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Stock assessment of the Queensland east coast red throat emperor (*Lethrinus miniatus*) fishery

CRC Reef Research Centre

Queensland Government
Department of **Primary Industries and Fisheries**

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The Department of Primary Industries and Fisheries (DPI&F) seeks a better quality of life for all Queenslanders—a quality of life supported by innovative world-class food and fibre industries, and by responsible and ecologically sustainable use of natural resources.

Our business is about:

- innovative science and commercial uptake of new technology by food and fibre industries
- sustainable use of natural resources
- food safety and protection against imported pests and diseases
- market-driven and ethical food and fibre production.

This publication provides an assessment of the state of the population of red throat emperor, one of Australia's important commercial and recreational reef fish, with recommendations for management, future research and data collection.

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Red throat emperor is Queensland's second most important reef fish by commercial catch weight, and is also a popular target fish for recreational fishers in the Coral Reef Fin Fish Fishery (CRFFF) of the Great Barrier Reef (GBR). Annual harvest in 2003 was approximately 800 tonnes for the commercial sector and 450 t for the recreational sector. The commercial catch has risen from about 200 t in 1980; the sizes of historical recreational catches are unknown.

A new Management Plan for the CRFFF was implemented in December 2003. Management changes applicable to red throat emperor include an increase in the minimum legal size, the introduction of individual transferable quotas (ITQs) for commercial fishers (introduced in July 2004) and three nine-day spawning closures in October, November and December of each year for all fishers (introduced in October 2004). In addition, the rezoning of the GBR by the Great Barrier Reef Marine Park Authority resulted in many previously open areas being closed to fishing in July 2004.

In this assessment, the red throat emperor fishery was analysed by an age-structured model that incorporated all available information on catch, catch per unit effort (CPUE) and age structure. The GBR was divided into five regions: Townsville, Mackay, Storm Cay, Swain reefs, and Capricorn Bunker. (There were no scientific data from a sixth region in the far north and therefore this region was combined with the next northernmost region, Townsville.)

Age structure varied greatly between regions, with fish aged 5–8 years predominating in the Townsville region, 4–7 yr in the Mackay, Storm Cay and Swains regions, and 2–3 yr in the Capricorn-Bunker region. These differences were explained by different age-dependent vulnerabilities to fishing between the regions. Vulnerability refers to the product of availability of fish and selectivity of fishing gear; population models do not need to distinguish these two effects but are concerned only with their product. Gear selectivity is unlikely to vary between regions, but availability may be subject to factors such as water temperature, currents and sea floor topology, which certainly vary between regions. Ages at 50% vulnerability were estimated to be about 9 yr for the Townsville region, 3 yr for Mackay and Swains, 6 yr for Storm Cay, and 1 yr for Capricorn-Bunker.

The model estimated that exploitable biomass fell to approximately 60% of virgin biomass in the late 1990s, due mainly to years of poor recruitment, but recovered to around 70% by 2004. Further recovery can be expected due to the fishery not meeting its total allowable commercial catch (TACC) of 700 t in recent years, although we do not expect this phenomenon to last once fishers become familiar with the ITQ system.

Recruitment levels in the 1990s were generally below the historical average but no correlation was found between recruitment and the previous year's spawning stock size.

Population age structure differed substantially between fished and unfished reefs, with fished reefs having less older fish. This finding implies that movement of red throat emperor between fished and unfished reefs is insufficient to overcome the effect of fishing pressure.

A surplus production model was also fitted to the catch and CPUE data; it produced more pessimistic results than the age-structured model (maximum sustainable yield 760–960 t for the commercial and recreational sectors combined). The surplus production model makes no use of age structure and cannot represent detail that is obviously important in the red throat emperor population. Our conclusions are therefore based on the age-structured model.

The current TACC of 700 t, combined with a recreational–charter catch of around 450 t, contains little margin for error, especially in view of high year-to-year variability of recruitment of red throat emperor and stresses on the GBR from land clearing, coastal development and climate change. The state of the population needs to be monitored closely. Further data on age structures after 2000 will provide more certainty to this assessment.

