of intra-reader variability. They do not validate the assigned ages but provide an indication of size of the error to be expected with a set of age estimates, due to variation in interpretation of an otolith. Beamish and Fournier (1981) have developed an index of average percent error (IAPE), which has become a common method for quantifying this variation. The IAPE is calculated as:

$$IAPE = \frac{100}{N}\sum_{j=1}^{N}\left[\frac{1}{R}\sum_{i=1}^{R}\frac{|X_{ij}-X_j|}{X_j}\right]$$

where N is the number of fish aged, R is the number of times fish are aged, X_{ij} is the $_i$th determination for the *j*th fish, and X_j is the average estimated age of the jth fish. The index has the property that differences in age estimates for younger fish will contribute more to the final value than will the same absolute error for older fish (Anderson et al. 1992).

To establish confidence intervals to these estimates of precision, a bootstrap technique was employed on the individual error estimates following methods described by Efron and Tibshirani (1993). Five hundred samples of error estimates (each the same size as the original) were randomly taken with replacement from the repeat readings, and a new IAPE calculated for each. The mean of these replicate IAPE's is the mean bootstrap IAPE and the standard deviation is the standard error of the mean. The bootstrap procedure exaggerates any bias present in the original estimate, so it is necessary to correct for this by adding the difference between the original statistic and the bootstrap mean, to the original estimate. The bias-corrected bootstrapped IAPE is thus calculated as:

Bias-corrected IAPE = Original IAPE + (Original IAPE- Mean Bootstrap IAPE)

The 95% confidence interval was calculated as:

95 % C.I. = Bias-corrected IAPE ± (1.96 Standard Error of Bootstrap IAPE)*

4.6. Population modelling

A single release tagging experiment was initiated in December 1998 and data obtained from this experiment were used to estimate the population size using the Petersen method (Seber, 1982). A subsequent continuous tagging experiment was initiated in December 1999 because insufficient numbers were available for a second single release of tagged fish. The two tag releases provided an opportunity to estimate the natural mortality of tagged fish and the release of some double tagged fish in the second study allowed estimates of the tag shedding rate for the two sizes of tag used.

To estimate population size in the continuous tagging experiment required a method that was more complex than the classical Petersen population estimate for mark-recapture studies. For example, Govender and Birnie (1997) use a maximum likelihood model to estimate total and fishing mortality rates and tag shedding rates for a population with two tag types using mark-recapture data and an annual time step with seasonal tag release and fishing periods. However they do not combine these estimates with an estimate of population size. Here, we extend the modelling framework of (Tuck et al., 2003) to directly estimate mortality and tag shedding rates when daily catch and release data are available. We extended existing tag shedding theory (Xiao 1996) to deal with single tagged fish of either type and double tagged fish where both tags are of the same type and hence found maximum likelihood estimates of tag shedding rates for each tag type. This permits estimation of the pre-tagging population where two types of tags have been used indiscriminately in an on-going mixed single and double tagging experiment We also calculate 95% confidence intervals for estimated parameters. The daily untagged population size is estimated from the initiation of the tagging programme in December 1998 through to November 2003.

The population of carp in Lake Crescent was estimated for several points in time including: the December 1995 population size (referred to as the 'pre-recruitment initial population'); the November 1998 population size immediately prior to the first release of tagged fish (the 'post-recruitment initial population'); and the September 2002 untagged population size (the 'current population'). We used two starting dates, Jan 31 1995 ('pre-recruitment model') and November 30 1998 ('post-recruitment model') for our population models although we focus on results from the post recruitment model. Any radio tagged fish were excluded from this analysis, as the recapture probability of radio tagged fish is clearly much higher than for other tagged fish.

4.6.1. Standard Petersen methods for mark-recapture studies

Estimates of population parameters can be obtained from mark-recapture studies by applying a variety of standard mark recapture techniques. Donkers (1999) used Petersen and Schnabel analyses (Seber, 1982) and investigated the use of the change of ratio method (Seber, 1982) to estimate the initial population size and the size of the two known recruitment events in Lake Crescent. This work, and other unpublished work at the IFS, produced estimates of a pre-recruitment initial population of 4899 fish, assuming no mortality and no tag shedding, and a combined recruitment of 3840 from the two successful spawning events. The Petersen method is most reliable for a short recapture period, such as immediately after the first tag study and will only provide an estimate of the population size at a single point in time. Deficiencies associated with the Petersen method include the assumptions of no tag shedding and no natural mortality.

4.6.2. Initial model - no tag shedding

Tuck et al. (2003) use a semi-parametric model to account for daily catches, releases and recaptures. This accommodates tag data which have been collected over an extended period. We base our model on their "Length-Independent Selection Model" (Tuck et al., 2003), and later extend this model to incorporate tag shedding. We implicitly assume that once fish become available to the fishery, they remain available regardless of age or length. This assumption seems reasonable given both the range of gear types used in this fishery and the fact that gear types are often used in combination.

The daily population dynamics are described by:

$$N_t = (N_{t-1} - C_{t-1})S \ + R(t), \qquad (1)$$

where N_t is the number of fish in the population on day t, including male and female fish as well as tagged and untagged fish, C_t the number of fish caught on day t, S is the daily survival rate related to natural mortality and $R(t)$ is the number of recruits to the fishery on day t. In this case, $S = e^{-M/365}$, where the parameter M relates to the annual finite natural mortality rate, $1\text{-}e^{-M}$, which is the probability of death through natural causes in a one year time interval. The mortality parameter, M, can either be estimated within the model or can be estimated independently from age composition data. For ease of interpretation and comparison of results, when we estimate mortality we report the annual probability of natural mortality (or annual mortality) rather than the parameter M.

Equation (1) is a daily version of the catch equation used in Cohort Analysis (Pope, 1972). The initial population is given by N_0, a parameter to be estimated by the model, with day *0* either chosen as January 31, 1995, for the pre-recruitment model or November 30 1998 for the post-recruitment model. Recruits are added to the population in November of each year so $R(t) \neq 0$ if day t corresponds to a recruitment day and $R(t)$

= *0* otherwise. Based on experience in the field, we assume recruits become available to the fishery at around one year of age, as they first became available to some of the fishing gear types around November. As there are only two confirmed recruitment events in Lake Crescent, this gives us two recruitment parameters to estimate, R_1 on November 1, 1996 and R_2 on November 1, 1997. Although we can theoretically estimate R_1 and R_2 from the data, without constructing an age or length based model, there are limited data available to distinguish between fish from different cohorts.

Apart from one exception when we assumed no recruitment, we set R_1 =3000 and R_2 = 1500 when estimating the pre-recruitment population. These values were based on recruitment estimates from length-frequency distributions of captured fish. By examining monthly length frequency distributions, fish from the two known recruitment events can be distinguished from each other and from the initial population in the lake and a rough estimate of the size of the two recruitment events can be made from the catch composition.

When estimating the post-recruitment population size, there is no need to estimate or make assumptions about recruitment as these smaller new recruits are already available to the gear types used by November 1998. Estimates of mortality rates and the projected final population size can be compared for pre- and post-recruitment population estimates.

Using a difference equation of the same form as used for the total fish population, N_t, the number of tagged fish in the population on day t, m_t, is

$$m_t = (m_{t-1} - r_{t-1})S \ + p_t, \qquad (2)$$

where p_t is the number of tagged fish released on day t, $m_0 = p_0 = 0$ and r_t is the number of tagged fish recaptured on day t. Note that the tagged population is zero until December 1998. Tuck et al. (2003) modify their recapture rate to allow for non detection of tags, but they assume no tag shedding and no increased mortality associated with tagging. We assume that non-detection or non-reporting of tags is not significant as every fish which is caught is examined thoroughly. As an extension to the models developed by Tuck et al. (2003), we develop models which account for tag shedding and which can be used to estimate tag shedding rates. We assume that tagged fish have the same mortality rate as untagged fish.

The number of observed recaptures on day t is assumed to follow a binomial distribution, $r_t \sim B(\beta_t, C_t)$, with mean μ_t defined by $\mu_t = E[r_t] = \frac{m_t}{N_t} C_t = \beta_t C$, where the expected fraction of the total catch on day t, C_t, which is tagged is equal to the ratio of tagged to (tagged + untagged) fish, m_t/N_t. Hence we maximise the following log-likelihood function:

$$L(r, C; N_0, R_y, M) = \sum_{t:\mu_t \neq 0} (r_t \ln(\mu_t / C_t) + (C_t - r_t)\ln(1 - (\mu_t / C_t))). \qquad (3)$$

4.6.3. Tag shedding – one tag type

The model described by Equations (1)-(2) assumes there is no loss of fish from the tagged population due to tag shedding. Further, it ignores double tagged fish, fails to distinguish between different tag types and it ignores any increase in mortality for tagged fish, either due to the immediate effects of tagging and handling, (type I tagging mortality (Xiao, 1996)), or due to longer term effects, (type II tagging mortality (Xiao, 1996)). Due to difficulties in estimating many parameters from limited data, we assumed no type I or type II mortality associated with tagging carp. Field experience showed high survival rates following surgical insertion of radio tags into tracker fish, and high survival of conventionally tagged ex-tracker fish, following expulsion of their internal radio trackers. These high survival rates for procedures more invasive than conventional tagging used to estimate population parameters, suggest that carp in these lakes are very robust to handling and tagging.

Given limited data on the number of double tagged fish which were recaptured, we believe that this is sufficient to estimate longer term tag shedding rates only. Following Xiao (1996), tag shedding can be separated into short term tag shedding, (type I shedding), due to the immediate effects of tagging and handling and a longer term tag shedding rate, (type II shedding), which is often assumed to operate at a constant rate over time. We assume that there is no type I tag shedding and that type II tag shedding rates follow a Poisson form.

With the additional simplifying assumption that we have one tag type or, equivalently, that the tag shedding rate is identical for each tag type, we need to estimate a single tag shedding parameter, *a.* For a fish tagged with exactly one tag, we assume that the probability of retaining this tag after t days is e^{-at}. We relax this assumption in the next section by considering two tag types.

The tag shedding data consist of the number of days at liberty for each double tagged fish, in this case assumed to be tagged with two tags of the same type, which is recaptured with both tags retained, $x_1,\ldots,x_p$ and the number of days at liberty for each double tagged fish recaptured with only one tag retained, $y_1,\ldots,y_q$. With the above assumptions, the probability of shedding neither tag in t days is $v_0(t)=e^{-2at}$, the probability of shedding exactly one tag in t days is $v_1(t)=2e^{-at}(1-e^{-at})$ and the probability of shedding both tags in t days is $v_2(t)=\left(1-e^{-at}\right)^2$.

If data are available on the number of days between release and recapture of double tagged fish which have shed both tags, $z_1,\ldots,z_r$, then estimating the tag shedding parameter, *a,* is simply a matter of choosing the value of $a > 0$, which maximizes the product of probabilities:

$$\prod_{i=1}^{p} v_0(x_i)\prod_{j=1}^{q} v_1(y_j)\prod_{k=1}^{r} v_2(z_k) \tag{4}$$

This is essentially finding the maximum likelihood for the parameter *a*, given the data, only in this case the likelihood is a true probability.

Double tagged fish which have shed both tags are virtually impossible to detect. Carp heal rapidly with little scarring, so we have no data on double tag shedding, $z_1,\ldots,z_r$. To avoid bias in estimating the parameter, *a,* due to the non-detection of double tag shedding, we condition the probabilities of shedding 0 or 1 tags, v_0 and v_1, on $v_2(t) = 0$ (Kirkwood and Walker 1984, Xiao 1996). Setting

$$w_k(t) = \frac{v_k(t)}{v_0(t) + v_1(t)}, \tag{5}$$

for $k=0,1$, the best estimate of a is the value which maximizes the following product of conditional probabilities:

$$\prod_{i=1}^{p} w_0(x_i) \prod_{j=1}^{q} w_1(y_j) \tag{6}$$

or, equivalently, which maximizes the log likelihood:

$$L(x_i, y_j; a) = \sum_{i=1}^{p} \ln(w_0(x_i)) + \sum_{j=1}^{q} \ln(w_1(y_j)). \tag{7}$$

To allow for tag shedding using the form described above, Equation (2) needs to be modified to include a tag shedding term,

$$m_t = (m_{t-1} - r_{t-1})S\ e^{-a} + p_t, \tag{8}$$

where the daily tag shedding survivorship function, e^{-a} , describes the probability that a tagged fish retains its tag for another day.

As the time taken to shed all tags will differ for single tagged and double tagged fish, Equation (8) needs to be further modified to distinguish between double and single tagged fish. To achieve this, let single tagged fish be represented by the superscript *s* and double tagged fish be represented by the superscript *d*, both for the numbers of tagged fish, *m,* and for the number of recaptures and releases of tagged fish, *r* and *p.*

With this notation, we need two tagged fish difference equations, one for single tagged fish,

$$m_t^s = (m_{t-1}^s - r_{t-1}^s)S\ e^{-a} + p_t^s + \left(m_{t-1}^d - r_{t-1}^d\right)2e^{-a}(1 - e^{-a}) \tag{9}$$

and another for double tagged fish

$$m_t^d = \left(m_{t-1}^d - r_{t-1}^d\right)S\ e^{-2a} + p_t^d. \tag{10}$$

With this formulation, the number of tagged fish at time *t* is given by

$$m_t = m_t^s + m_t^d, \tag{11}$$

where this equation replaces Equation (8), so the system is now described by Equations (1), (3) and (11).

The likelihood function for estimating the tag shedding rate with one tag type, Equation (7), can be maximized independently of the population estimates, producing a single parameter estimate for the daily tag shedding rate, *a*. Alternatively, we can estimate *a* in combination with estimates of initial population size, N_0, recruitment, *R(t)*, and mortality, *M*, by adding the log likelihoods given by Equations (3) and (7). As with mortality rates, we report tag shedding rates as annual tag shedding probabilities to enable easier interpretation and comparison.

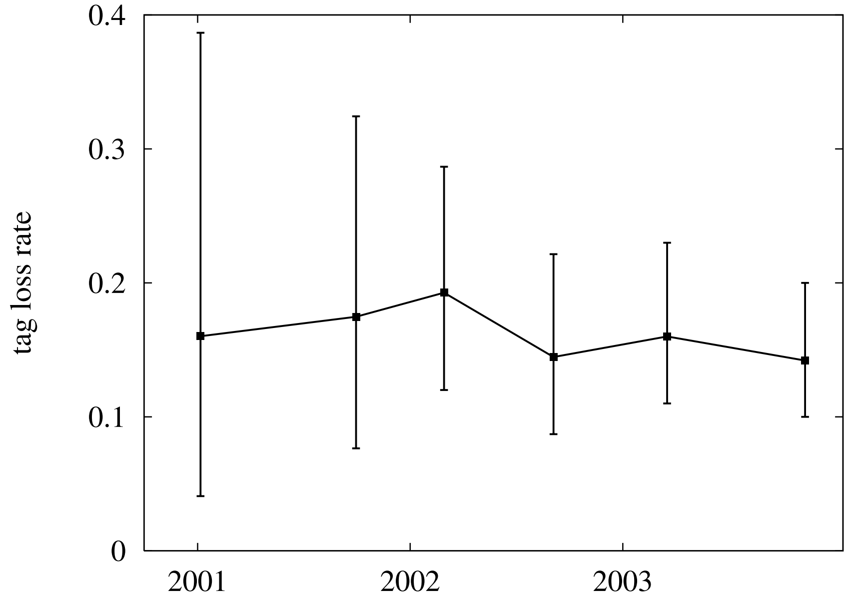


Fig 4.6.3.1 Tag shedding rates with 95% confidence intervals, assuming one tag type, calculated using data collected up to 5 different dates. Note that the confidence interval decreases as more data is added, and that there appears to be no consistent trend over time.

4.6.4. Tag shedding – two tag types

Carp in Lake Crescent were single tagged with two different types of tags – large and small. There were 725 releases of fish tagged with a single large tag (L), 176 releases of a fish tagged with a single small tag (S). In addition there were 92 releases of fish double tagged with two large tags (LL), 26 releases with one small and one large tag (SL) and 8 releases with two small tags (SS). Small tags were intended for use on smaller fish, but in practice, large and small tags were used on both small and large fish. Anecdotal evidence from field workers suggests that tag shedding rates for small tags was much greater than tag shedding rates for large tags. We extend the arguments outlined in Section 3.4 to allow for two different tag shedding rates and to estimate two tag shedding parameters, a_1 and a_2, for small and large tags respectively.

Given two different tag types, our data on tag shedding need to be reclassified, distinguishing between the three different types of double tagged fish and tracking the type of tag which has been shed when exactly one tag is shed. Let $x_1^1,\ldots,x_p^1$ represent the number of days between the release of those fish tagged with two small tags and the subsequent recapture with two tags still present. Let $y_1^1,\ldots,y_q^1$ represent the number of days between the release of fish tagged with two small tags and the recapture of the same fish with only one tag present. Similarly, let $x_1^2,\ldots,x_m^2$ and $y_1^2,\ldots,y_n^2$ represent the numbers of days between release and recapture of fish tagged with two large tags, and recaptured with two large tags and one large tag respectively. Finally, for fish released with one large and one small tag, let $x_1^3,\ldots,x_u^3$ represent the number of days between release and recapture with both tags intact, $y_1^4,\ldots,y_v^4$ represent the number of days between release and recapture with only one large tag and $y_1^5, \ldots, y_w^5$ represent the number of days between release and recapture with only one small tag.

Tag shedding probabilities now depend on the type of double tagged fish. For fish tagged with two identical tags, the probability of shedding neither tag in *t* days is:

$$v_0^i(t) = e^{-2a_i t}, \tag{12}$$

and the probability of shedding exactly one tag in *t* days is:

$$v_1^i(t) = 2e^{-a_i t}\left(1 - e^{-a_i t}\right), \tag{13}$$

for *i=1,2*. For fish released with one small and one large tag, the probability of shedding neither tag in t days is:

$$v_0^3(t) = e^{-(a_1+a_2)t}, \tag{14}$$

the probability of shedding the small tag only is:

$$v_1^4(t) = e^{-a_2 t}(1 - e^{-a_1 t}), \tag{15}$$

and the probability of shedding the large tag only is:

$$v_1^5(t) = e^{-a_1 t}(1 - e^{-a_2 t}). \tag{16}$$

To avoid bias due to non-detection of double tag shedding events, these probabilities are again conditioned on the event that the double tag shedding probability is zero. For the cases where both tags are of the same type, *i=1,2,*

$$w_0^i(t) = \frac{v_0^i(t)}{v_0^i(t) + v_1^i(t)} \tag{17}$$

and

$$w_1^i(t) = \frac{v_1^i(t)}{v_0^i(t) + v_1^i(t)}. \tag{18}$$

For the case of two different tag types, these conditional probabilities are

$$w_0^3(t) = \frac{v_0^3(t)}{v_0^3(t) + v_1^4(t) + v_1^5(t)}, \tag{19}$$

$$w_1^4(t) = \frac{v_1^4(t)}{v_0^3(t) + v_1^4(t) + v_1^5(t)} \tag{20}$$

and

$$w_1^5(t) = \frac{v_1^5(t)}{v_0^3(t) + v_1^4(t) + v_1^5(t)}, \tag{21}$$

with the same notation for subscripts and superscripts as above.