1. Introduction

1.1 Background

Red throat emperor (*Lethrinus miniatus*) is Queensland's second most important commercial reef fish by catch weight, with an annual harvest of approximately 800 tonnes in the Coral Reef Fin Fish Fishery (CRFFF) of the Great Barrier Reef (GBR). The commercial harvest has risen from about 200 t in 1980, giving cause for concern about the long-term sustainability of the fishery. Red throat emperor is also a popular target for recreational anglers with about 450 t harvested each year.

This stock assessment of red throat emperor from waters off the Queensland east coast has been undertaken as a joint project between the Queensland Department of Primary Industries & Fisheries (DPI&F) and the Cooperative Research Centre for the Great Barrier Reef World Heritage Area (CRC Reef Research Centre) to provide managers with the best possible information on which to base decisions about sustainable management of the fishery.

The stock assessment is based on information aggregated over calendar years because much of the catch is taken around the middle of the year and spawning takes place shortly after the middle of the year (see Section 1.4.3).

A commercially caught red throat emperor (picture: CRC Reef).

1.2 Taxonomy

It is often difficult to identify species of emperor due to similarities among species and varied colour patterns of individual species. Such difficulties have led taxonomists to consider emperors as one of the most problematic families of tropical marine fish to classify. The classification of red throat emperor has recently been revised, but misidentification remains a problem for the species. Red throat emperor was known as *Lethrinus chrysostomus* (Richardson 1848) prior to the 1990s, but was reclassified as *L. miniatus* (Schneider 1801) by Carpenter and Allen (1989). Previously, however, the name *L. miniatus* was often given to the long-nosed emperor, *L. olivaceus* (Carpenter 2001), thus many past records of red throat emperor are likely to be erroneous.

Red throat emperor is known in Australia by a variety of local common names including sweetlip, sweetlip emperor, lipper, tricky snapper and tricky. In Norfolk Island they are known as trumpeter and in New Caledonia as guile rouge. The FAO refers to the species as trumpet emperor (Carpenter 2001).

1.3 Distribution

Reports of red throat emperor are widespread throughout the tropical and subtropical regions of the Indian and western Pacific Oceans (Figure 1). However, red throat emperor most likely has a much more restricted distribution, as many reports of the species have been misidentifications or cannot be confirmed. Red throat emperor is confirmed to occur along the tropical and subtropical coasts of eastern and western Australia, New Caledonia, eastern Philippines and the Ryukyu Islands of southern Japan. These confirmed reports reveal a disjunct distribution separated by the equatorial zone, and a narrow longitudinal range between approximately 110ºE and 170ºE.