The best estimates for a_1 and a_2 are the values which maximizes the following log likelihood:

$$\begin{aligned} L(x_i^j, y_k^l; a_1, a_2) = &\sum_{i=1}^{p} \ln\left(w_0^1\left(x_i^1\right)\right) + \sum_{k=1}^{q} \ln\left(w_1^1\left(y_k^1\right)\right) + \sum_{i=1}^{m} \ln\left(w_0^2\left(x_i^2\right)\right) \\ &+ \sum_{k=1}^{n} \ln\left(w_1^2\left(y_k^2\right)\right) + \sum_{i=1}^{u} \ln\left(w_0^3\left(x_i^3\right)\right) + \sum_{k=1}^{v} \ln\left(w_1^4\left(y_k^4\right)\right) + \sum_{k=1}^{w} \ln\left(w_1^5\left(x_k^5\right)\right). \end{aligned} \tag{22}$$

Xiao (1996) gives the likelihood function for the case of two different tag types, where all double tagged fish have one tag of each tag type. We extend this analysis to include the scenario where fish can also be double tagged with the same tag type. With this extension, we now need 5 equations to replace Equations (9) and (10) describing the dynamics of the 5 possible combinations of single and double tagged fish, and allowing tagged fish to move from a double tagged category to the appropriate single tagged category by shedding tags of the appropriate type:

$$m_t^{SS} = (m_{t-1}^{SS} - r_{t-1}^{SS})S\ e^{-2a_1} + p_t^{SS}, \tag{23}$$

$$m_t^{LL} = (m_{t-1}^{LL} - r_{t-1}^{LL})S\ e^{-2a_2} + p_t^{LL}, \tag{24}$$

$$m_t^{SL} = (m_{t-1}^{SL} - r_{t-1}^{SL})S\ e^{-(a_1+a_2)} + p_t^{SL}, \tag{25}$$

$$m_t^{S} = S\ [(m_{t-1}^{S} - r_{t-1}^{S})e^{-a_1} + 2(m_{t-1}^{SS} - r_{t-1}^{SS})e^{-a_1}(1-e^{-a_1}) + (m_{t-1}^{SL} - r_{t-1}^{SL})e^{-a_1}(1-e^{-a_2})] + p_t^{S}, \tag{26}$$

$$m_t^{L} = S\ [(m_{t-1}^{L} - r_{t-1}^{L})e^{-a_2} + 2(m_{t-1}^{LL} - r_{t-1}^{LL})e^{-a_2}(1-e^{-a_2}) + (m_{t-1}^{SL} - r_{t-1}^{SL})e^{-a_2}(1-e^{-a_1})] + p_t^{L}. \tag{27}$$

The superscripts *S* and *L* refer to small and large tags respectively and a double superscript refers to a fish which is double tagged. With this formulation, the number of tagged fish at time *t* is given by

$$m_t = m_t^S + m_t^L + m_t^{SS} + m_t^{SL} + m_t^{LL}, \tag{28}$$

As with the single tag type model, the likelihood function for tag shedding with two tag types can be maximized independently of the population estimates, producing parameter estimates for the two daily tag shedding rates, a_1 and a_2. Similarly, we can estimate these rates in combination with estimates of initial population size, N_0, recruitment, *R(t)*, and mortality, *M*, by adding the log likelihoods given by Equations (22) and (3).

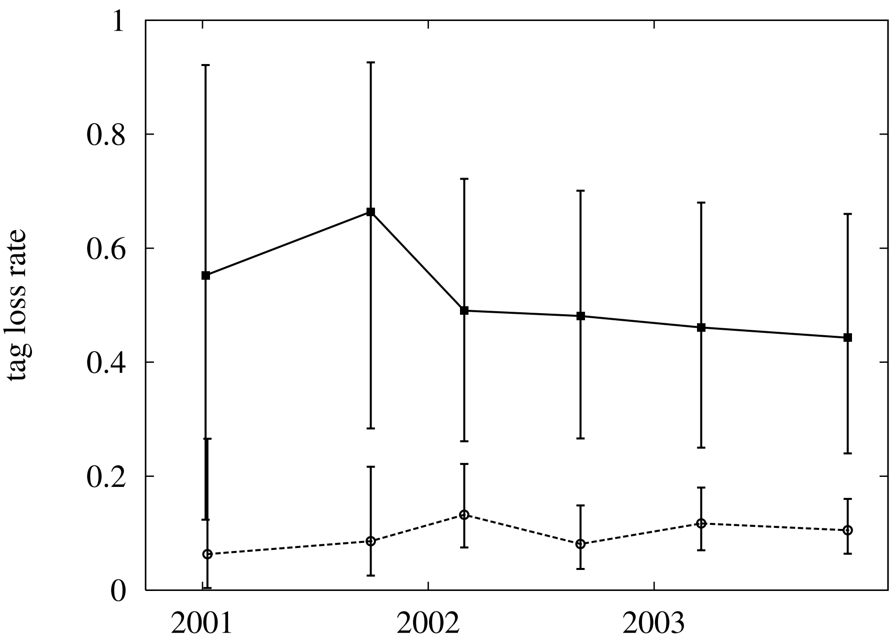


Fig 4.6.4.1 Tag shedding rates with 95% confidence intervals, assuming two tag type, calculated using data collected up to 6 different dates. Note that the confidence interval decreases as more data is added, and that there appears to be no consistent trend over time. Note also that the 95% confidence intervals do not overlap for the last 5 data points.

4.6.5. Incorporating tag shedding data into models

Problems with tag shedding records occurred in a large capture event on October 23, 2001, when a total of 190 fish were caught. Several of the double tagged fish captured and re-released on October 23, 2001 were recaptured again 12 days later with one tag missing. We believe that this increased tag shedding rate was due to problems associated with processing a large number of fish in a short time period, and a subsequent increase in tag shedding probability for fish caught and re-released on this date. We excluded the obvious tag shedding events associated with this 12 day period from our analysis. In addition to the temporary increase associated with this one event, other false tag shedding events have been reported when fish previously reported to have lost a tag were recaptured with the two original tags intact. To avoid these problems, we estimated tag shedding rates using data available to four different dates for both the one and two tag type models. This also allows exploration of a trend in the tag shedding rates over time.

When the same data are used to estimate tag shedding rates for either the one or two tag type models, the negative log likelihood values can be used to compare the fit of these two models using either the likelihood ratio test or Akaike Information Criterion (AIC) (Hilborn and Mangel, 1997). However, because additional data are used in estimating the tag shedding rates, the AIC cannot be used to compare models when tag shedding rates are estimated simultaneously with initial population size and mortality rates.

4.6.6. Sex Ratio

Given we want to remove all the female fish from the population, it would be useful to know the proportion of female fish in the untagged population. When fish were large enough to distinguish their sex this information was recorded. We made a preliminary analysis of these data to examine whether seasonal or longer term changes occur in the sex ratio of fish caught. To analyse the long term, or yearly trend, the short term monthly variability was filtered and linear, cubic and general additive models were fit to the resulting data.

4.6.7. Confidence Limits

The likelihood profile method (Hudson 1971, Cox and Hinkley, 1974, Venzon and Moolgavakar 1988, Hilborn and Mangel, 1997) can be used to calculate confidence intervals around point estimates for each parameter estimated. If the parameters estimated are represented as a vector, $\boldsymbol{x}$, the approximate confidence intervals for each parameter in turn, x_i, are the minimum and maximum values for $x_{i,sub}$ which satisfy:

$$L(r; x_i = x_{i,sub}, \overline{\boldsymbol{x_i}} = \overline{\boldsymbol{x_{i,opt}}}) - L(r; \boldsymbol{x} = \boldsymbol{x}_{opt}) = \chi^2_{1,1-\alpha} / 2, \qquad (29)$$

where $L(r;\boldsymbol{x}=\boldsymbol{x}_{opt})$ is the negative log-likelihood corresponding to the maximum likelihood estimate ($\boldsymbol{x}_{opt}$ represents the optimal parameter estimates) and $L(r; x_i = x_{i,sub}, \overline{\boldsymbol{x_i}} = \overline{\boldsymbol{x_{i,opt}}})$ is the lowest negative log-likelihood when parameter x_i is set to the sub-optimal value $x_{i,sub}$, $\overline{\boldsymbol{x_i}}$ represents the remaining parameters to be estimated, excluding parameter x_i, and $\overline{\boldsymbol{x_{i,opt}}}$ represents the optimal parameter estimates for the remaining parameters conditional on parameter x_i being equal to $x_{i,sub}$.

4.7. Future management options

A primary objective of this project was to provide advice to the Inland Fisheries Service on the probability that carp could be eradicated from Tasmanian lakes through physical removal and the level of effort that would be required. First, we analyse the catch and tagging/recapture data from Lake Crescent to estimate trends in catchability over time. We then extrapolate from these observations to predict what will be required to complete the eradication of carp from Lake Crescent.

In addition, we describe a database management system designed to assist IFS field technicians in recording carp catch, tagging and recapture data in a manner that will facilitate future analysis of mark and recapture data from lakes Crescent and Sorell. A major difficulty in this project was in using field data recorded on EXCEL spreadsheets in statistical models of the carp population. Difficulties arose because of inconsistent recording, inadequate field descriptors, and a lack of input verification. CSIRO and the IFS collaborated to design an ACCESS database that will resolve these shortcomings in the data and should facilitate routine updating of the population dynamics models.

5. Results & Discussion

5.1. Biological observations

Since 1995, there have been five successful spawning events, where success is measured by the recruitment of juveniles. Two of these recruitment events occurred in Lake Crescent during the summers of 1995/1996 and 1996/1997. In Lake Sorell, three recruitment events are known to have occurred, with low numbers of recruits during the summers of 1995/1996 and 1997/1998 and higher numbers of recruits from a spawning event in 2000.

In addition to these recruitment events, two further spawning events were observed in Lake Crescent in the summers of 1999/2000 and 2000/2001. Both these spawning events coincided with discharges of water from Lake Sorell to Lake Crescent through a 1km canal during periods of warm weather. The inflow of water to Lake Crescent attracted spawning aggregations. These aggregations were detected and spawning fish were caught and removed on both occasions. In 1999, carp were observed spawning on macrophytes in the canal and 247 carp were captured. An excavator was used to remove all macrophytes in the canal, thus reducing the likelihood of successful recruitment. There has been no evidence of successful recruitment from the 1999 spawning (new recruits are first caught when aged around 4 months old) but a subsequent spawning event probably in the summer of 2000/2001 appears to have limited recruitment with around 50 juvenile fish caught in Lake Crescent in the last two years. In November 2000, 182 fish were caught in two spawning aggregations, spawning on debris in the canal and spawning in the Clyde Marshes, again with some macrophyte and debris removal.

One option for improving capture rates of female fish in Lake Crescent is to stimulate a spawning event. When the lake level was lower and spawning habitat limited, spawning could be stimulated by the release of water down the canal joining Lake Crescent to Lake Sorell. Now that the lake level has risen and there is spawning habitat available in the western marshes, the release of water down the canal no longer stimulates a spawning event.

The repeated spawning events in Lake Sorell (1995/1996; 1997/1998; 2000) changed the management objectives for that lake. Instead of considering the release of additional male fish to stimulate aggregations, effort was concentrated on capturing the juveniles, while a few adult carp were still caught associated with the radio tracker fish. While the fish from the larger spawning in 2000 have remained juveniles and therefore indistinguishable by sex, all captured fish have been removed, because the risk of returning female fish to the lake was considered greater than any advantage that may have been had through improved monitoring using mark and recapture methods. Therefore there are no mark and recapture data to analyse for Lake Sorell and analyses in this report are restricted to Lake Crescent.

There are more marsh areas providing suitable spawning habitat in Lake Sorell than Lake Crescent. One of the approaches used to restrict spawning in Lake Sorell has been to exclude fish from the marshes with permanent fences. In some places the fences have been used as leads to steel traps where fish that have been moving along the fence in the spring (to start spawning and/or feeding aggregations) are caught (often with damage to their faces from the persistent pushing).

5.2. Trends in catch and effort data

Total effort per month, catch per month and catch per unit effort by month are presented in the following figures, where the unit of effort is shot (Fig. 5.2.1a), day (Fig. 5.2.1b) and elapsed time (Fig. 5.2.1c). Note that there is a significant amount of missing data on hours of effort, especially prior to 1997. Fishing techniques have improved consistently since the start of the eradication campaign (Section 4.3), so a unit of effort in 1996 is not strictly comparable to a unit of effort in 2003. Thus trends in catch per unit effort over time will underestimate the true decline in abundance, at least up the point, when gear avoidance increases.

Peak effort, as measured by number of shots, was in the spring and summer of the 1998/9 season (Figs. 5.2.1a & 5.2.2a). The peak in catch per shot was in 1996, with a steady decline since then. Monthly catch per shot data peaked in 1996 and 1997 and has declined rapidly since then. Tagged fish were not released until 1998 and it took several years for the number of tagged fish and catch rates to increase (Figs. 5.2.1a & 5.2.2a).

Catch per unit effort (by shot) decreased rapidly from peak values (average per month) of close to 40 in 1996 and 1997 to less than 10 since then (Fig. 5.2.1a). In contrast to the rapid reduction in catch per shot after 1996 and 1997, catch per day and catch per hour (Figs 5.2.1b and 5.2.1c) declined more gradually over time. Peaks in the monthly catch per unit effort (by day) remained close to 40 between 1996 and 2000 before declining consistently since then (Fig. 5.2.1b). The differences in these two measures of catch per unit effort result from changing effectiveness of the fishing effort (an increased number of shots per day between 1996 and 1999) and may also reflect the impact of handling time on the number of shots that could be made in a day in earlier years when large catches would have required greater processing time.

There is a strong seasonal concentration of effort in all years, representing the increased tendency for carp to aggregate during the peak reproductive season (spring and summer), and increased effort targeted to reduce the chances of a successful spawning occurring. The success of concentrating effort during the peak reproductive season is shown by the increases in catch and catch/effort at these times.

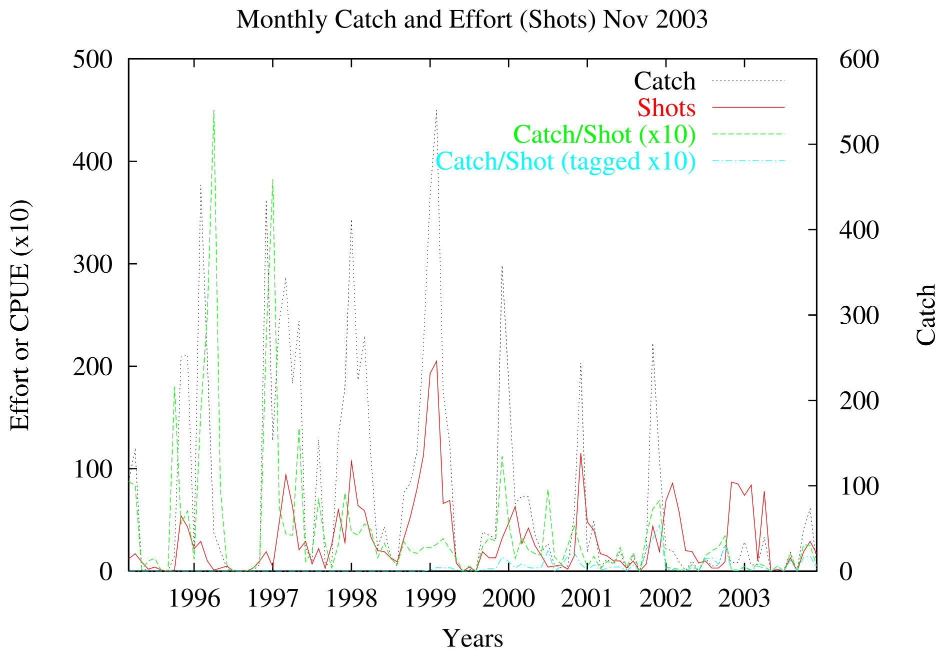


Fig 5.2.1a Monthly data for catch (dotted line, right axis) and effort (number of shots, solid red line, left axis) from February 1995 to November 2003. Also included are monthly averages for total catch per shot (dashed green line, left axis) and catch per shot for tagged fish only (dash-dotted blue line, left axis). Both sets of catch per shot data are scaled (x10) for clarity.

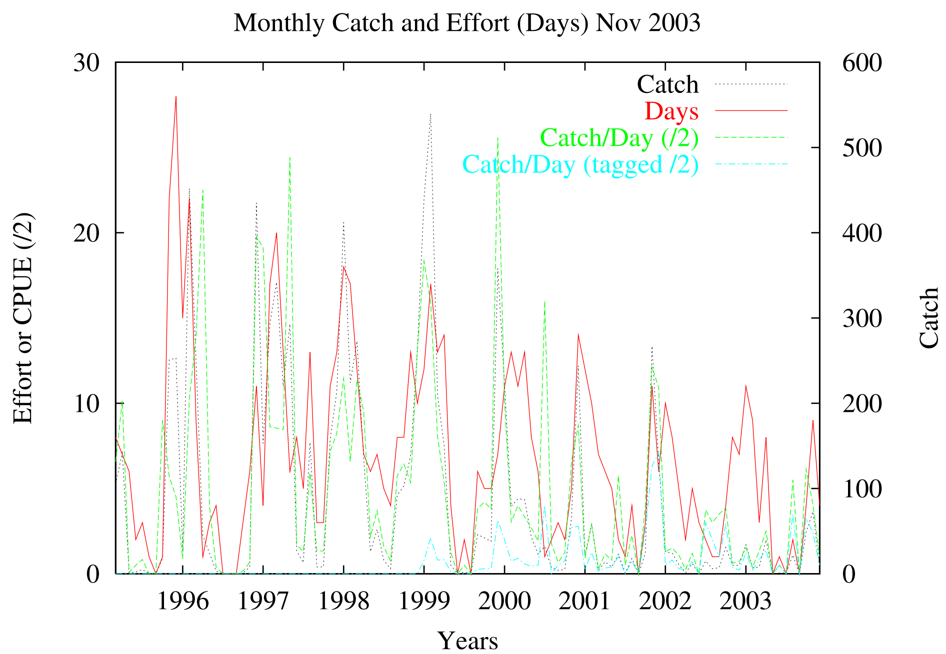


Fig 5.2.1b Monthly data for catch (dotted line, right axis) and effort (number of days, solid red line, left axis) from February 1995 to November 2003. Also included are monthly averages for total catch per day (dashed green line, left axis) and catch per day for tagged fish only (dash-dotted blue line, left axis). Both sets of catch per day data are scaled (/2) for clarity.

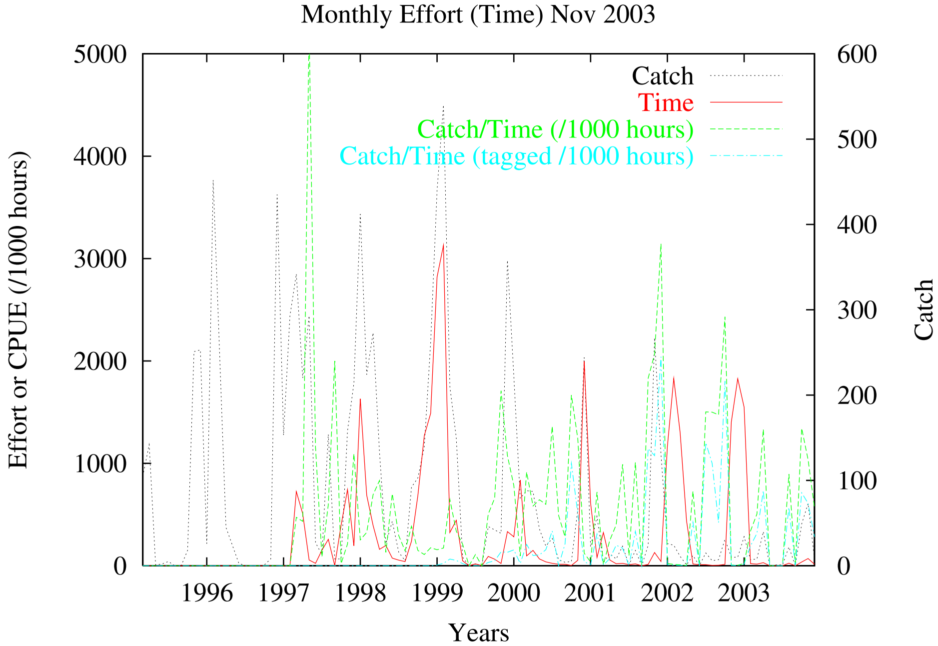


Fig 5.2.1c Monthly data for catch (dotted line, right axis) and effort (hours, solid red line, left axis) from February 1995 to November 2003. Also included are monthly averages for total catch per 1000 hours (dashed green line, left axis) and catch per 1000 hours for tagged fish only (dash-dotted blue line, left axis). Both sets of catch per day data are scaled (/1000) for clarity.