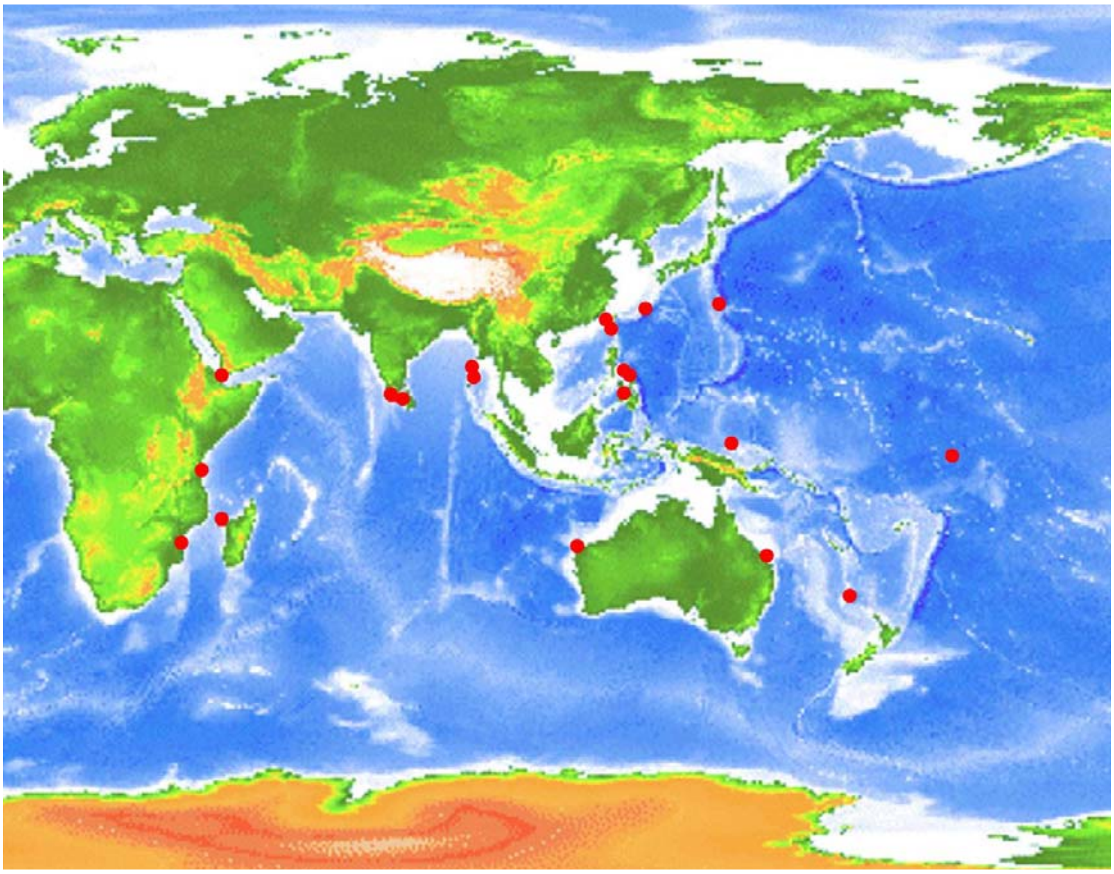

Figure 1: Map of the world distribution of red throat emperor.
Source: http://www.fishbase.org (Froese and Pauly 2000) and CSIRO c-squares mapper; points for Norfolk Island and Western Australia have been added. Species identification west of Western Australia is unconfirmed.

In Australia, red throat emperor occurs along the west coast from the Dampier Archipelago (~20ºS) to the Houtman Abrolhos Islands off Geraldton (~27ºS). The largest populations of red throat emperor in Australia are found on the Queensland east coast along the GBR between approximately 18ºS and 24ºS (Figure 2).

For this assessment we divided the GBR into five regions, which we have called Townsville, Mackay, Storm Cay, Swains and Capricorn-Bunker (see Section 2.1 below).

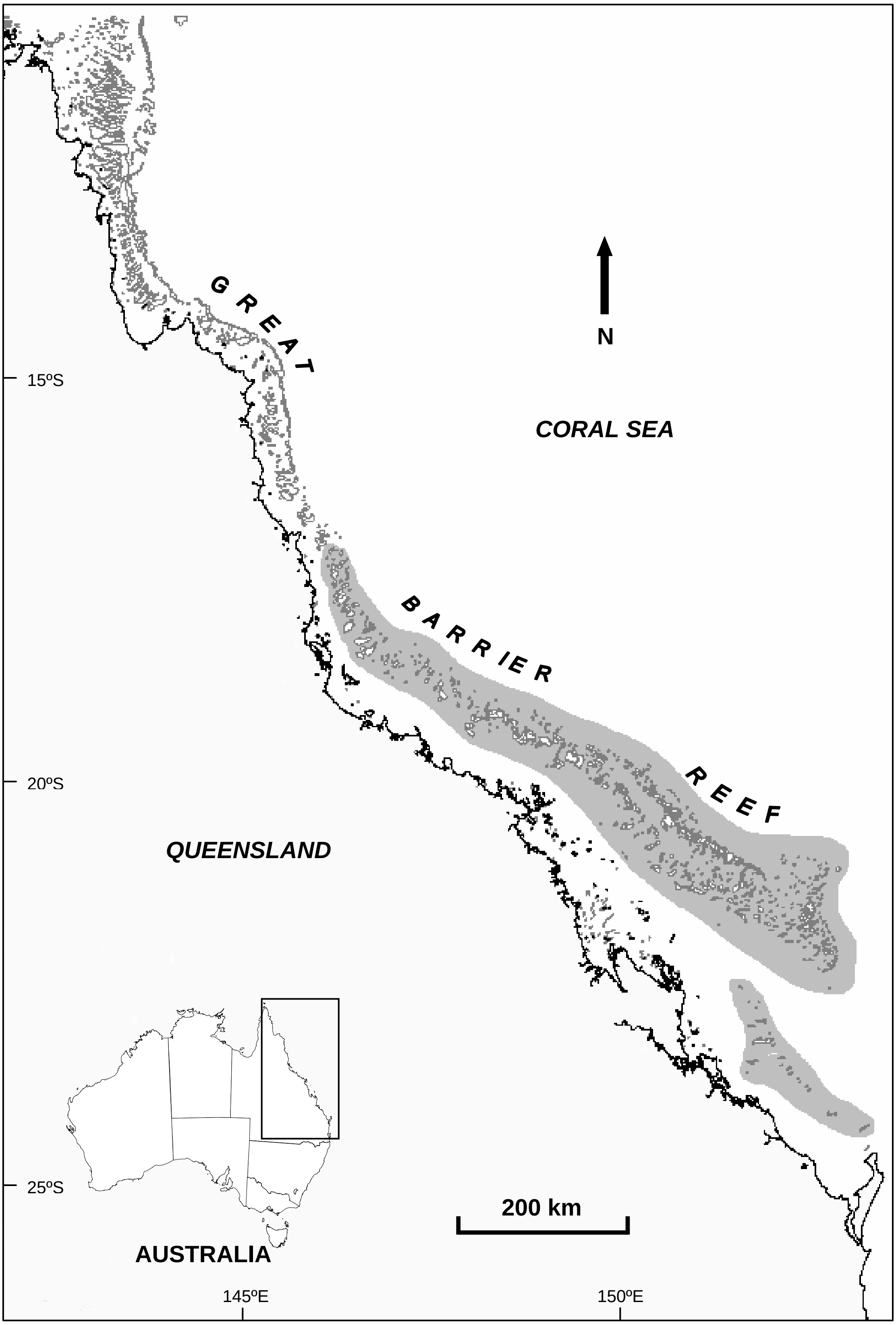

Figure 2: Approximate distribution of red throat emperor on the Great Barrier Reef Indicated by shaded area (Williams 2003).

1.4 Biology and ecology

1.4.1 Habitat and diet

Red throat emperor is strictly a marine species typically associated with coral or rocky reefs, although it is also commonly encountered on shoal and rubble habitats between reefs (Newman and Williams 1996). Along the GBR red throat emperor is nearly exclusively found on mid and outer shelf reefs to a maximum depth of at least 128 m, and is rarely found on inshore reefs (Newman and Williams 1996).

Red throat emperor is a demersal carnivorous predator consuming mainly crustaceans, echinoderms, molluscs and fish. Within this wide range of taxa, red throat emperor appears to exercise some selective feeding, preferring particular species of crab, sand dollar and sea urchin, all of which are in relatively low abundance and either red or purple in colour (Walker 1975, 1978).

Movement patterns of red throat emperor are not well known. An early tagging study suggested that red throat emperor are very site-attached and move only small distances within a reef (<500 m) and not between reefs (Beinssen 1989). This study was limited to a period of only three weeks, and thus the results should be treated with some caution, as movements over greater distances may occur over larger time scales. Recent recaptures of tagged red throat emperor indicate that individuals are capable of moving among reefs, with one recaptured fish having moved about 106 km over a period of two years (W. Sawynok, Infofish, unpublished data). Williams (2003) hypothesised a net northward migration of red throat emperor in order to account for regional differences in age structure of the population. Red throat emperor can be solitary but often form large schools of similar sized individuals.

1.4.2 Stock Structure

Research on the stock structure of red throat emperor concluded that there was no evidence for distinct genetic stocks on the GBR (van Herwerden *et al.* 2003, Davies *et al.* 2005). Otolith microchemistry was found to vary significantly between reefs but not between regions of the GBR (Davies *et al.* 2005). However, studies on the population biology of red throat emperor from the same locations have identified significant variation in a range of demographic parameters between regions of the GBR, which may be more relevant for management (Williams 2003, Williams *et al.* 2003). Therefore, although populations may be genetically homogenous across the GBR, productivity of red throat emperor, and the response of populations to fishing, can vary significantly among regions of the GBR.