The yearly CPUE figures give a clearer indication of the long-term trends. Note that the last data point is for only 10 months of data, whereas other points indicate a full 12 months worth of data. Total catches were relatively similar between 1996 and 1999, but since 1999 show a consistent decline to the current low levels.

Effort in shots increased from 1995 to 1998 and subsequently decreased to a level comparable with earlier years. (Fig. 5.2.2a), while effort in days has decreased steadily since 1997 (Fig. 5.2.2b). Effort in terms of elapsed time has been variable and given its strong dependence on gear type and the missing data before 1997 is probably not a meaningful effort measure.

Catch per shot peaked in 1996 and decreased consistently since then (Fig. 5.2.2a). Catch per shot of tagged fish increased between 1998 and 2001 as the number of tagged fish released increased and has remained relatively stable (or declined slightly) since then reflecting changes in the abundance of tagged fish.

Catch per day peaked between 1996 and 1999, with a general decline since then. Catch per hour peaked in 1998, but missing data and changes in fishing methods over time means catch rates per hour are less meaningful than catch per shot or catch per day of fishing effort.

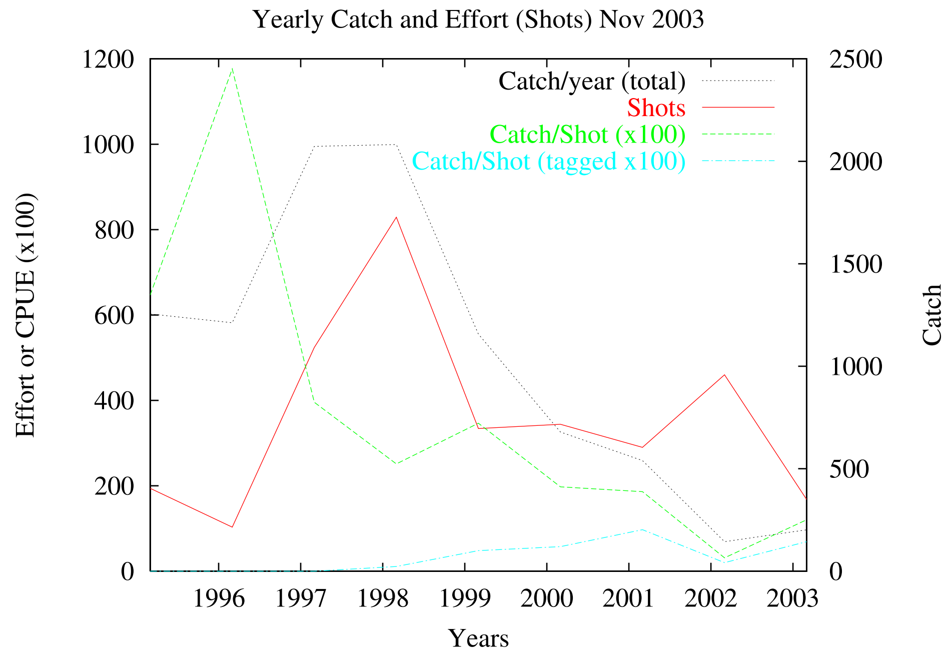


Fig 5.2.2a Yearly data for catch (dotted line, right axis) and effort (number of shots, solid red line, left axis) from February 1995 to November 2003. Also included are yearly averages for total catch per shot (dashed green line, left axis) and catch per shot for tagged fish only (dash-dotted blue line, left axis). Both sets of catch per shot data are scaled (x100) for clarity.

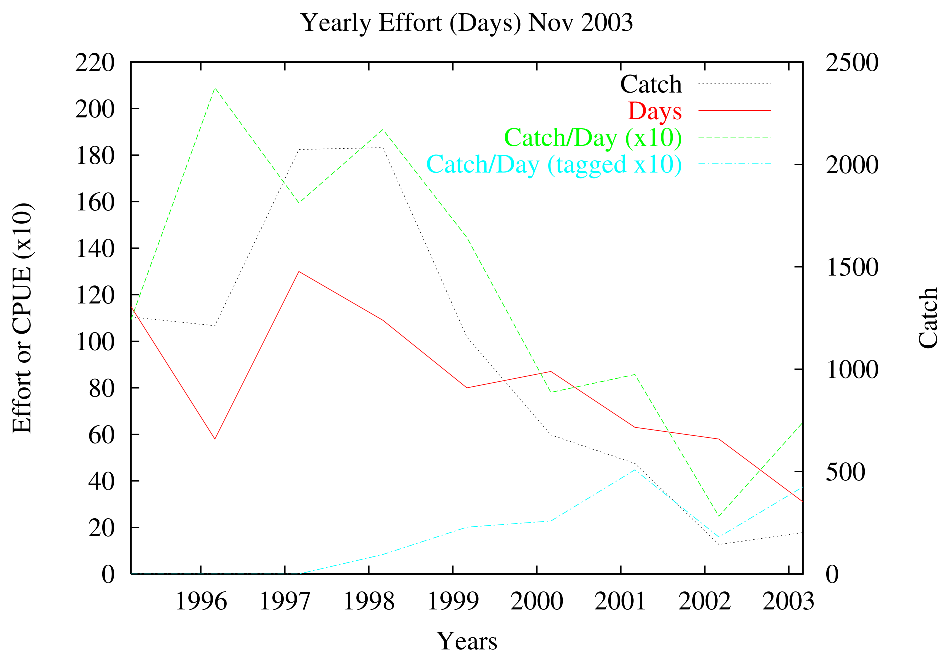


Fig 5.2.2b Yearly data for catch (dotted line, right axis) and effort (number of days, solid red line, left axis) from February 1995 to November 2003. Also included are yearly averages for total catch per day (dashed green line, left axis) and catch per day for tagged fish only (dash-dotted blue line, left axis). Both sets of catch per shot data are scaled (x10) for clarity.

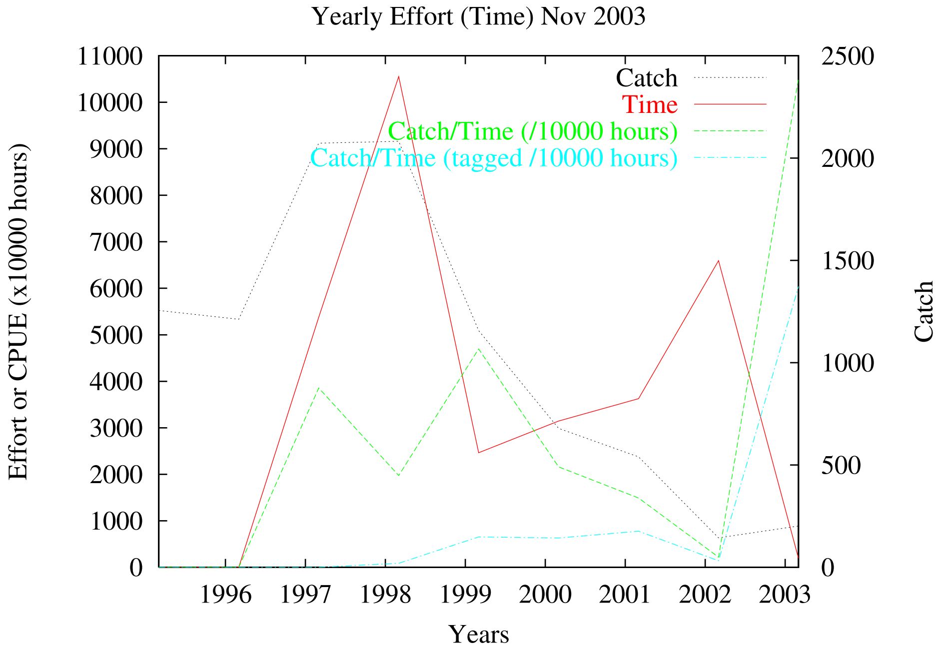


Fig 5.2.2c Yearly data for catch (dotted line, right axis) and effort (number of hours, solid red line, left axis) from February 1995 to November 2003. Also included are yearly averages for total catch per 10,000 hours (dashed green line, left axis) and catch per 10,000 hours for tagged fish only (dash-dotted blue line, left axis). Both sets of catch per hour data are scaled (/10,000) for clarity.

This variability in units of effort as the researchers learned to tailor their fishing methods towards a consistently diminishing resource, and the lack of any restrictions on the new techniques they could trial (eg. tracker fish) complicates the use of catch per unit effort data as an index of abundance. Observed changes in the behaviour of tagged and tracker fish – increased flightiness – that have been targeted and caught many times, further complicates the use of catch per unit of effort as an abundance index, especially when estimating the small population remaining near the end of the fishdown.

For these reasons we determined that the catch per unit effort data would not add to the information on population abundance based on the mark and recapture data and these data were not used in subsequent analyses of abundance.

5.3. Changes in sex-ratio over time and testing the aggregation hypothesis

The proportion of male untagged fish declined consistently from above 60 percent in 1996 to close to 10 percent in 2002 (Fig. 5.3.1). The increase in proportion of male fish in 2003 is based on a sample of less than 50 fish. The sex ratio was biased towards male fish (proportion male greater than half) in the first two years, followed by a 3 year period (1997-1999) with the sex ratio about even, followed by a rapid decline in the proportion of males in the untagged population.

The trend in sex ratio is likely to result from the differential growth rates between the sexes. Male fish mature more quickly than female and are likely to be available to the fishery earlier than the females. If the initial sex ratio is 0.5, then this will naturally bias the sex ratio in later years towards females. The vast majority of untagged fish captured in recent years have been female. An increase in the number of male fish caught in the last 12 months initially suggested a larger than previously estimated male population. However, closer analysis showed that the increase is due to the maturation of a new cohort: 13 of the 17 untagged males caught were old enough to be sexed, but were small enough fish that they can be assigned to the 2000 cohort. These new recruits were excluded from the analysis in Figure 5.3.1. Of the 36 female fish caught in 2003, 8 are likely to have been from the 2000 cohort. The final sex ratio is 0.125 (i.e. one male fish for every 7 females). A conservative approach would be to assume that all remaining untagged fish in the population are female.

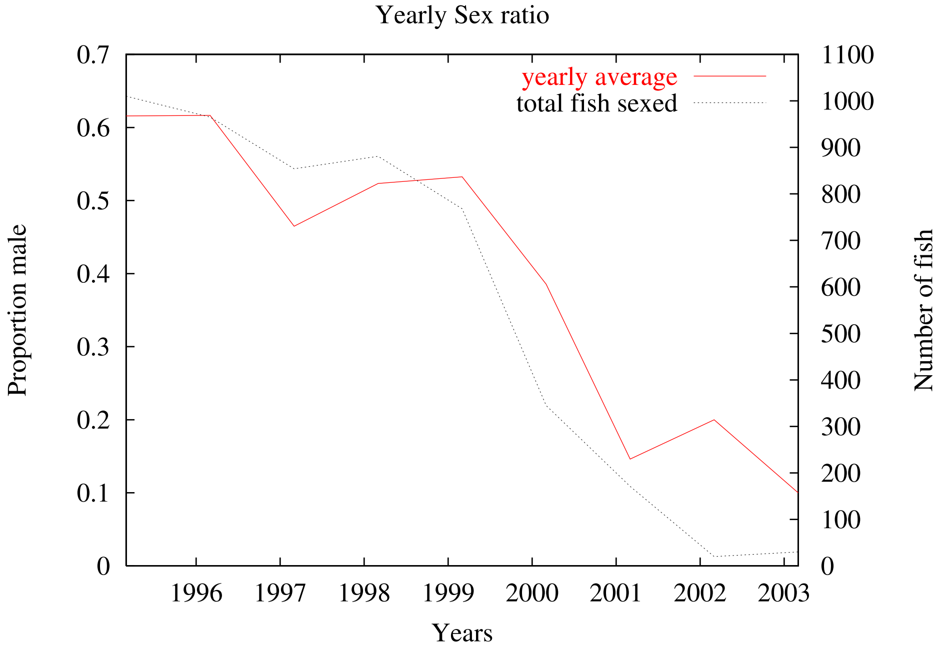


Fig 5.3.1 Yearly data showing the average sex ratio (solid red line, left axis) and the numbers of fish sexed (dotted line, right axis) from February 1995 to November 2003.

One method that was tested to increase the probability of catching the last female fish was to return male fish to the lake in the expectation that a large number of male fish would provide an aggregation, including female fish, that could be targeted, especially given the presence of tracker fish. Conversely, the concern was that if the number of males decreased below a certain level, then the females would not aggregate as frequently.

Given the confounding effects of the population decline over time, this aggregation hypothesis is difficult to test. Figure 5.3.2 shows the number of male fish plotted against the number of female fish for all individual catches which are greater than 30 fish, with catches sorted by year of capture. These data are based on catches per shot, and not on catches per day, so they are usually indicative of large catches using a single method at one location, rather than a combination of several smaller catches caught in different locations on the same day. The solid line shows where the number of males equals the number of females and the two dashed lines show where the absolute difference in the number of males and females caught is either 20 or 40. If female fish only aggregated with male fish (and vice versa), then catches would be expected to distributed close to the solid line. If female fish aggregated alone, then we would expect catches in the lower right quadrant; catches in the upper left quadrant would indicate that male fish aggregated alone.

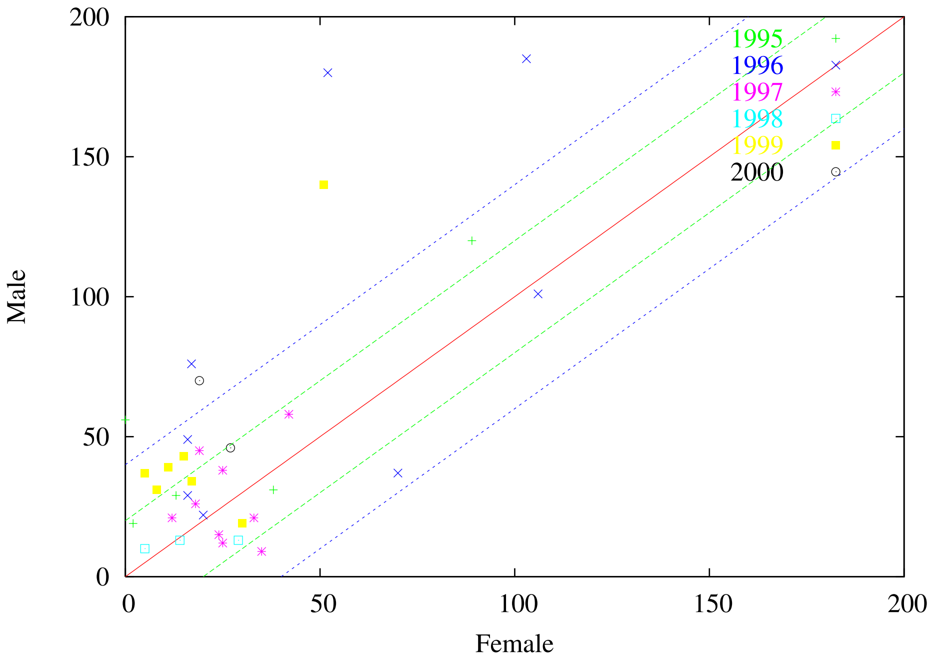


Fig 5.3.2 Numbers of male and female fish identified in any single shot where more than 30 carp were caught, classified by year of capture

In 1995, there were two catches with almost exclusively male adult fish, one catch with 19 males and 2 females (this catch included an additional 29 immature fish, which were not sexed) and another catch with 56 males and no females. In 1996, there were 3 large catches in which the number of male adult fish exceeded the number of females by 40 or more (185-103, 76-17 and 180-52). In 1999, there was a catch of 140 males and 51 females and in 2000 a catch of 70 males and 19 females. Apart from these two exceptions, large single catches have not been seen since 1996, and there appears to be no consistent bias in the sex ratio of these aggregations. There has been only one catch of more than 20 fish in a single shot since 2000 and only 11 catches in the range 10-20 in this period.

We conclude therefore that, although there may be a very slight tendency for male fish to aggregate by themselves, the overwhelming tendency is for male and female fish to aggregate together. There is a small qualification to this conclusion, namely that as only male fish were used as tracker fish, and (especially in recent years) fishing was targeted when 2 or more tracker fish were in the same location, there would have been a bias towards fishing aggregations that contained at least some males, and a bias away from aggregations consisting primarily of female fish.

The second conclusion is that there is little tendency for fish to aggregate (in numbers greater than 30) once the population declines beyond a certain level. In this instance, there was only one single shot involving catches above 20 fish since 2000, when the total population dropped below 1000 fish (see section 5.6). Thus although the aggregation hypothesis may be valid, it would require a much larger release (or retention) of adult males than was planned for in Lake Crescent.

Given that tagging began in December 1998, there is little evidence in these data that the additional male fish tagged and returned to the lake have contributed to an increase in aggregations, let alone any particular sex bias in aggregations.

Closer examination of catches was attempted to better bound the population size at which aggregations greater than 30 fish ceased, and whether the last few aggregations were predominantly of one sex or the other. Catches greater than 30 fish per shot were identified from the effort file, but sex ratios could only be obtained from fish in the biological file, and often the discrepancy between the number of fish in the effort file and the biological file is great. Part of the discrepancy is due to the fact that tagged fish which are captured and re-released appear in a separate tagged fish file, and while the date of these captures can be found, they cannot always be identified by shot. For example on November 30, 1999, there was a single catch of 191 fish, yet only 84 fish are recorded in the biological file. In the tagged fish file, there are 109 tagged fish released on this day, so in this case it is safe to assume that the extra fish are male. There are 7 cases with a discrepancy of 20 fish or more, where this discrepancy cannot be easily resolved by considering the tagged fish file and with discrepancies in both directions. The sex ratios are also affected by the numbers of tagged fish, which are almost all male fish, which are usually not recorded in the effort file. Sometimes these tagged fish are recorded in the biological file when they are killed but tag releases are not recorded in the biological file.

Assuming the inconsistencies in the data set don't affect this analysis, there is only one single shot where 20 or more fish were caught after November 2000 – 37 fish were caught on November 4 2001, but due to several other small captures on this date, it is unclear which fish in the biological file came from this event. Hence there is no information on the sex ratio of this particular catch. The only catches since tagged fish were returned to the lake are the 1999 and 2000 catches. Note that the first tag release in December 1998 included juvenile fish (both sexes) and the second tag release experiment started in December 1999.

Analysis of the daily catch rates (rather than the catch rate per shot) shows similar trends to the above analysis, but with one outstanding large catch. On October 23 2001, 190 fish were caught of which 71 were killed and sexed (51 female, 20 male). There were also 116 tagged fish released on this day (presumably all males), and 102 recaptured tagged fish. This additional data point does not change the conclusions drawn above.