1.4.3 Reproduction

Red throat emperor has recently been confirmed to be a protogynous hermaphrodite, whereby individuals mature first as females before changing sex later in life (Bean *et al.* 2003, Williams 2003, Sumpton and Brown 2004). The mechanism that triggers sex change is not known, but the large overlap in sizes and ages of males and females (Williams 2003, Sumpton and Brown 2004) suggests that it is most likely socially controlled rather than genetically predetermined (Vincent and Sadovy 1998). The fact that some of the oldest fish in sampled populations have been female (Williams 2003, Sumpton and Brown 2004) suggests that not all individuals change sex, and highlights the plasticity of sex change in red throat emperor. Reported sex ratios for red throat emperor populations vary among regions of the GBR, but all have been female biased, which is typical for an exploited protogynous hermaphrodite (Sadovy 1996).

Available estimates of female maturity for red throat emperor show some differences. Sumpton and Brown (2004) estimated the size and age at first maturity for female red throat emperor from the Swains and Capricorn-Bunker regions of the GBR to be 300–340 mm fork length (FL) (325–370 mm total length, TL) and 2 years of age, and indicated that it was not until females reached 400 mm FL (430 mm TL) and 6 years of age that the majority were mature. In contrast, Williams (2003) estimated the size and age at which 50% of females from the Capricorn-Bunker region were mature to be 280 mm FL (305 mm TL) and 1–2 years. We believe that Sumpton and Brown's (2004) estimates of age and length at maturity are likely to be overestimates because it is difficult to distinguishing resting mature from immature females during non-spawning periods, and they probably classified some resting mature females as immature. Williams' (2003) maturity estimates from did not suffer from this problem as all samples were collected during the spawning season when mature resting females could be distinguished easily from immature females.

The spawning season for red throat emperor is relatively protracted and appears to be similar among regions of the GBR with peak spawning occurring between July and November (Williams 2003, Sumpton and Brown 2004). It is not known whether there are intra-seasonal peaks in spawning associated with the lunar cycle. However, the frequency of eggs at different developmental stages in the ovaries of spawning females suggests red throat emperor are batch spawners and may spawn more than once during the spawning season (A. Williams, pers. comm.). The spawning behaviour of red throat emperor is not known, and the only available information is derived from fishers' observations. Fishers' reporting large catches of red throat emperor during the spawning season has led to the belief that they form large aggregations during spawning, but this has not been confirmed.

Williams (2003) found a significant regional difference in the proportion of females spawning during the spawning period. In the Townsville region of the GBR, up to 100% of females were ripe during the spawning season, while in the Storm Cay region further south less than 43% of females were ripe. This phenomenon was related to size, with fewer smaller females spawning than larger females. It is not clear why a large proportion of females do not spawn each year in the southern region of the GBR, but it may be linked to low food availability, reduced water temperature and/or geographic position at the edge of the species distribution (Williams 2003).

1.4.4 Eggs, larvae and juveniles

Little is known about the early life history of red throat emperor due to difficulties in identifying emperor larvae to the species level and a lack of information about the juvenile habitat. Red throat emperor eggs are approximately 0.6 to 0.9 mm in diameter (Walker 1975), but the appearance of larvae has not been described. The duration of the larval phase and the size at settlement is also unknown.

The juvenile habitat of red throat emperor is unknown, as individuals less than 150 mm FL have not been collected or observed from anywhere throughout their distribution. Williams and Russ (1994), however, hypothesised that juveniles occur in relatively deep water (> 40 m) adjacent to coral reefs, based on the fact that juveniles have not been observed during extensive surveys of shallow reef and seagrass habitats. This hypothesis is still regarded as speculative.

1.4.5 Age and growth

Red throat emperor is a relatively large coral reef fish reaching a maximum size of approximately 600 mm FL (650 mm TL) and a maximum weight of around 3 kg (Church 1985, Brown and Sumpton 1998, Williams 2003, Williams *et al*. 2003). Reports of red throat emperor reaching 900 mm FL and 9 kg in weight (Carpenter and Allen 1989, Carpenter 2001) are likely to be other emperor species, such as *Lethrinus nebulosus*, *L. laticaudis*, *L. erythacanthus* and *L. xanthochilus*, that have been misidentified. Early research on red throat emperor reported a maximum age of 7 years using counts of increments in scales (Walker 1975). More recent research, using counts of validated annual increments in otoliths (Williams *et al*. 2005), has revealed a maximum age of at least 20 years (Brown and Sumpton 1998, Williams 2003, Williams *et al*. 2003). Otoliths are now the preferred means of ageing red throat emperor (see Section 1.5.3 below).

Red throat emperor can reach their maximum size at around 6 years of age, but there is a substantial amount of variability in size at age among individuals (Williams 2003). Patterns of growth for red throat emperor have been found to vary significantly among locations on the GBR (Brown and Sumpton 1998, Williams 2003, Williams *et al.* 2003). Generally, populations in the southern regions of the GBR reach a larger maximum size than populations in the northern region (Williams 2003, Williams *et al.* 2003; see also Section 2.3 below).

1.5 Fishery description

1.5.1 Fishery sectors

Red throat emperor is an important species in the catch from the commercial, charter and recreational sectors of the CRFFF on the GBR (Mapstone *et al.* 1996, Higgs 2001, Slade and Williams 2002). Red throat emperor is caught in all months of the year by hook and line in all sectors, and occasionally by spear in the recreational and charter sectors. All sectors operate throughout the distribution of red throat emperor on the GBR (see Section 1.3), although outer-shelf reefs are less accessible to recreational fishers than to commercial and charter fishers.

The majority of the commercial sector operates from 4–7 m dories working from 8–19 m primary vessels. The most active commercial operations have 2–5 dories, whilst the majority of operations have no dories and report relatively little catch and effort (Mapstone *et al.* 1996). Red throat emperor are usually retained whole on ice or filleted, skinned and frozen on board the primary vessel. Annual commercial catches of red throat emperor steadily increased from around 200 t in 1980 to over 800 t in 2001, 2002 and 2003 (Queensland Fish Board published data, DPI&F unpublished data). A fall in the catch to about 400 t in 2004 was associated with a restructure of the fishery in response to the introduction of new management measures.

Recreational fishing occurs from both privately owned and charter vessels that take single- or multi-day trips to the GBR. The annual harvest of red throat emperor by recreational anglers is estimated to be approximately 400 t (see Section 3.2.3 below). The harvest from the charter sector was approximately 80 t in 2003, up from about 50 t in 1996 when charter logbooks became compulsory. As with the commercial sector, a fall in the charter catch to around 15 t in 2004 was probably associated with a major restructure of the fishery.

A recreationally-caught red throat emperor (picture: CRC Reef).

1.5.2 Management history

Management of the CRFFF, of which red throat emperor is a significant component, is the responsibility of DPI&F. Minimum size restrictions specifically relating to this species have been legislated since the *Fisheries Act 1957*. The size and recreational bag limits have changed under various Queensland legislation; the major changes are listed in Table 1. Other historical management tools have included limited commercial entry, and gear specifications.

Additional controls were introduced by the *Fisheries (Coral Reef Fin Fish) Management Plan 2003*, especially an annual total allowable commercial catch (TACC) and individual transferable catch quota (ITQ) system for the commercial sector (Table 1). ITQs came into effect in July 2004 and nine-day spawning closures in October, November and December 2004. Also, areas closed to fishing under the *Great Barrier Reef Marine Park Act 1975* were extended in July 2004 as a result of the Great Barrier Reef Marine Park Authority (GBRMPA) Representative Areas Program (RAP).

Table 1: History of red throat emperor management.
(Sources: DPI&F staff and Andersen et al. 2005).

Year	Management	Legislation
1957	Minimum size limit 12 inches total length.	*Fisheries Act 1957*
1975	Inclusion of no-fishing zones in the Great Barrier Reef.	*Great Barrier Reef Marine Park Act 1975*
1976	Minimum size limit 300 mm total length.	*Fisheries Act 1976*