5.4. Age composition and growth of captured fish (from CAF 2002)

Age estimates were determined by counting incremental structure along a transect from the primordium to edge on either the dorsal or ventral side. Figures 5.4.1a-d illustrate the position of increments found in otoliths for fish aged between 0+ and 3+ years respectively. A lot of incremental structure is visible in otolith sections which makes age estimation difficult, however, once the reader came more familiar with the morphological and incremental structure increments were relatively easy to count.

The presence of a spawning check in the otolith was not found. Whether the increments counted were deposited as a result of spawning activities or natural changes in environmental conditions is unknown. Increments counted may have been formed as a result of spawning. Because carp otoliths can be very interpretational with many growth checks present it is too difficult to attribute an increment or check to a particular event.
Interpretation of otoliths was based on those developed for carp captured in Victoria. Validation of annual increment periodicity has been completed on carp using oxytetracycline staining techniques (in press).

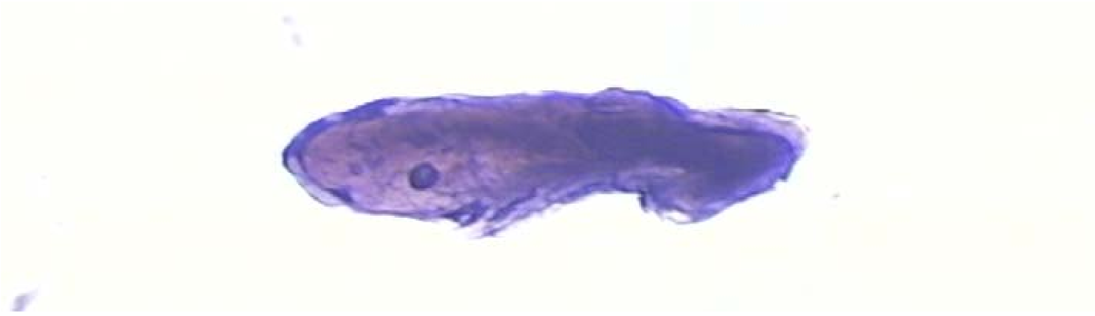


Fig. 5.4.1a. Transverse section of a carp lapillus. Arrows indicate position of increments. Estimated age 0 years.

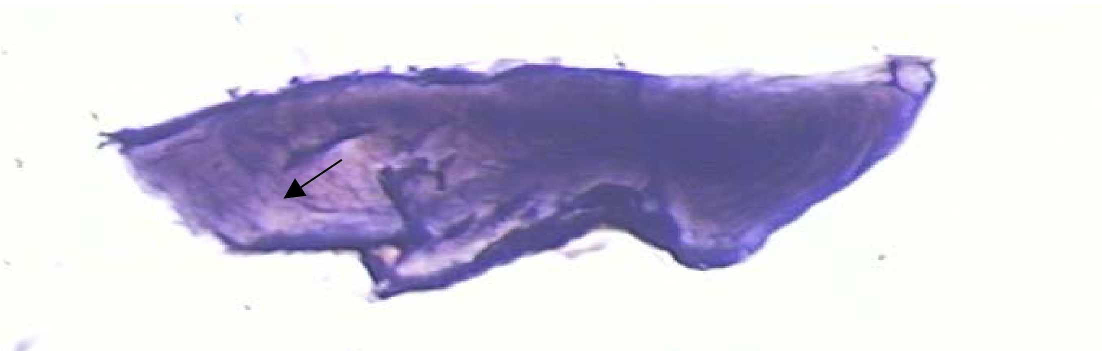


Fig. 5.4.1b. Transverse section of a carp lapillus. Arrows indicate position of increments. Estimated age 1 years.

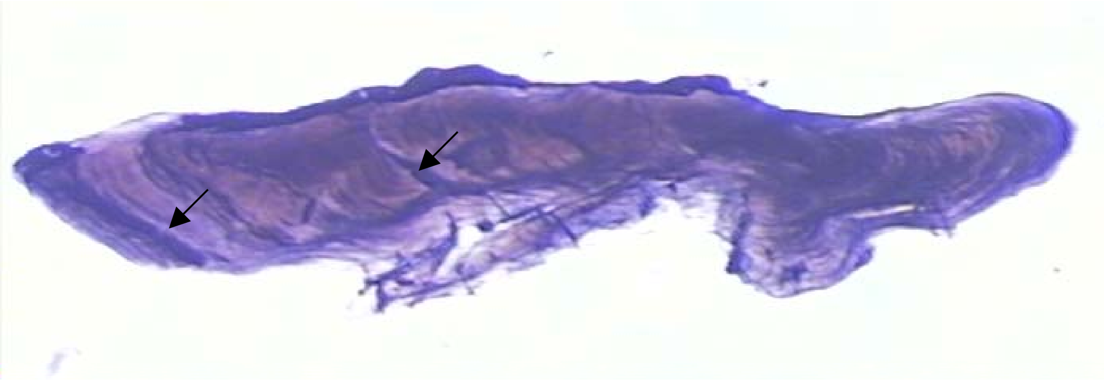


Fig. 5.4.1c. Transverse section of a carp lapillus. Arrows indicate position of increments. Estimated age 2 years.

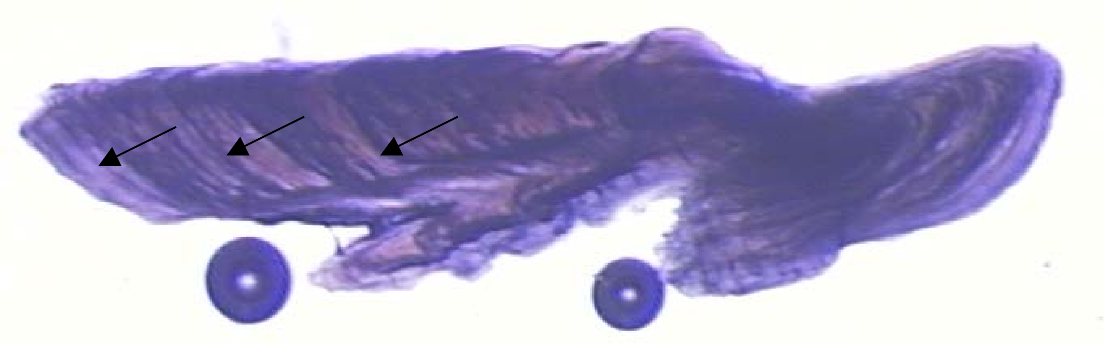


Fig. 5.4.1d. Transverse section of a carp lapillus. Arrows indicate position of increments. Estimated age 3 years.

5.4.1. Precision of age estimates

A total of 371 samples were re-aged. The IAPE for repeated readings was 4.82% which indicates the precision of the age estimates to be at an acceptable level. Experience with a range of species indicates that values should be less than 5% (Morison et al. 1998). The bias-corrected bootstrap IAPE was 4.83% with a 95% confidence interval of 3.9-5.7%. These figures are comparable to repeated readings from carp captured in Victoria.

5.4.2. Daily age estimation

Both sagitta and lapilli were used to estimate daily age of juvenile fish. Increments were relatively easy to recognise and were counted from the primordium to the edge along a transect of clearest incremental clarity (Fig. 5.4.2). Back-calculating the age to determine hatch date revealed that carp hatched between October and November.

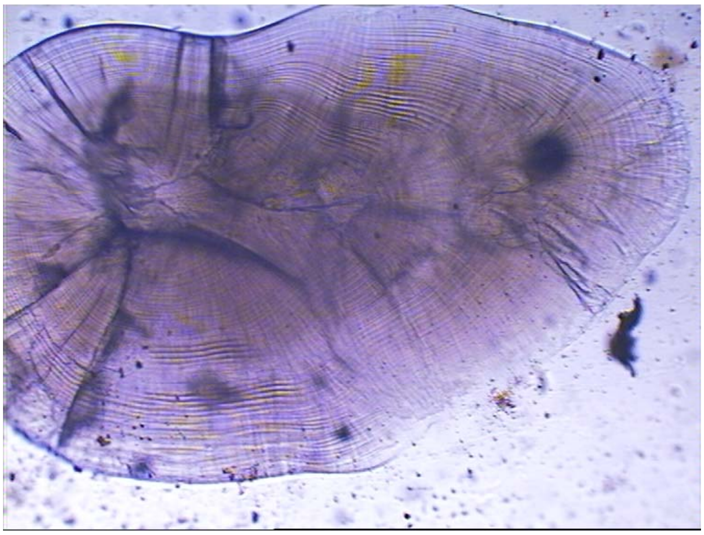


Fig. 5.4.2. Ground sagitta used for daily age estimation

5.4.3. Age of Lake Crescent carp from otolith data

Carp from Lake Crescent were estimated to be between 0 and 6 years old (Fig 5.4.3). Modal ages were between 2 and 4, indicating full recruitment occurs at about 2 years of age. Strong recruitments from fish that were age class 0 in 1995 and 1997, can be seen consistently in the annual age compositions from 1997 to 2000.

By comparison, carp elsewhere have been reported to live for more than 15 to 17 years, with anecdotal information suggesting ages of up to 60 years (Koehn et al. 2000). The oldest fish in sample of 603 carp from the lower Murray River was 15 years (Vilizzi and Walker 1999), while the oldest age in recent study in the same river was 23 years old (Brown and Walker 2003).

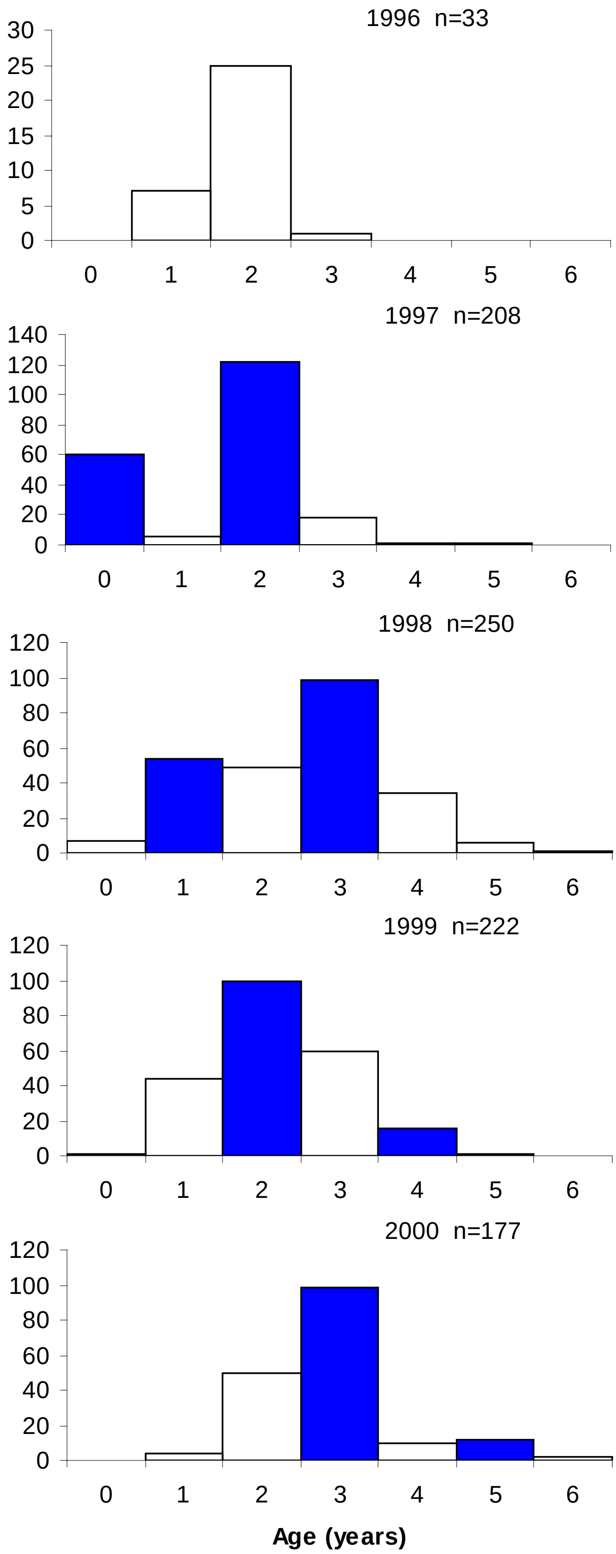


Fig. 5.4.3. Estimated age compositions from carp sampled from Lake Crescent (From CAF 2002)

5.4.4. Age of Lake Sorell carp from otolith data

The sample size of otoliths for ageing of carp in Lake Sorell was restricted to less than 30 fish per year (Fig. 5.4.4). There are no obvious differences in the age composition of carp in the two lakes. There is a suggestion of a strong recruitment event from fish that were aged 1 in 1999.

Fig. 5.4.4. Estimated age compositions from carp sampled from Lake Crescent (From CAF 2002)

5.4.5. Age-growth relationship from otolith data

The age-length data and the fitted von Bertalanffy growth curve are given in Fig. 5.4.5. For comparison, von Bertalanffy growth parameters from Campaspe and Barmah are given in Table 5.4.1. In comparison to these two mainland watersheds, carp in Lake Crescent grow far more rapidly, although final lengths are comparable. This is presumably because of the low population numbers in Lake Crescent, as temperatures are lower in these lakes than for the mainland watersheds, or alternatively there is a problem with the age data.

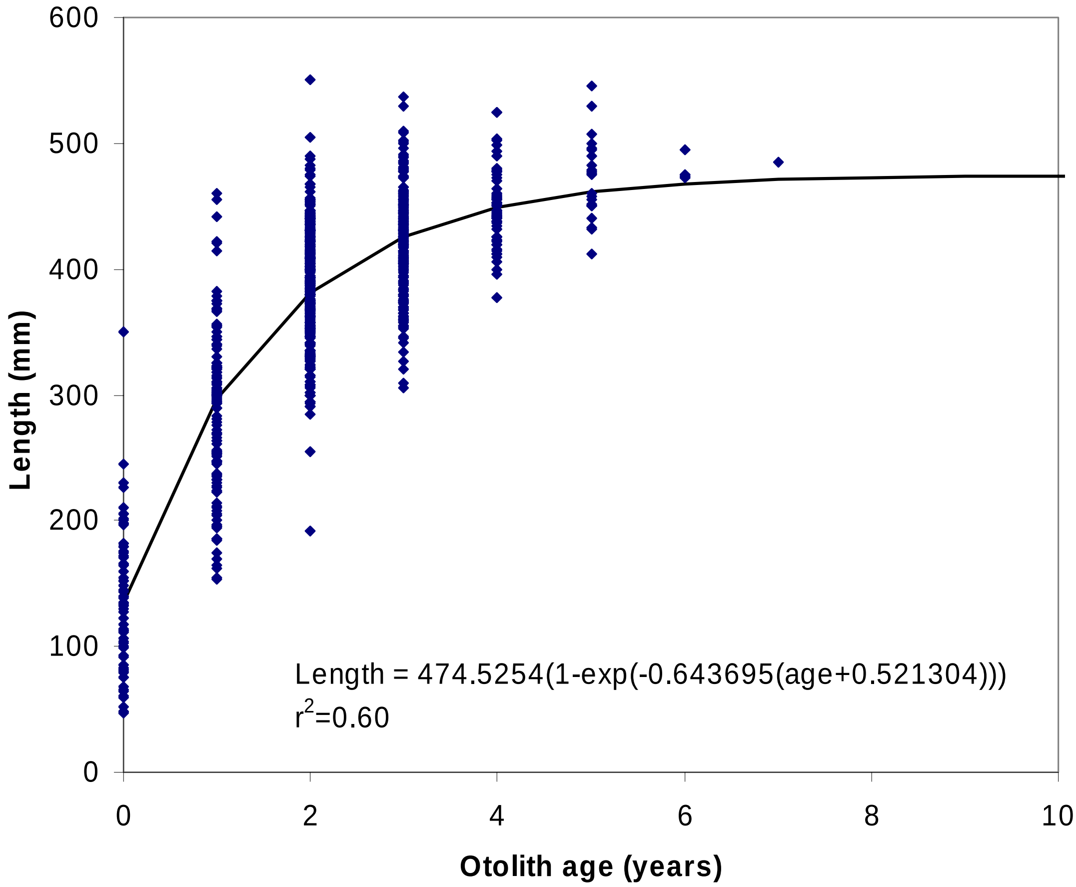


Fig. 5.4.5. Age-length composition of Lake Crescent carp and fitted von Bertalanffy growth curve (From CAF 2002).

Table 5.4.1. Estimated von Bertalanffy growth parameters from Lake Crescent and 2 mainland watersheds.

Lake	Sex	L•	K	t_0	Source
Crescent	Both	475	0.644	-0.521	This study
Campaspe	Male	495	0.475	-0.291	Brown and Walker 2003
	Female	538	0.380	-0.391	Brown and Walker 2003
Barmah	Male	489	0.249	-0.519	Brown and Walker 2003
	Female	594	0.177	-0.609	Brown and Walker 2003

5.4.6. Comparison of otolith ages with tagged fish results

Inland Fisheries Service fykenet surveys detected new cohorts of juvenile carp in Lake Crescent in January 1997 and in Lake Sorell in January 2001. As these cohorts have been caught in subsequent years they have provided growth estimates of growth for fish of a known age. Daily aging carried out by the Central Ageing Facility (CAF) on the Sorell carp fry otoliths from January and February 2001 indicated that the fish were between 2 and 3 months old.

The juvenile fish first caught in Lake Sorell in 2001 came from the first successful recruitment event in this lake for some years. There is no evidence of further recruitment in this lake since then. Length data were collected as this cohort aged, providing a distribution of fish lengths for fish aged 0, 1, 2 and 3 years old from this cohort. These distributions can be compared with the size distributions provided by CAF. The most notable feature of the observed size distribution, when compared to the predicted size distribution from the otolith ageing is the much smaller maximum size for each of these year classes (except age 0), and also a lower median size and a lower minimum size (Fig. 5.4.6).

Growth patterns for individual fish can also be obtained by following the growth rate of tagged fish over a period of up to five years, depending on when and if the tagged fish are recaptured. The ages of these tagged fish cannot be obtained independently, but an indication of the growth rates for fish with a range of initial sizes can be obtained. Not all of these fish will be from the same cohort. The initial tagging experiment (December 1998) included 75 adult fish and 291 juvenile fish. Given the spawning and recruitment history, these juveniles were at least two years old.

The first of the tagged juveniles from Lake Crescent to be recorded over 400 mm in length was caught in February 2000, when it would have been at least 4 years old (Figure 5.4.7). In contrast, otolith aging yielded five 400 mm plus carp at age 1 year and 43.6% of 2 year otolith aged carp were over predicted to be greater than 400 mm long (Figure 5.4.6). Similarly the first tagged juvenile to be recorded at over 450mm was in September 2003, aged at least 7 years old.

Similar analysis of the adults tagged in 1998, assumed to be at least 3 years old when tagged, indicates that the youngest tagged adult to reach 500mm was at least 6 years old and most fish that were at least 7 years old were less than 500mm long. The otolith ageing suggests that 2 year old fish can reach 500mm length.

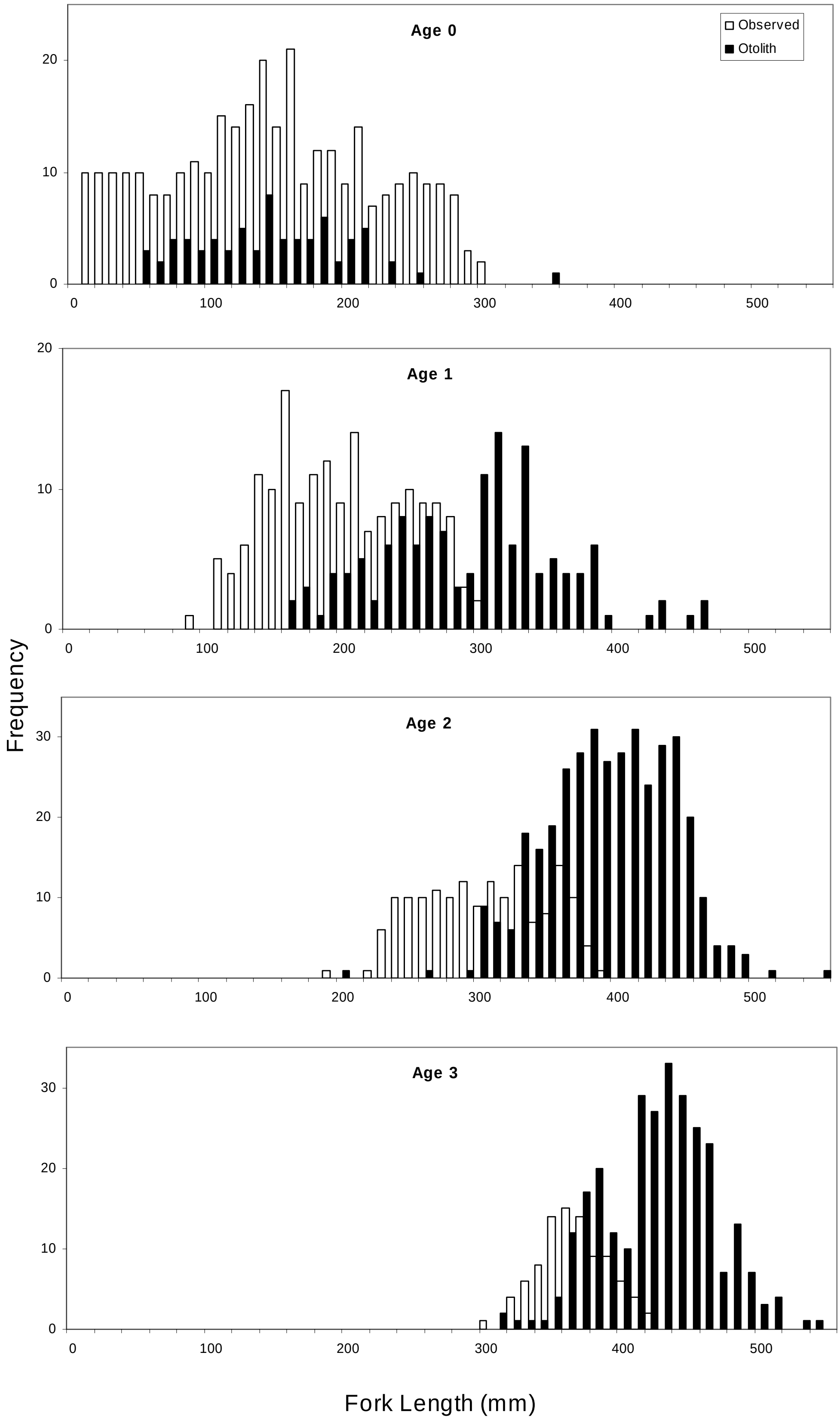


Fig. 5.4.6. Age-length composition of carp as indicated by catches of 2000 Lake Sorell cohort and lengths of Lake Crescent carp aged by otolith increment counts (From CAF 2002).

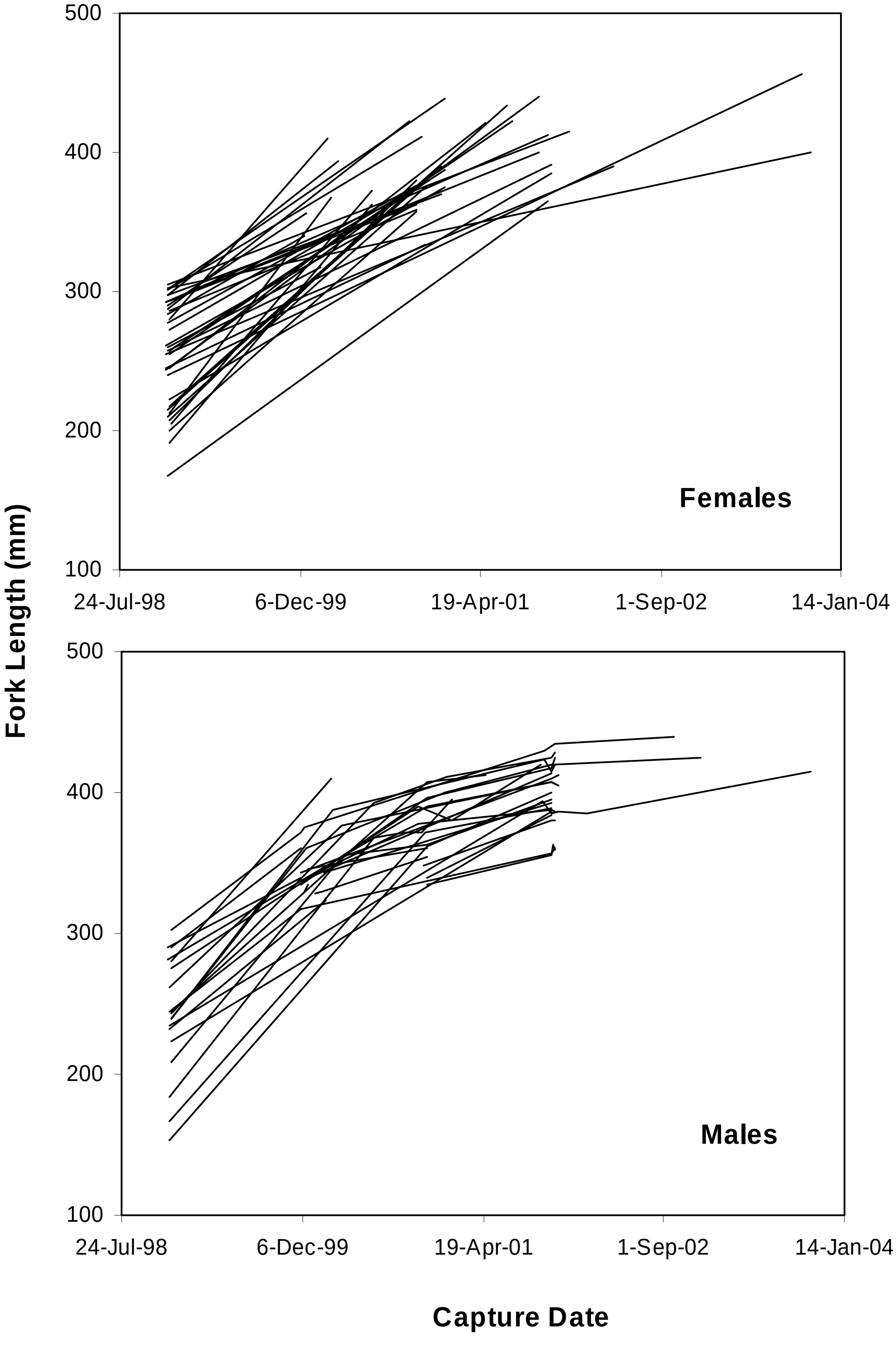


Fig. 5.4.7. Change in length of tagged carp from Lake Crescent.

Observed growth rates for the Sorell 2000 cohort support the accuracy of the daily aging by CAF of carp fry. Again, however, there are discrepancies between observed growth and yearly aging. A total of 643 year 0 carp were captured by April 2001. Fork lengths for these fish ranged from 59 to 174 mm (Fig. 5.4.6). Otolith aging yielded 72 Year 0 carp of which 19 were greater in length than the longest observed year 0 carp. The contrast between observed and otolith aged fish (Figure 5.4.6) increases to 56.4% of the 282 year 3 CAF aged carp being greater in fork length than the largest of the 244 year 3 Sorell fish captured by IFS.

5.5. Mark and recapture data

Individual catches (crosses) and tagged fish releases (circles) from 1995 to 2003 are shown in Fig. 5.5.1. As shown in the previous section there has been a rapid decline in catch size (catch per shot over time), with the frequency of larger catches declining over time. The first marked releases occurred in December 1998. Marked fish have been released at many times during each year since 2000. This figure gives a flavour of the seasonality of the frequency and size of catches and releases.

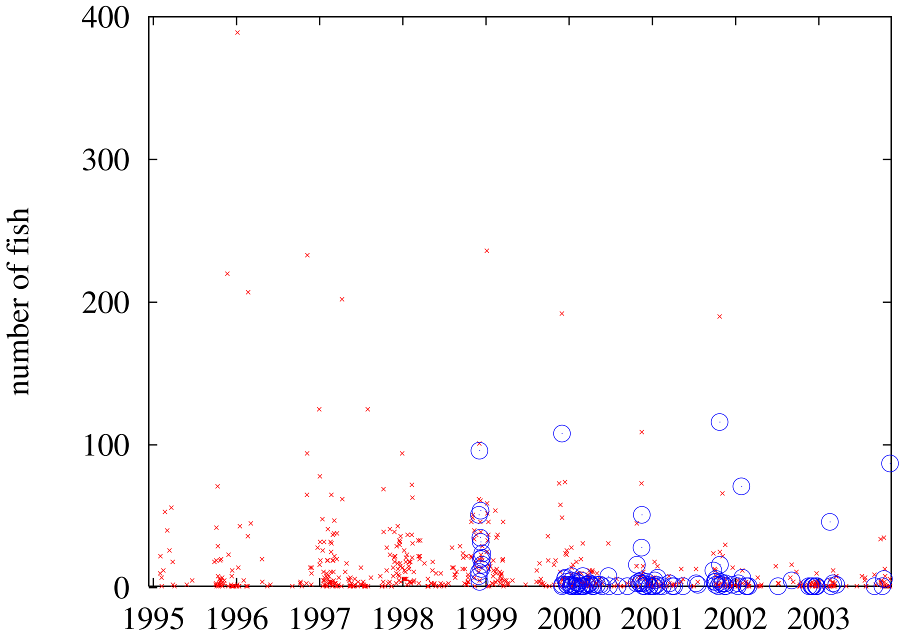


Fig 5.5.1 Daily catch (crosses) and tagged release (circles) data from February 1995 to November 2003.

5.6. Population modelling

The estimated total population (Fig. 5.6.1 red line) has declined steeply since 1998, due to the decline in the untagged population (green line), while the tagged population (black dotted line) has remained relatively flat since tagging started in 1999. This has led to a steep increase in the proportion of tagged fish (blue dotted line, right hand axis). Daily carp catch sizes above 20 (black asterisks) have steadily declined in number since the start of the fishery. Catches between 10 and 20 (yellow asterisks) and below 10 (blue asterisks) have also declined in frequency over the same period.

Two fixed recruitment events have been assumed for the model run that produced Fig. 5.6.1. Three thousand fish (assumed to be roughly one year olds) entered the population in late 1996 and a further 1500 fish entered the population in late 1997. These recruitment estimates are "intelligent guesses" using length frequency data, following the growth of these cohorts over time and estimating the numbers caught from the different age groups.

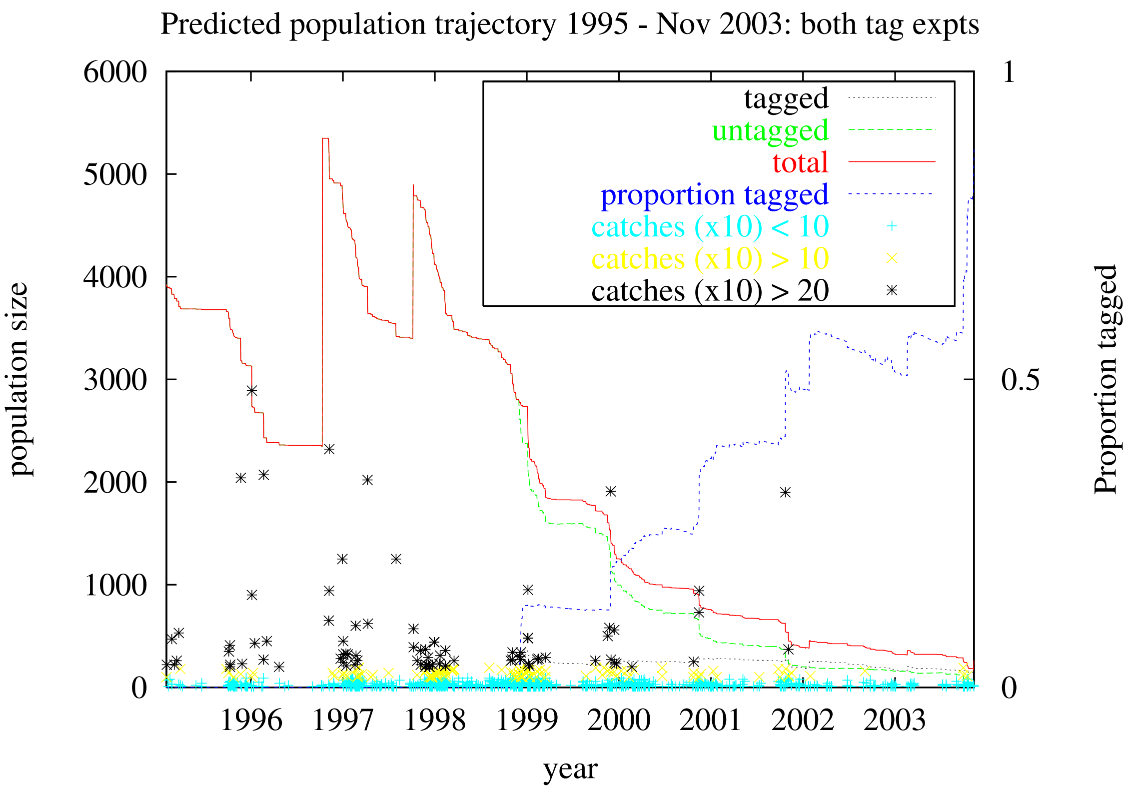


Fig. 5.6.1 Projected population trajectory from February 1995 to November 2003 (solid line, red, left axis), assuming recruitment events of 3000 fish in November 196 and 1500 fish in November 1997. This population trajectory is broken up into tagged (dotted line, black) and untagged (dashed line, green) fish and the proportion of tagged fish (small dashes, blue, right axis is also indicated. Daily catch sizes are plotted with catches greater than 20 fish (asterisks, black), catches between 10 and 20 (cross, yellow) and catches less than 10 (plus symbols, blue), with these daily catch figures all scaled (x10) for clarity.

Removing the assumption of when and how the fish entered the population (the actual number is determined for the start of the first tagging experiment), leads to a graph of the period from December 1998 (the beginning of the first tagging experiment) to March 2003 (Fig 5.6.2).

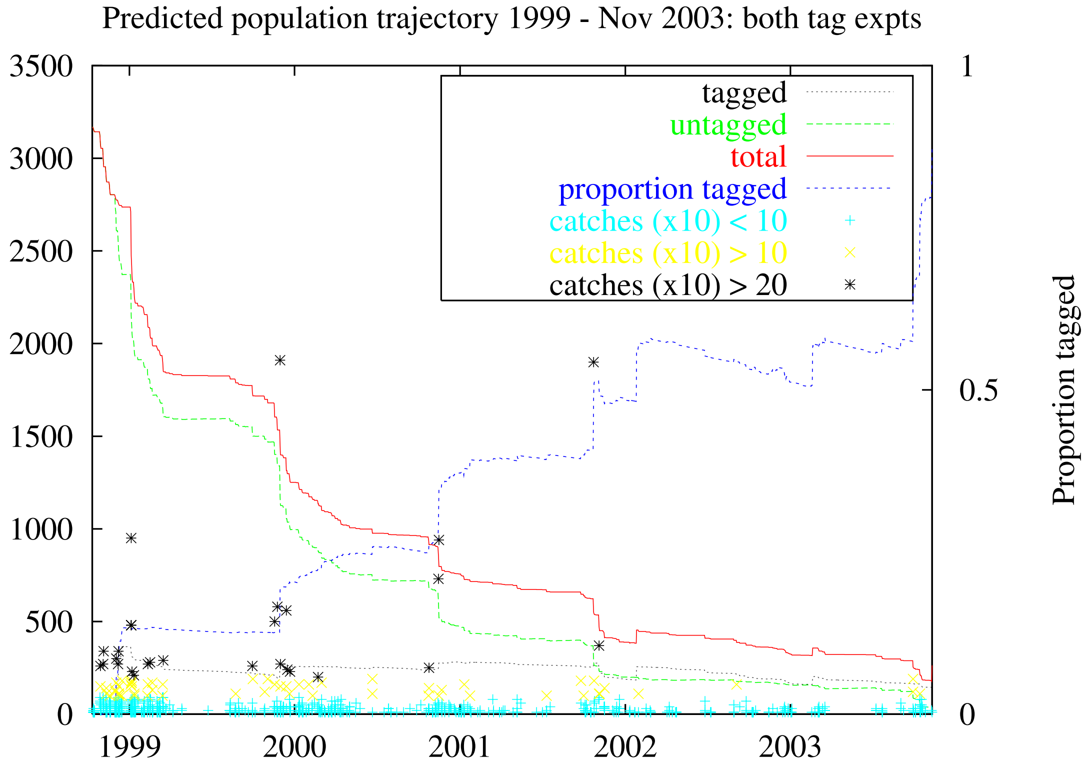


Fig. 5.6.2 The same data as in Figure 5.6.1, over a restricted time period, from November 1998, just before the first tagging experiment began through to November 2003.

The strongest trend is an overall decline in catch sizes as the total population declines. It is instructive to compare the estimated population decline in the model to that indicated by the catch and effort data alone. Between February 1999 and November 2003, the estimated population declined from 1900 fish to 33 (representing a decline to 1.7% of the population. By comparison, over the same time period, there was a decline from 3.5 to 0.7 in fish caught per shot (Fig. 5.2.2a) and a decline from 14.5 to 3.7 in fish caught per day of fishing (Fig. 5.2.2b) representing 20% and 25% declines in CPUE respectively. This illustrates the increased effectiveness of the IFS fishing strategies over time, and the reason why catch per unit effort is an unreliable indicator of abundance in a fishery where rapid technology developments are taking place.

5.6.1. Comparison of estimated and observed data

Population trajectories in the above two figures depend on the ratio of tagged to untagged fish. Examining the residuals of the expected (model) from the observed (field) tag ratios for each recapture event illustrates how well the model fits the data and whether there is a systematic bias in the fit (Fig. 5.6.3). For a good fit the residuals should fall either side of the predicted line, and the data points should generally follow this line, with more weight attached to the larger catch sizes. For example, if only 2 fish are caught, the sex ratio can only be, 0. 0.5 or 1, whereas the expected ratio can be exact as it is based on the whole population.

The observed tag ratio (circles) show considerable deviation from the expected tag ratio (line), which is to be expected as there are many environmental and behavioural effects that would effect the tag ratio in field operations, but which are not represented in the model. Deviations are especially high for small catches (represented by the smaller circles), where stochastic events might be expected to exert the most influence. However, larger catches, where stochastic effects are reduced, tend to follow the trend line and there is no evidence of a systematic bias in the model fit.

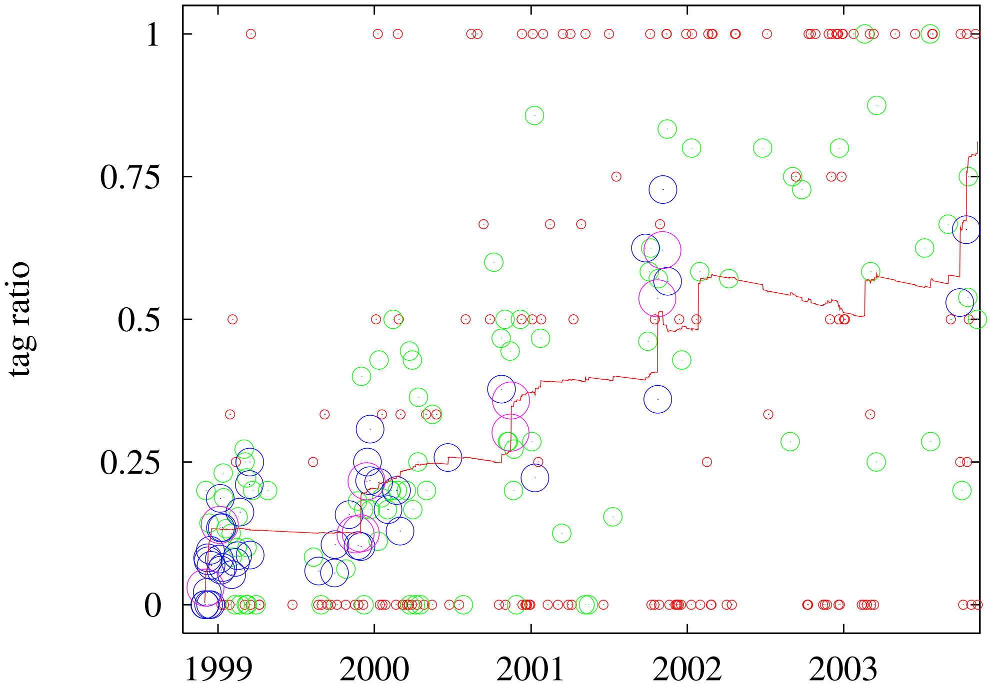


Fig. 5.6.3 Residuals for the tag ratio of the population model from the start of the tag shedding experiment. The solid line is the predicted daily tag ratio, which varies over time as fish are captured and as tagged fish are released, and the circles show the observed tag ratio of daily catches. The size of the circle is proportional to the catch size on that day, with, the smallest circles representing catches of size 1-4, and circles of increasing diameter for catches from 5-16, 17-64 up to 65-256, for the largest circles.

5.6.2. Consistency of model fits through hindcasting

To a make some assessment of the consistency of model predictions and the information value of additional data, we estimated the parameters only using the data collected up to six time points, with successive time points occurring at roughly 6 monthly intervals (Table 5.6.1).

The estimate of initial population size has remained very stable over time, altering by less than 1 percent. There has been some variability in estimates of tag loss, and a trend for a lower estimated tag loss for small tags, especially in the last time period. Variability in the tag loss of larger tags has been less, although in contrast to that for small tags, there has been an increasing trend. Estimates for natural mortality varied over several orders of magnitude, however the estimated values are so small that they are essentially noise in the model and would not noticeably affect other parameter estimates. The variation in individual parameter estimates, overstates the variation in other model outputs based on these estimates, as the parameters (especially the two tag losses and natural mortality) are highly correlated and tend to cancel each other out.

Table 5.6.1 Parameter estimates made using only the data available up to six different dates.

Date	Initial pop	tag loss small	tag loss large	mortality
06-Jan-01	3840.96	0.49245	0.030903	0.000264
30-Sep-01	3821.97	0.610846	0.05421	0.001967
28-Feb-02	3809.33	0.361612	0.088436	1.26E-05
04-Sep-02	3829.63	0.391748	0.058238	4.83E-08
18-Mar-03	3831.41	0.318516	0.08574	0.000114
10-Nov-03	3934.61	0.178822	0.068672	1.82E-06

The primary model output of interest is the estimated untagged population size – this is the number of fish remaining to be caught (Table 5.6.2). Population estimates for a fixed time, but based on different periods of data remained very consistent, varying less than 7 percent, until the most recent update (10 November 2003). Including the most recent data result in an increase in the untagged population estimates of 20->100 percent at all 6 time points, with the largest increases in estimates for the most recent times. Given that more than 100 fish have been caught in the last 8 months of data collection, the untagged population estimate of 65 untagged fish made using the data to March 18, 2003 is clearly wrong.

There are several possible explanations for the recent changes in model estimates:

- There has been a change in the behaviour of carp in the lake that has not affected tagged and untagged carp in a similar fashion (catchability is not modelled but it is assumed that tagged and untagged fish have the same catchability);
- The reduced estimate of tag loss for small tags is possibly driving the increased population estimate. Tag loss estimates are based on double tagged fish, few of which remain. The change in tag loss may be a statistical artefact;
- There has been unrecorded tag loss of single-tagged fish, whose scars have healed sufficiently quickly to be indistinguishable from untagged fish upon recapture;
- There is a sub-population in the lake that is only very occasionally available to capture (ie. they rarely associate with tracker fish). These fish will be gradually caught, and estimates of initial and current population size will gradually increase;
- Tagged fish (some of which have been caught and released 9 times) are becoming increasingly hard to catch, leading to an increase in the ratio of untagged/tagged fish caught (see next section);
- Environmental conditions in the spring of 2003 have been more suitable for successful carp spawning than in the previous three years and, as a result of increased spawning activity, recent catch rates have risen.
- The last of the females from the recruitment events in 1996/97 are maturing and have become available for capture in spawning aggregations.
- A combination of the above.

Table 5.6.2 Projected untagged population size at various times points. Each row contains projections using data up to the date specified in the first column.

Data available to	06-Jan-01	30-Sep-01	28-Feb-02	04-Sep-02	18-Mar-03	10-Nov-03
06-Jan-01	390.385					
30-Sep-01	362.689	286.575				
28-Feb-02	372.184	299.929	313.123			
04-Sep-02	384.571	309.315	333.631	95.7747		
18-Mar-03	387.133	313.98	333.537	104.399	65.0646	
10-Nov-03	468.738	390.306	438.578	177.033	138.002	32.4953

The IFS also produced separate population estimates for juveniles and adults, producing two November 1998 population estimates: 2566 fish for the Petersen estimator and 2423 for the Schnabel estimator. This contrasts with a November 1998 estimate of 2710 with 95% confidence intervals of (2694-2724) using the population method described below.

5.7. Effects of repeated multiple recaptures on subsequent recapture probability and population estimates

As the population in the lake has declined and many of the remaining fish are tagged, the number of times that tagged fish have been recaptured and re-released increases. Many fish have been re-released multiple times. Tracker fish have been observed to display net avoidance and boat avoidance behaviour, indicating that some individual fish learn how to avoid being recaptured.

The simplest analysis of tagged fish uses the assumption that all tagged fish behave identically and are equally likely to be caught. We investigate the validity of this assumption using two methods. The first method compares observed and expected number of fish in each "recapture number" class, with the expected number calculated by assuming equal probability of recapture for all fish, independent of the number of previous times an individual fish has been captured. The second method compares population estimates made only using the data from tagged fish in restricted subsets of the full range of "recapture number" classes.

To calculate the expected number of fish in each recapture class, we estimated daily totals of tagged fish in the lake by tracking the number of fish in each tag category (S, L, SS, SL, LL). These estimated daily totals include: daily catch information; daily transfers from category to category, through tag shedding (including known tag shedding events and fractional leakage at the estimated daily tag shedding rate) or through known additional tagging; and tracking the number of previous recaptures for each fish. Using these data, the expected numbers of fish in each recapture number category can be estimated, based on a binomial probability distribution and compared to the observed numbers for a given daily catch of tagged fish. We summed the observed and expected numbers in each category using the data to November 2003 (Table 5.7.1). A more sophisticated analysis would involve comparing the daily observed and expected numbers and checking for any temporal trends, but this analysis has not yet been carried out.

Table 5.7.1 Observed and expected number of recaptures, classified according to the number of previous recaptures (data to November 2003)

	Actual fish left	Expected fish left	Ratio of actual to expected
Fish alive but never recaptured	54.62	39.23	1.39
Number of recaptures	Actual recaptures	Expected recaptures	Ratio of actual to expected
1	507	602.10	0.84
2	184	174.86	1.05
3	112	89.49	1.25
4	70	41.99	1.67
5	40	19.67	2.03
6	15	8.46	1.77
7	8	3.40	2.36

If the probability of catching a tagged fish was independent of past capture history, then the ratio of actual to expected would equal one. However, this table shows a larger than expected number of fish that were tagged and never recaptured. This may result from the short-term loss of tags after tagging. Tags are thought to be more vulnerable to loss until they have become well embedded in the flesh. In contrast to the actual number of first, second, third recaptures of tagged fish, it is not possible to count the actual number of tagged fish which have been never recaptured, as these fish are never observed again. The number of actual fish left is calculated by monitoring daily catch data, and imposing the maximum likelihood values for mortality and tag shedding on any of these fish in this class (hence the fractional numbers of fish), and removing any fish that are recaptured for the first time. The first row of Table 5.7.1 is reporting numbers of fish that have not been captured while the other rows are counting fish that have been captured, so the ratio of actual to expected has contrasting meanings. A value greater than 1 for the first row suggests that these fish are less likely to be captured than would be expected if the assumption of equal catchability holds, so these fish are less likely to be recaptured than any of the other recapture classes.

Table 5.7.1 shows an increase in the recapture probability for the fish which are recaptured as the number of recaptures increases. There are several ways of explaining these data:

- These fish start to become “trap-happy” - the more times they are caught the more willing they are to be caught again. This observation does not match field observations on radio-tracked fish that seem to have become increasingly flighty as the number of times they have been caught increases;
- There is an inherent variability in the behaviour of the carp making them more or less likely to be caught. Carp that had been caught multiple times would be those inherently more amenable to capture. Observations on electronically tagged fish suggest two distinct behaviours. One behaviour is for the fish to

move around and these fish seem to be susceptible to capture at all times of the year. The second behaviour is for the fish to stay in one spot for many days (sometimes being "visited" by the more mobile fish). These fish can return to the same spot for several months, even when they are electrofished every day on the off chance that other fish area associated with them. When these resident fish start to move, it typically indicates that a spawning aggregation is about to occur.

The second explanation has serious implications for the population estimates and the fishdown. If there is a natural variability in willingness to be caught (or avoidance capability), then as the population declines, the remaining fish will be increasingly composed of hard to catch fish. These fish may only be available to the fishing gears when there is a spawning aggregation. In addition, population estimates will gradually increase (as observed in Table 5.6.2) as the harder to catch fish are eventually caught.

Given the differences in the observed and expected ratios, we examined a range of population estimates made using only the data from tagged fish in restricted subsets of the full range of "recapture number" classes. We first excluded high recapture number fish - fish that had been recaptured and released more than x times (where x went from 1 to 8). This accounts for any bias introduced due to the apparent increase in catchability for tagged fish with increased number of recaptures. This is equivalent to redefining the number of tagged fish in the population to be the number of tagged fish that have been re-released less than *x* times. The maximum number of re-releases was 8, so for *x*= 8, this is equivalent to including all tagged fish.

Excluding high recapture number fish results in an increase in the final population estimate of untagged fish, and simultaneous increases in the initial population estimate and tag shedding estimates (Table 5.7.2). These increases are initially small, corresponding to relatively small numbers of high recapture number fish being excluded (small differences in the number of "tag releases").

Including high recapture number fish in the analysis appears to bias the final untagged population estimates downwards. One way to reduce this would be to exclude high recapture number fish from the analysis.

Table 5.7.2 Parameter estimates, November 2003 tagged and untagged population predictions and negative log likelihood for a range of models which progressively exclude tagged fish re-released after an increasing number of recaptures.

No. of recaps used	Untagged fish	Tagged fish free	Pen fish	Small tag loss	Large tag loss	mortality	Init pop 1998	Likelihood (-ve log)	Tag releases
8	31.6	141.7	87	0.192	0.069	0.00027	2801	1850.18	1173
7	31.6	141.7	87	0.192	0.069	0.00027	2801	1850.18	1173
6	32.9	142.4	83	0.194	0.070	0.00052	2805	1851.72	1168
5	32.9	144.6	77	0.193	0.070	0.00043	2816	1856.13	1157
4	44.0	141.6	67	0.191	0.071	0.00052	2834	1856.52	1134
3	59.8	137.7	46	0.193	0.075	0.00001	2878	1859.77	1078
2	88.8	127.8	29	0.201	0.082	0.00000	2968	1848.80	991
1	126.9	95.2	13	0.231	0.091	0.00014	3101	1773.93	848
0	159.4	56.8	0	0.278	0.102	0.00002	3303	1539.39	626

The last row of Table 5.7.2 suggests there we expect 57 tagged fish that are in the lake which have been captured once, tagged and never recaptured, allowing for the effects of average mortality and tag shedding. To investigate the possible bias from zero and low recapture number fish, analyses were run including all fish released more than 5 times, but successively excluding the tagged fish from the analysis before a particular number of recaptures (Table 5.7.3). The number of tag releases available for the estimates rapidly declines, as the number of fish excluded increases, limiting the reliability of the latter rows. The most significant result from this table is that including fish on their first recapture appears to bias the population estimate upwards, possibly due to the fact that the model seems to over predict the number of fish in the tagged and never recaptured category. If we assume that these 57 tagged and never recaptured fish are still in the lake, and the reality is that there are fewer of these fish (due to tag shedding or mortality anomalies), then the final population estimate is biased upwards. There also appears to be a downward trend in the final population estimate as more low recapture number fish are excluded, although this trend may be confounded slightly by variation in the tag shedding estimates, and low number of tag releases in the last two rows.

Table 5.7.3 Parameter estimates, November 2003 tagged and untagged population predictions and negative log likelihood for a range of models which progressively exclude data on tagged fish before a specified number of re-releases.

No. of recaps ignored	Untagged fish	Tagged fish free	Pen fish	Small tag loss	Large tag loss	mortality	Init pop	Likelihood (-ve log)	Tag releases
0	31.6	141.7	87	0.192	0.069	0.00027	2801	1850.18	1173
1	18.1	62.7	87	0.238	0.067	0.00014	3334	968.72	547
2	12.6	31.1	74	0.282	0.073	0.00000	3505	669.64	325
3	6.3	8.6	58	0.282	0.086	0.00017	3604	465.59	182
4	13.8	6.0	41	0.421	0.097	0.00004	3680	308.08	95
5	9.9	2.5	20	0.438	0.103	0.00001	3706	169.59	39

Given that there appears to be bias in estimates using high recapture number fish (Table 5.7.2) and biases using the fish on their first release (Table 5.7.3), we examined population estimates from fish released and recaptured at least once, but not more than x times (Table 5.7.4)). As before (Table 5.7.2), including high recapture number fish in the analysis appears to bias the final untagged population estimates downwards. Note that the number of tag releases is significantly lower than the estimates used for Table 5.7.2, as this analysis excludes the first release of all tagged fish, or more than half of the records (626 out of a total of 1173).

Table 5.7.4 Parameter estimates, November 2003 tagged and untagged population predictions and negative log likelihood for a range of models which exclude data from tagged fish on their first release and which progressively exclude tagged fish re-released after an increasing number of recaptures.

No. of recaps used	Untagged fish	Tagged fish free	Pen fish	Small tag loss	Large tag loss	mortality	Init pop	Likelihood (-ve log)	Tag releases
8	18.1	62.7	87	0.238	0.067	0.00014	3334	968.72	547
7	18.1	62.7	87	0.238	0.067	0.00014	3334	968.72	547
6	19.4	63.3	83	0.245	0.068	0.00009	3338	967.68	542
5	22.4	66.0	77	0.250	0.069	0.00010	3347	967.81	531
4	26.8	63.0	67	0.256	0.069	0.00013	3362	954.33	508
3	37.7	58.9	46	0.290	0.076	0.00000	3403	929.29	452
2	65.0	54.2	29	0.326	0.088	0.00000	3496	866.32	365
1	100.4	28.5	13	0.361	0.101	0.00012	3634	682.45	222

Finally, we repeat the exercise one more time to obtain population estimates using just the data obtained from particular release numbers (Table 5.7.5). These can be considered statistically independent estimates of the population size as each estimate depends only on data from one recapture number class. The most important result from this table is that when only the first release is considered, we expect an overestimate of the final population. While we would expect an underestimate of the final population as we move down this table, the estimates are unlikely to be very accurate past the second recapture class due to the small numbers of tag releases on which these estimates are based (see the figures in the final column).

Table 5.7.5 Parameter estimates, November 2003 tagged and untagged population predictions and negative log likelihood for a range of models which only include data on tagged fish from the specified number of re-releases.

No. of recaps used	Untagge d fish	Tagged fish free	Pen fish	Small tag loss	Large tag loss	mortality	Init pop	Likelihood (-ve log)	Tag releases
0	159.4	56.8	0	0.278	0.102	0.00002	3303	1539.39	626
1	100.4	28.5	13	0.361	0.101	0.00012	3633	682.45	222
2	64.9	24.9	16	0.409	0.096	0.00000	3675	458.21	143
3	5.83	2.5	17	0.430	0.089	0.00000	3651	327.86	87
4	27.4	5.7	21	0.417	0.101	0.00000	3711	241.40	56
5	100.3	6.3	10	0.442	0.106	0.00001	3807	129.66	23
6	19.3	0.0	6	0.443	0.105	0.00001	3727	92.01	11

Variation in tag shedding estimates between rows of the tables in this section can impact the final population estimates. The effects of this can be quantified by fixing tag shedding rates. While this changes the absolute values of the final population estimates, the same trends are still apparent in all cases, with the exception of Table 5.7.3, where the estimates are also limited or confounded by small numbers of tag releases.

Results from the previous 4 tables are combined in Table 5.7.6, listing only the November 2003 untagged population predictions. Results from the previous 4 tables are listed respectively in the first column, the last row, the second column and the diagonal.

Table 5.7.6 also includes some additional estimates to fill all the entries in this table, Table 5.7.7 shows the number of tag releases used in making these final untagged population estimates.

Table 5.7.6 November 2003 untagged population predictions as functions of the numbers of multiple recapture fish excluded from the analysis. Moving down the columns corresponds to including more high recapture number fish and moving across the rows corresponds to excluding more lower recapture number fish.

	Exclude lower recapture numbers below:									
Exclude higher recapture numbers above:		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	0	159.4								
	1	126.9	100.4							
	2	88.8	65.0	64.9						
	3	59.8	37.7	30.2	5.83					
	4	44.0	26.8	20.0	11.3	27.4				
	5	32.9	22.4	17.3	12.5	33.3	100.3			
	6	32.9	19.4	14.2	8.6	20.7	29.9	19.3		
	7	31.6	18.1	12.6	6.3	13.8	9.9	*	*	
	8	31.6	18.1	12.6	6.3	13.8	9.9	*	*	*

Table 5.7.7 The number of tag releases used in the population estimates reported in Table 5.7.6.

	Exclude lower recapture numbers below:									
Exclude higher recapture numbers above:		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	0	626								
	1	848	222							
	2	991	365	143						
	3	1078	452	230	87					
	4	1134	508	286	143	56				
	5	1157	531	309	166	79	23			
	6	1168	542	320	177	90	34	11		
	7	1173	547	325	182	95	39	16	5	
	8	1173	547	325	182	95	39	16	5	0

The results in Table 5.7.1 suggest problems with estimates made by including fish from the zero recapture class, as these fish appear to be over represented in the final population, assuming equal catchability of fish from each recapture class. We earlier suggested that this over representation may be a result of problems with mortality and tag shedding estimates. If the number of fish in this class (fish tagged once and subsequently never recaptured) is actually smaller than the model estimate of 55 fish, then the final untagged population estimate will be biased upwards (overestimating the number of untagged fish left). Table 5.7.6 enables a comparison of the effect of removing these first release fish from the analysis, by comparing columns 1 and 2. This line by line comparison shows a drop in the final population estimate if the first release fish (recapture number = 0) are excluded from the analysis. While there may be some bias from the zero recapture class, there is also a large amount of information, provided by the large number of first post-tagging captures of fish, all of which come from this class. By comparing the entries in columns 1 and 2 of Table 5.7.7., it can be seen that excluding these zero recapture class fish reduces the number of tag releases used in the population estimate by more than half in all cases.

Table 5.7.1 also suggests a bias from the high recapture number fish, which appear to be recaptured more often than expected, assuming equal catchability of fish from each recapture class. Including these high recapture number fish in the analysis will result in an increase in the tag fish ratio in catches, which will result in a downward bias on the estimate of the untagged fish population. Table 5.7.6 generally confirms this bias. Moving down the columns in Table 5.7.6 generally results in a decrease in the final untagged population estimate, as high recapture fish are included in the analysis. The exceptions to this general rule occur when the number of tag releases used to make the estimate is relatively small, and hence these estimates are not so reliable.

There is clearly a trade off to be made in excluding sources of bias. Including low recapture number fish bias the estimates up and including high recapture number fish biases the estimate down. As well as balancing these conflicting sources of bias, some balance need to be found in including sufficient tag releases to get a reliable final population estimate.

Interpretation of these results is not clear-cut. If we exclude fish recaptured less than once and more than 6 times and (somewhat arbitrarily) restrict ourselves to instances where the number of tag releases is more than 300, then the final untagged population estimate lies somewhere in the range of 14-65 fish (ignoring confidence intervals around these estimates). If we expand the acceptance criteria to include tag releases greater than 200 fish, the range increases to 14-100 fish. Given the uncertainties involved in the behaviour of fish and possible tag loss, this seems a reasonable guide to the November 2003 population estimate.

5.8. Estimated time-frame to extinction assuming no recruitment events

Fishing success per day of fishing effort can be split up into the probability of catching any fish, and a conditional probability of catching a particular proportion of the available population of fish, given that some fish were actually caught. We examined trends in the data for daily fishing success and catch sizes as a function of the predicted untagged population size.

The probability of catching at least one fish on a particular day ranges from 0.29 (1995) to 0.83 (1998), with considerable variation in this probability from year to year. There appears to be an initial increasing trend in probability of capture to 1998, followed by a decreasing trend to 2002. The most recent 2003 data should be treated with caution as they result from only a partial year's fishing. The change from an increasing trend to a decreasing trend in probability of capture in 1998 coincides with the introduction of the final significant technological advance – the introduction of radio-tagged tracker fish. Thus it is possible to explain the increase in probability of recapture by technological advances (learning by the fishers). The decline in probability of capture since 1998 coincides with the start of the major population reduction in the lake, and thus may be due to learning by the fish.

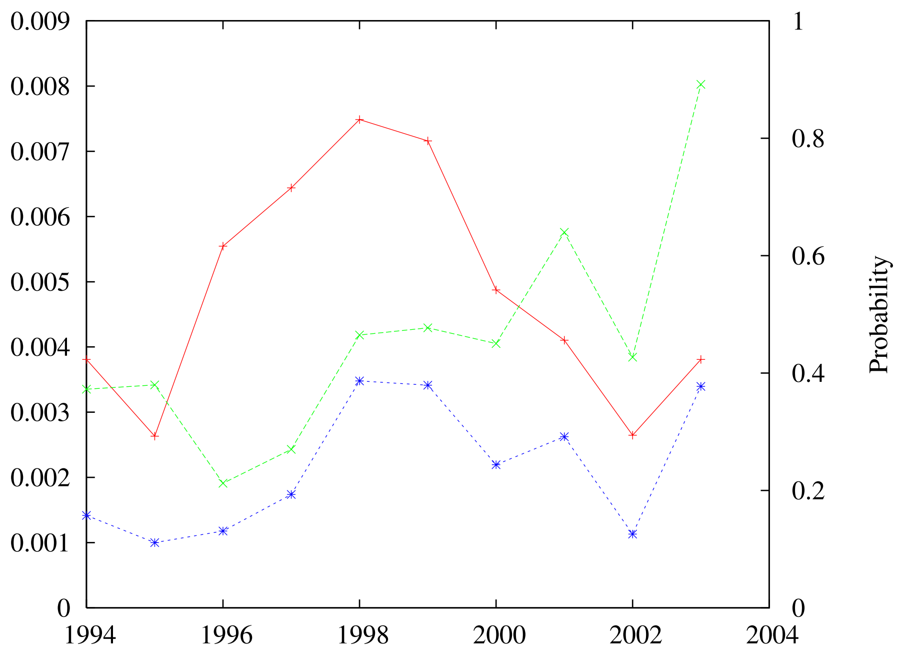


Fig. 5.8.1 Probability of catching fish per day of effort (red line, right hand axis; arithmetic mean of daily values). Proportional reduction in the population size, given that fish are caught (green line, left hand axis; geometric mean of daily values). Expected proportional reduction in population size per day of fishing effort (blue line, left hand axis; product of the first two probabilities). All probabilities are calculated on a yearly basis, where the fishing year begins on July 31.

The annual (geometric) mean proportion of the population caught, given that fish are caught on a particular day, increased from the range of 0.002—0.003 (0.2-0.3%) between 1994 and 1997, to 0.004—0.006 (0.4-0.6%) between 1998 and 2002. The 2003 value should be treated with caution as is it is based on a partial year's data (Fig. 5.8.1), however it is possible that fishing success increased in 2003[1]. The increase in mean proportion of the population caught on successful fishing days is expected for a species that forms aggregations that can be targeted. If carp were randomly distributed in the lake then the proportion of the population caught on successful fishing days would remain constant as the population declined.

Multiplying the probability of a successful day's fishing by the proportion of the population caught given successful fishing, gives the expected proportion of the population caught on any day. The expected proportion of the population caught per fishing day increased from between 0.001 and 0.002 (0.1-0.2%) for 1994 to 1997, to more than 0.003 (>0.3%) in 1998 and 1999. Since 1999, the expected proportion appears to be declining back down to the levels observed at the start of the fishdown operation. The increase in 2003 may be an anomaly for the reasons given above.

[1] 2002 was a dry year, which provided hard ground to fish from in 2003; the water in the creeks was relatively clear in 2003 which made them easier to fish; many of the fish which failed to spawn in 2002 (no spawning cues, water in Lake Sorell too cold to stimulate a spawning event) would have been ready to spawn in 2003.

These observations of the success of fishing and the proportion of the population caught on successful fishing days can be used to predict what the fishing success will be in the future, and therefore how long it will take to eradicate the population. The complication of course is that the probabilities of a successful day's fishing and the expected proportion of the population caught on those days may not be constant over time, especially as the population declines to low levels. We have described possible trends in fishing success and proportion of population removed in the data for 1994-2002 (Fig 5.8.1), although we have not accounted for other factors (environmental or operational) that could also have contributed to the observed trends. It could be argued, for example, that both the probability of a successful fishing day and the proportion removed have remained constant over time. The assumptions that we make about the trends in captures to date, will exert considerable influence about what we predict will happen in the future. Given these uncertainties it is best to bound the possibilities and provide the range of possible future scenarios.

One bound is to assume that there has been no trend in the probability of capture or proportion of population removed on successful fishing days and take the mean of the annual probabilities of a successful day of fishing effort as a predictor of future success. This value is 0.54. Alternatively, it could be argued that there has been a downward trend in probability of capture since 1998, in which case, extrapolating the trend in Figure 5.8.1, a value closer to 0.2 would be more likely for this year, and a level of 0.1 (or lower in future years). This suggests that the probability of future successful fishing trips will be in the range 0.1 to 0.5. Assuming current untagged fishing populations of 60, 45, 30 and 15, and assuming that on each successful fishing trip in future, only one untagged fish is captured (to remove the difficulty in removing fractional fish), we estimated the probability of removing all remaining untagged fish given various levels of fishing effort (Table 5.8.1).

Table 5.8.1 Number of fishing days required to achieve given probability thresholds of removal of all untagged fish for initial populations of 60, 45, 30 and untagged fish, given different fixed probabilities of catching a single fish per day of fishing effort.

Current population size	Probability threshold	Probability of catching a fish per fishing day								
		0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
60	**0.50**	597	299	199	149	119	100	85	75	66
	0.75	648	322	214	160	127	105	90	78	68
	0.95	726	359	237	176	139	114	96	83	71
	0.99	785	387	254	188	148	121	101	86	74
45	**0.50**	447	224	149	112	89	75	64	56	50
	0.75	491	244	162	121	96	80	68	59	51
	0.95	560	277	182	135	106	87	73	63	54
	0.99	612	301	198	146	114	93	78	66	56
30	**0.50**	297	149	99	74	59	50	43	37	33
	0.75	333	166	110	82	65	54	46	39	34
	0.95	391	193	127	94	74	60	50	43	37
	0.99	435	213	140	103	80	65	54	46	39
15	**0.50**	147	74	49	37	29	25	21	18	16
	0.75	173	86	57	42	33	28	23	20	17
	0.95	215	106	69	51	40	32	27	23	19
	0.99	249	122	79	58	45	36	30	25	21

While this analysis requires a number of simplifying assumptions, it suggests that if the untagged population is around 30 fish, which is the maximum likelihood value produced by the population model using all available data, around 80 more days of fishing effort are required to be reasonably (>99%) confident of having removed all of the remaining fish, when probability of a successful days fishing remains constant at 0.5. If, however the declining trend in capture probability continues and the probability of a successful day's fishing drops to 0.1, then an additional 335 days of fishing will be required to reach the same probability of removing all the fish. If current population size is overestimated, then so will the number of fishing days required, and *vice versa* (Table 5.8.1).

The greatest weakness of this analysis is that it assumes the probability of catching a fish on a given day of fishing is fixed (independent of the number of remaining untagged fish in the lake) or linearly related to the number remaining. Catching the last few fish may turn out to be more difficult. Balancing this, any multiple captures of fish on a given day will decrease the required number of fishing days. Given the difficulty in extrapolating from the existing data set to areas with very low population sizes and the possibility of very different fish behaviour when the population size gets to be very low, it seems sensible to explore a range of possible behaviours and a range of possible responses to different management options, rather than to predict a particular outcome.

5.9. Stopping rules for fishing

The previous section gives coarse estimates of the number of fishing days required to fish out the remaining carp population in Lake Crescent. These numbers are not prescriptive and will need updating as more data become available. In particular analysis of future data will be needed to test the hypotheses of a time-invariant probability of capturing a fish against a linear decline in probability with time, against other relationships yet to be described. Are there other indicators of when to stop fishing?

One response is: Don't stop! Given the cost of an unmonitored successful spawning, continual fishing (or at least monitoring) should be done for a number of years – probably indefinitely – especially if there is any risk of further reintroduction. Targeting this effort in the spawning season would be the most sensible, as any further spawning is likely to set the eradication program back by around 7 years.

Figure 5.9.1 shows the number of fishing days between successful captures of male and female fish. Typically the unsuccessful runs appear to occur more often in the mid year period. There also appears to be a trend towards increasing gaps, but the most recent data suggest that females are still being caught reasonably frequently, but the gaps between catches of male fish are increasing, suggesting that the number of remaining untagged males is very small. These data should be updated as fishing continues.

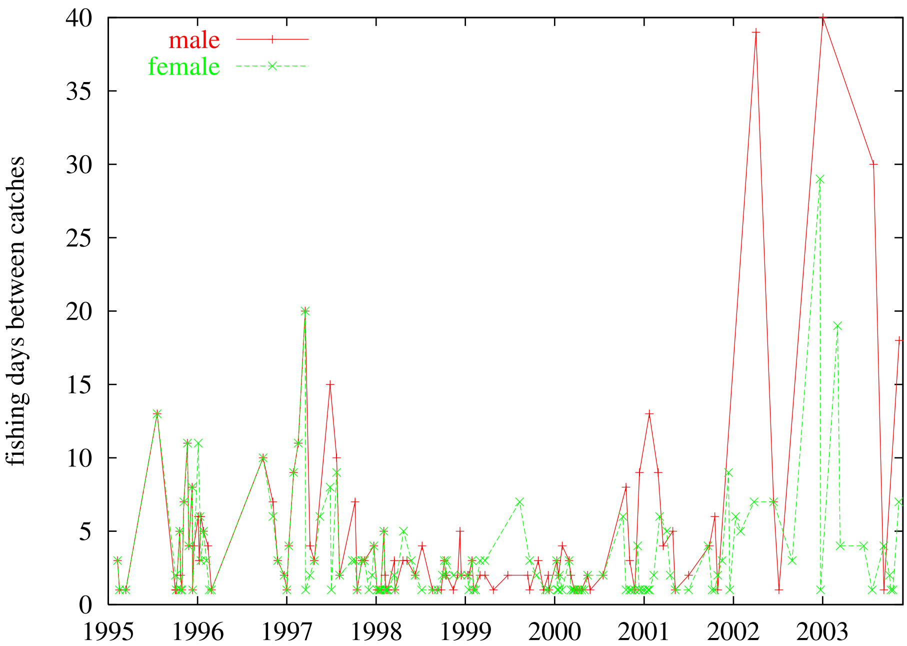


Fig. 5.9.1 Number of successive unsuccessful fishing days between capture sorted by sex of fish, plotted against the date of the end of an unsuccessful run of fishing.

Figure 5.9.2 is similar to the previous figure but this time shows the length of unsuccessful fishing runs for immature fish, rather than for mature males or females. These data indicate two different recruitment events of juveniles, with one recruitment becoming apparent in the summer of 1996/7 and another in the spring of 2001. The pattern prior to recruitment, showing a series of large gaps between successful fishing events, is the sort of pattern we may expect to see as either adult males or females become rarer in the population. However, removing juveniles is easier than removing adults, as they can be removed from the population either by fishing them out, or letting them grow to sexual maturity (in the absence of any further recruitment of course).

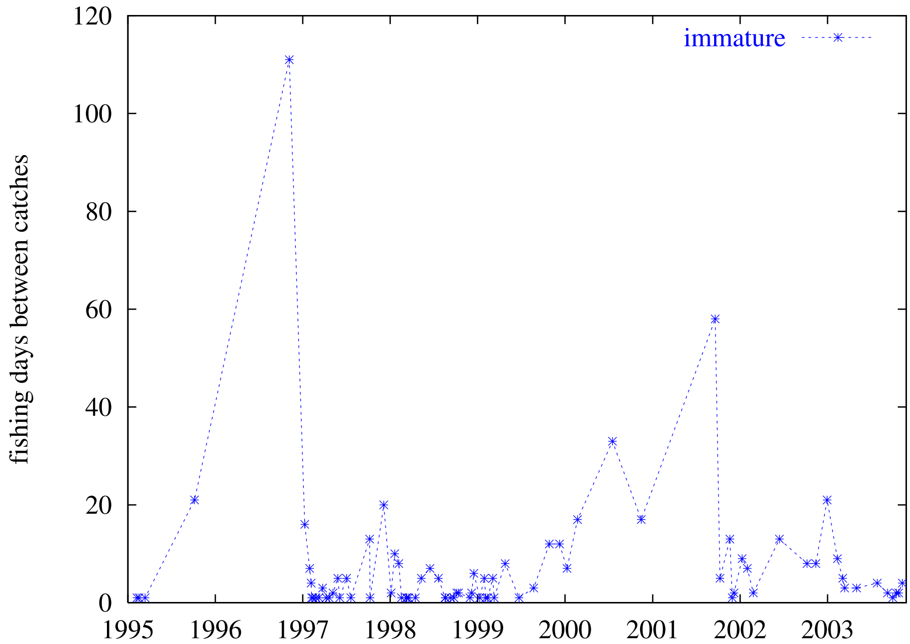


Fig. 5.10.2 Number of successive unsuccessful fishing days between capture for immature fish, plotted against the date of the end of an unsuccessful run of fishing.

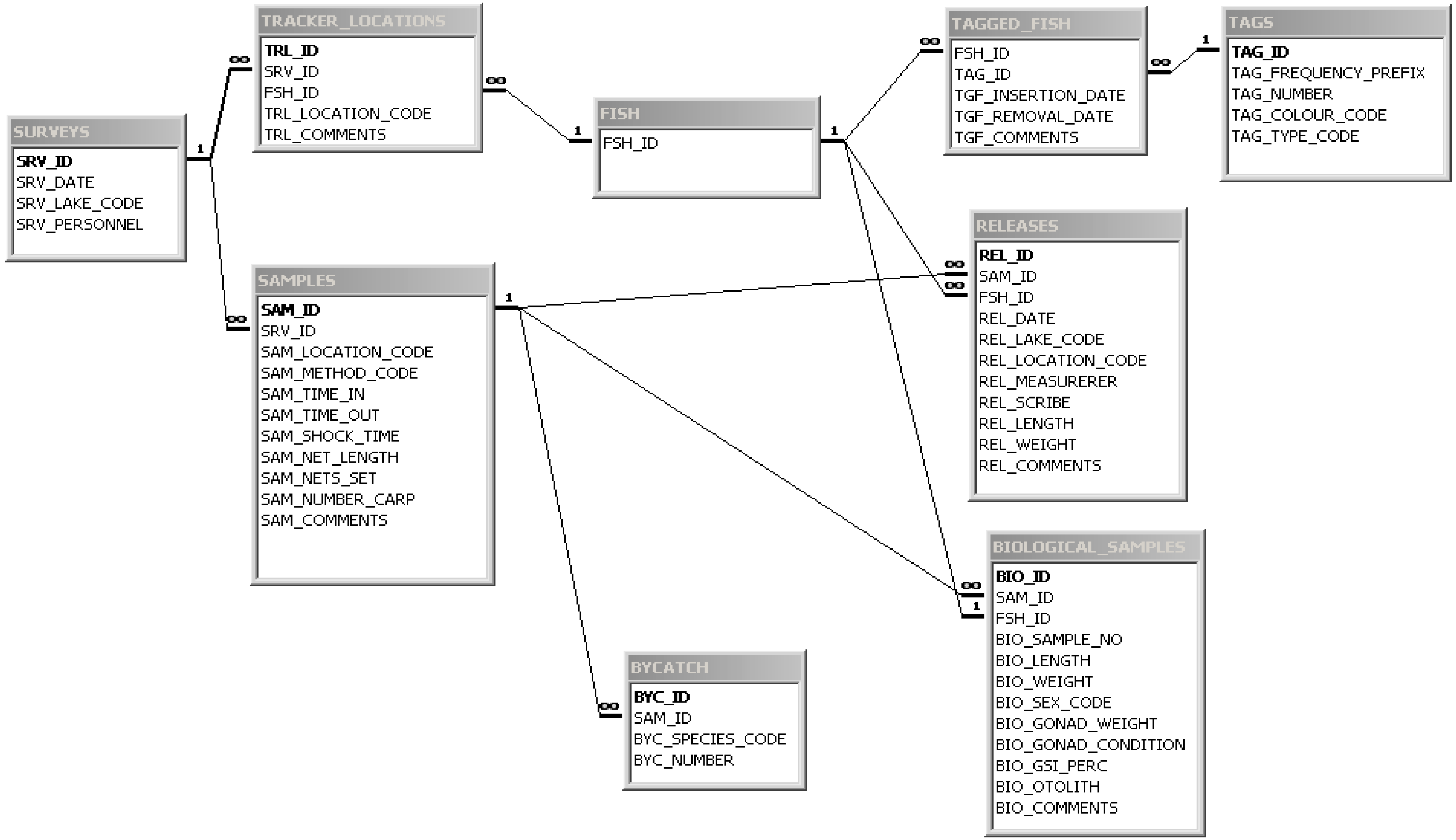
As a general rule one would want to fish at least as many days after the capture of the "last" fish as the greatest gap in days between the capture of fish to date (currently 40 days). It would not be unreasonable to consider fishing at least 3 times as many days after the last fish has been caught as the greatest gap between the capture of fish observed to date (ie. 120 days). We would expect the number of unsuccessful fishing days between captures to increase above 40 days as the population continues to decline.

6. ACCESS Database

In order to provide more readily accessible data for interpretation, the existing Lake Crescent data have been manipulated into an access database. The database has relationships that will allow users to interrogate the data to a greater level of detail and accuracy than was previously available. Through the matching of tag numbers it is now possible to follow data on a carp from the moment it was tagged, any recaptures and releases, location positions if it was used as a tracker fish and finally a biological sample when the carp is killed. With the creation of standard queries it is possible to extract information at any moment on the current status of many helpful indicators in the carp eradication programme. The database also provides a standard format for the entry of data through a codes table. This will be more important for future data but will help provide more robust and accurate data through the reduction of data entry errors and duplication. If in future, data for Lake Sorell or other lakes is collected it can also be stored in this database.

Figure 6.1 shows the relationships between the tables in the carp database. The TAGS table holds the data on each tag and transmitter. The use of the TAGGED_FISH and FISH tables provide for the ability to add and remove tags from a fish at anytime, hold historical data on tags or transmitters that have been removed, or to trace fish that have shed tags if they had been double tagged. These tables provide for the concept of a fish which can then be related to any recapture and release information on a fish through the RELEASES table. If the fish has or had a transmitter attached its location history can be traced through the TRACKER_LOCATIONS table. Any fish that has been killed has sex and other data stored in the BIOLOGICAL_SAMPLES table. The SURVEYS table provides for information regarding any fishing trip on a lake. The SAMPLES table is intrinsically related to the SURVEYS table which provides further data on the fishing effort in any location as set out by Inland Fisheries for each survey. The SAMPLES table also relates to RELEASES and BIOLOGICAL_SAMPLES so location, fishing method and other indicators can be attached to a release or fish kill event. Lake level data are located in the ENVIRONMENTAL_DATA table and can be related to SURVEYS through the date if required.

Figure 6.1 Carp Database Entity-Relationship Diagram



7. Benefits

There are two main sets of beneficiaries from this work. The main beneficiary is the State of Tasmania, with whom we have developed a detailed analysis of the mark and recapture work conducted as part of the carp eradication in Lake Crescent. That analysis provides a more robust estimate of the current population size than that available from other methods and improved estimates of the progress of the fishdown to date.

Detailed examination of tag loss and natural mortality has shown the variability in tag loss associated with different sized tags and has led to the recommendation that in the future all fish to be tagged should be double tagged with identical tags (or at least a common pair of tags).

Analysis of the trends in capture and recapture data for tagged fish has shown the variability in availability to capture of different individuals; results substantiated by the radiotracking data that can be used to separate the carp into resident fish (that stay in the same place for many days) and mobile fish that regularly move around the lake. Different targeting tactics are needed for the two behaviours and this has implications for future fishdowns in Lakes Crescent and Sorell and the mainland. It is possible that these two different groups of fish can be targeted by selecting resident and mobile tracker fish. When resident fish start to move it seems to indicate the start of a spawning aggregation.

Combining the information on current status with the observed trends in catchability enabled us to define a range of scenarios for the future of the Lake Crescent fishdown that will inform managers deciding how much longer to continue with the eradication attempt (assuming that future spawnings can be prevented).

Finally, it was clear working with the Inland Fisheries Service that the data recording technique being used (colour—coded EXCEL spreadsheets) was not ideal. There was no facility for checking or cross-referencing data during data entry, leading to numerous inconsistencies and data analysis was complicated by having non-numeric attributes and no clear identifiers. As an addition to this project, CSIRO and IFS jointly developed an ACCESS database that will be used for data entry, especially when a mark and recapture study is initiated in Lake Sorell.

The second set of beneficiaries is the wider group of Australian (and overseas) scientists and managers working on carp eradication. The specific techniques developed in the fishdown of carp in Tasmania and the detailed analysis of the interaction of fish behaviour and fishing success provide useful input to other carp fishdown attempts, either as part of a stand-alone project in small lakes or as part of the larger Australian carp control programs that are being funded through the Murray Darling Basin Commission. Results from this project have been presented at national and international meetings and in review in an internationally reviewed journal.

8. Further development

A goal at the start of this project was to test the degree to which leaving male carp in Lake Crescent would promote the aggregation of male and female carp that could be fished leading to the eventual eradication of female carp from the lake. It was then planned that technique would be then be transferred to Lake Sorell, where male carp would be added to the lake to aggregate remaining females so that they could be caught.

The Lake Crescent eradication has not gone according to plan for several reasons. First as water levels in the lake rose, it became harder to monitor and fish spawning aggregations before eggs were fertilised and released. A small spawning event in November 2000 in the Clyde marshes and on debris in the canal joining Lake Crescent to Lake Sorell led to juveniles recruiting to the lake and these juveniles are now entering the fishery. Fishing in Lake Crescent will have to continue for several years to ensure that the fish from the 2000 cohort are removed. At the same time, with an estimated 30 adult fish in the lake, fishing would have had to continue anyway to catch these adults. The aggregation hypothesis does not seem to have worked as well as hoped. While it is rare for females to aggregate without male fish (subject to the bias of fishing being targeted on male tracker fish), there were limited tendencies for fish to aggregate (in numbers greater than 30) once the population dropped below 1000 fish. Alternative techniques are needed to stimulate aggregations for smaller population sizes. Stimulation of spawning by release of water down the canal from Lake Sorell led to spawning aggregations, when Lake Crescent water level was low, but as water levels rose and habitat was no longer limiting this technique no longer worked. Eradication of a population through fishing requires the further development of techniques that are effective at low population sizes, so that all mature fish can be removed before they have had the opportunity to spawn. Development of carp pheromone attractants is one possibility being explored by Professor Sorenson (University of Minnesota, Fisheries, Neuroscience, and Ecology Program), that needs to be followed up. A simpler approach will be tested in Lake Sorell, where ripe males and/or females will be isolated in metal traps at the end of long mesh leads used to separate the fish from suitable marsh habitat for spawning. It is hoped that these sexually mature fish will attract other fish into the trap. The race to fish the population down before spawning can occur will be even more pronounced on the mainland where higher temperature will lead to a more rapid onset of maturity.

The mark and recapture models used to estimate the population remaining in Lake Crescent were useful in determining the bias introduced by differential tag loss, leading to the recommendation that in future all fish be double tagged. They have also provided more robust and consistent estimates of population size than the traditional mark and recapture methods that have produced quite variable population estimates, especially as the population has declined to low levels. There is still considerable room for improvement in the population modelling. Ideally the models would have been age and sex based, but the lack of confidence in the ageing data led to us not incorporating these data. A Bayesian forward modelling approach would have been preferable to the backwards maximum likelihood approach used, as this would have facilitated exploration of future management strategies. But perhaps the most important area for future development is how to incorporate information on the diversity of fish behaviour into the model. A difficulty in extrapolating from the current results to the removal of the final few fish was that there appeared to be trends in the availability of fish to fishing over time (potentially due to the early removal of easily caught fish) and also trends in increased effectiveness of the fishing effort. Accounting for these trends in a Bayesian forward modelling approach would greatly improve the quality of management advice that could be provided.

It was disappointing that the age composition data obtained from counting circuli on the otoliths was not in good agreement with data obtained from following cohorts of known age or the growth of tagged fish. Ideally additional analysis would be undertaken to try and resolve this interpretation of circuli.

The fishdown of carp in lakes Crescent and Sorell has been characterised by a continual advance in the effectiveness of the fish techniques used. One innovation that has proved especially useful has been the release of radio-tagged males that can be targeted when they aggregate. This approach needs to be further improved to account for the behaviour of different fish (eg. differentiating resident from mobile fish) and would ideally be automated to give maximum warning to the field crews of when an aggregation was starting. More recently, the use of fish traps and exclusion fences blocking access to carp spawning areas has proved to be highly effective.

9. Planned Outcomes

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Year 1:At the end of year 1, we plan to deliver a report to IFS that will detail the number of male fish that need to be left in the lake, the number of male fish that need to be radio tagged, and the fishing intensity required to eliminate female carp from Lake Crescent at a variety of risk levels.

During the course of this project we have been in regular contact with the Inland Fisheries Service, jointly developing mark and recapture models of the Lake Crescent cap population and interpreting the catch data. The number of male fish to be radio tagged and fishing intensity required to eliminate female carp from the Lake was not offered at this time, as population numbers were still relatively high and it was clear that maximum available effort would be required for several years. Advice on future mark and recapture studies was provided, in particular the desirability of double tagging all fish, and the opportunity that the new daily mark and recapture model provided to release tagged fish at any time and record daily recaptures.

Year 2:At the end of year 2, we plan to provide a long-term population model of the carp population in Lake Crescent, validated with catch per unit effort data and mark and recapture population estimates. This will document the success of the control strategy to date, and provide an assessment of the risks and benefits of releasing additional males into Lake Sorell.

A population model incorporating all catch data and individual mark and recapture data was developed and population estimates for Lake Crescent updated. Catch and effort data could not be reliably used, because of the rapid development of fishing techniques by IFS officers that complicated interpretation of effort data and the lack of agreed age composition data that restricted development of an age-based model from which selectivity could be estimated. The question of whether or not it would be advisable to release males into Lake Sorell to stimulate aggregations was deferred following the successful spawning event in that lake in 2000. Instead of considering the release of additional male fish to stimulate aggregations, effort was concentrated on capturing the juveniles. While the fish from the larger spawning in 2000 have remained juveniles and therefore indistinguishable by sex, all captured fish have been removed, because the risk of returning female fish to the lake was considered greater than any advantage that may have been had through improved monitoring using mark and recapture methods, or stimulating future aggregations.

Year 3:At the end of year 3, we will provide a report of the success of the eradication campaign in Lakes Crescent and Sorell, and the success of model predictions. We will then generalise the model so that it can be used to eradicate carp in enclosed water bodies on the mainland.

The eradication campaigns in the two lakes have not proceeded as rapidly as first hoped. In particular, the successful spawning events in both lakes in the summer of 2000/01 means that the eradication efforts will have to be continued for several years after the fish have become fully available to the fishing. The main difficulty encountered in applying the model to Lake

Crescent was the quality of data collection. Considerable effort was spent to link data from the different Lake Crescent data spreadsheets that had been collected over several years, often by different research officers. Inconsistencies between the catch and effort spreadsheet and the biological data spreadsheet have led to data being unavailable for some of the analyses. To facilitate the use of the model (and other analytical tools) on other lakes, an ACCESS database was developed. This database provides a consistent interface for data entry, regardless of possible changes in research officers, and also provides error checking capability during data entry so that the catch data and biological data are explicitly linked.

With the analyses complete we were able to complete some of the outcomes of earlier years, in particular describing the conditions under which the aggregation approach might work (>1000 fish for Lake Crescent) and estimating the days of fishing effort required to remove the remaining untagged adults (about 30 fish, primarily female) from Lake Crescent under alternative assumptions of trends in catchability.

10. Conclusion

The project was designed with two primary objectives. First to provide advice to the Inland Fisheries Service on the levels of fishing effort that would be required to eradicate carp from Lake Crescent and second to determine whether returning male carp to the lake would promote aggregations that could be targeted and fished, thus removing the last few female fish with less effort than if they were by themselves. In this way we hoped to be able to circumvent, or at least reduce the increasing costs associated with removing the final members of a population.

There are three conditions that need to be met if eradication is to be successful (Parkes 1990; Bomford and O'Brien 1995; Myers et al 2000):

1. All animals must be at risk of death or sterilisation
2. The probability of recolonisation must be zero. Realistically the probability of zero recolonisation cannot be achieved unless the species goes globally extinct. So the eradication strategy is essentially one of sustained control with a target density of zero (Parkes in review).
3. The animals must be killed at rate faster than their increase at all densities.

Other considerations and constraints are (Bomford and O'Brien 1995; Parkes in review):

4. Economic analysis should favour eradication over sustained control and there should be sufficient funding at the start to complete the eradication attempt. Eradication should have broad socio-political support.
5. Animals should be detectable at low densities.
6. Detailed knowledge of the species might reveal an 'Achilles Heel'
7. Non-target risks must be acceptable and outweighed by the benefits of successful eradication.

We cannot say with confidence that for this eradication attempt all animals are at risk of death. Analysis of the rate of recapture of tagged fish that were captured and released up to 7 times, indicates a larger than expected proportion of fish that were tagged and never recaptured, and an increase in recapture probability for fish as the number of times that they have been recaptured increases. Some of the deviation from expected proportions can be explained by the short-term loss of tags (before they have become well embedded in the flesh), but to explain the data fully, we need to invoke an inherent natural variability in the fishes behaviour. Radio tracking indicates that fish can be characterised as mobile or resident. Resident fish are generally not available to targeted fishing methods and only appear to move from their station when a spawning aggregation is to occur. This suggests that as the population declines, the remaining fish will increasingly be those with resident behaviour and catching the last few fish will be difficult, unless a spawning aggregation forms naturally or can be stimulated. The presence of a subset in a population that is less amenable to capture is not unusual. For example, 1000 hunter days were required to kill the last four goats on Raoul Island. Three of these four goats had survived a good part of the 20 year hunting operations (Parkes 1990). Unless spawning aggregations can be stimulated it may prove difficult to remove the last few carp from lakes Sorell and Crescent. Pheromone attractants being worked on by Professor Sorenson (University of Minnesota, Fisheries, Neuroscience, and Ecology

Program) provides one option. Combining the use of pheromones with the increased use of metal traps strategically located in areas of suitable spawning habitat may provide an extra tool to help catch the last few fish.

The risk of recolonisation of the lakes from outside is considered to be close to zero, although as it is not known for certain how the carp arrived in the first instance, the threat of reintroduction cannot be dismissed entirely. The risk of recolonisation of Lake Crescent is greater because fish can (and have) escape from Lake Sorell through the canal and into Lake Crescent. This has been controlled to the extent possible by erecting a weir at the entrance to the canal. Because carp have not been observed to establish below the weir separating Lake Crescent from the lower watershed, recolonisation of Lake Crescent after eradication would not be a disaster, however the extra work required in surveying and fishing both lakes, instead of just Lake Sorell, would reduce the level of effort that could be applied to eradicating the Lake Sorell population.

A crucial question for this eradication is whether the carp can be removed at a greater rate than the population grows. Carp are a fecund fish that can produce 80,000 (1.25 kg fish) to 1,500,000 eggs per female (6 kg fish) (Hume et al 1983). The successful spawning of even one spawning female (and male) can potentially lead to thousands of survivors that will need to be fished out before another spawning event takes place. This is one reason why fishing effort is targeted during spring and summer, when there is an increased tendency for carp to aggregate prior to spawning, to reduce the chances of a successful spawning. If spawning does occur before the fish are caught the spawning areas have been limed to hopefully kill all the eggs. In one instance when carp spawned on loose vegetation in the canal joining the two lakes, an excavator was used to remove the vegetation and eggs. Of course liming the eggs requires knowing that a spawning event has occurred. While this is possible in Lake Crescent, where spawning habitat is limited, it is not so easy in Lake Sorell where there are many more areas suitable for spawning. Fences have been erected to close off some of these spawning areas from the fish. Fishing is conducted daily during the spawning season to detect any aggregations, while outside of the spawning season effort is directed towards fencing off more marsh habitat in Lake Sorell, although some effort is needed to catch the tracker fish for the spring and summer fishing season. The use of tracker fish increased fishing success in Lake Crescent. Tracking both the resident and mobile parts of the population may be necessary to fish the whole population.

There is no estimate of the population numbers in Lake Sorell at present – fish from the 2000 spawning have been juveniles and therefore it has not been possible to identify male fish to tag and return. The predicted untagged population size in Lake Crescent was ~30 fish in November 2003. It is conservative to assume that all these fish are females as, males recruit to the fishery earlier and the sex ratio has become increasingly dominated by female fish since the fishdown began. It would be quite simple to estimate the number of days of fishing required to remove these last 30 fish, if fish behaviour and fishing effectiveness remained constant. However this study is no different from many others in suggesting that fishing effectiveness has not remained constant. There was a gradual increase in effectiveness between 1995 and 1998 as new techniques were developed and knowledge of fish behaviour increased. However, since 1998, the probability of catching a fish on any given fishing day has declined from >0.8 to ~0.3 in 2002 (although probability may have increased to 0.4 in 2003, based on limited data). The expected proportion of the population caught per day of fishing also rose from ~0.001 in 1994-1996 to peak in 1998 at over 0.003. The proportion declined back down to ~0.001 in 2002, but may have increased again to close to over 0.003 in 2003 (based on limited data). Given a population size of 30 fish, and assuming the probability of catching a fish is 0.3 (the 2003 value), then 140 days of fishing will be required to have a 99 percent probability of removing the last fish. If the probability of catching a fish is continuously declining, as indicated by the data between 1998 and 2002, then 213 -- 435 days will be required. These estimates should overestimate the fishing days required as it is assumed that only one fish is removed on each successful fishing day. If the fish continue to aggregate then more than one fish will be removed on many days and the population will be reduced more rapidly.

The eradication attempts in lakes Crescent and Sorell are a race between the rate at which the population can be fished down and the number of years for which spawning can be prevented. It is complicated by the observation that some of the carp (the resident carp) may only be available during a spawning aggregation, suggesting that the capture of these last fish will be high risk. Aggregations are fished as soon as they are detected, and early detection is enhanced through the use of radio tracked fish that aggregate with the spawners. At the moment, fishing of the adults in both lakes continues to control numbers and reduce the risk of future recruitments. It is hoped that the number of juveniles from the 2000/01 spawnings will be small enough that they too can be rapidly fished down. This is especially the case in Lake Sorell where it has historically been difficult to catch fish older than three years (>400 mm). Additional procedures are being used to reduce the chances of future successful spawnings and thus increase the time available for eradication. While restricting access to the marsh spawning habitat may work, it seems possible that additional techniques will be needed to eradicate carp from Lake Sorell. The same is likely to apply to mainland lakes, where habitat is less likely to be restricted due to low temperatures and maturation rates are likely to be more rapid, giving less time to fish the juveniles out.

The eradication of carp from lakes Sorell and Crescent has been facilitated by strong and consistent government and public support. These two lakes are the only place in Tasmania where carp have been found and their removal is seen as necessary to preserve the multi-million dollar trout fishery. However, there are still restrictions on the type of eradication techniques that can be used; poisoning was dismissed as an option early on due to the presence of an endemic species of galaxiid in the lake, and the use of the lake water in the catchment downstream. Eradication through fishing has been the only viable option. While fishing has controlled the populations, it has as yet not caused their eradication. New developments such as pheromone attractants (either artificial or produced by isolated caged females) may be needed before eradication succeeds.

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12. Appendix 1: Intellectual Property

The intellectual property arising from this work is property of the Inland Fisheries Service, CSIRO and FRDC.

13. Appendix 2: Staff

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