1984	Line fishery ‘L’ symbol introduced under the primary fishing boat policy. Limited entry for primary licences.	*Fishing Industry Organisation and Marketing Act 1982*
1987	Delegation of management responsibility for coral reef fish stocks in Commonwealth waters from the Commonwealth to Queensland. Restriction on the number of tender vessels.	Policy
1988	Restriction on sale of fish by recreational fishers to 50 kg of whole fish per permit, with a maximum of 12 permits to be sold to any individual annually. (Prior to 1988 there were no restrictions on the quantity of fish that a recreational fisher could sell.)	*Fishing Industry Organisation and Marketing Regulation*
1990	Ability of recreational fishers to sell catch stopped. Discussion Paper for CRFFF released: A review of the reef line fishery and proposed management measures.	*Fishing Industry Organisation and Marketing Regulation*
1993	Minimum size limit 350 mm total length. Recreational possession limits of 10 red throat emperor per fisher, and a combined total of 30 coral reef fish covering 26 species. Charter vessel possession limit arrangements—extended charters in excess of 48 hrs allowed double the prescribed possession limit. Restructure of commercial line fishery into regional endorsements—the existing L symbol was introduced into legislation with the numbers L1–L9 depicting different regions of operations. New format for landed fish—where a fish has been filleted there must be two fillets equal to one whole fish. Skin not to be removed from fillets by recreational fishers, except in the case of charter vessels in excess of 48 hrs where the majority of the skin may be removed provided a minimum is left for identification.	*Fishing Industry Organisation and Marketing Regulation*
1995	Reef Fisheries Management Advisory Committee (ReefMAC) established.	*Fisheries Regulation* under *Fisheries Act 1994*
	Refinement of management responsibilities for coral reef fish in Commonwealth waters.	*Offshore Constitutional Settlement*
1996	Discussion Paper 2 for CRFFF released: Queensland tropical coral reef fish species.	
1997	Investment Warning for the CRFFF released 19 May 1997. Issues Paper released—Excess fishing capacity in the commercial sector of the tropical coral reef fish fishery—an approach for inclusion in a statutory Fisheries Management Plan.	
1998	Investment Warning was re-issued 3 September 1998.	

1999	Draft Management Plan and Regulatory Impact Statement (RIS) for CRFFF released.	
2002	Revised Draft Management Plan and RIS released 28 September 2002.	
2003/04	Fisheries (Coral Reef Fin Fish) Management Plan implemented. Minimum legal size increased to 380 mm total length in December 2003. Recreational in-possession limits reduced to 8 red throat emperor per fisher, and a combined total of 20 coral reef fish. Anglers on charter boat trips of more than 72 hours have double the bag limit; trips of eight days or longer can retain up to 60 fish per fisher. Recreational fishers are limited to handline, rod and line (limit of 3 lines at a time with a maximum total of 6 hooks or lures), hand-held spear and spear gun (no SCUBA or hookah). Commercial fishers limited to a handline or rod and line. All commercial vessels must hold an RQ licence. RQ licence holders must hold appropriate line units (RTE units) to take red throat emperor, which take the form of individual transferable quotas. The total yearly catch of red throat emperor available for allocation is currently 700 t. New reporting requirements. Seasonal closures across the GBR for nine days around the new moon period in October, November and December each year.	*Fisheries (Coral Reef Fin Fish) Management Plan 2003*
2004	GBRMPA implemented new zoning arrangements for the Great Barrier Reef Marine Park. Under the rezoning approximately 33% of the marine park area is protected through closed green zones within which extractive uses are restricted.	*Great Barrier Reef Marine Park Zoning Plan 2003*

1.5.3 Research history

There have been several studies on red throat emperor. Loubens (1978, 1980a, b) provided information on the population biology of red throat emperor in New Caledonia during a study of the biology of a range of reef fish species. Church (1985) provided details of the population biology of red throat emperor around Norfolk Island as well as a description of the local fishery on the island.

Walker (1975), however, was the first to study populations of red throat emperor on the GBR. In addition to reviewing the taxonomy of lethrinids, Walker provided preliminary details on various aspects of red throat emperor biology, including information on dietary habits and parasites, estimates of age, growth and mortality, and descriptions of the reproductive biology. Although the descriptions of reproductive development and spawning season were accurate, more recent studies have revealed that the use of scales to estimate age resulted in a significant underestimate of age and, therefore, biased estimates of growth and mortality (Brown and Sumpton 1998, Williams 2003).

The most recent research on red throat emperor has arisen from two major projects. The first project was a DPI&F study focussed on the Capricorn-Bunker and Swains regions (see Section 2.1 and Figure 3 below) and provided estimates of age, growth, total mortality, sex ratios, size and age at maturity and sex change, and spawning season of red throat emperor sampled from reefs open to fishing (Brown *et al.* 1994, Brown and Sumpton 1998, Sumpton and Brown 2004). This study was the first on the GBR to examine otoliths of red throat emperor to estimate age, and therefore provided the first reliable estimates of age-based population parameters for the species on the GBR.

The second project was the CRC Reef Research Centre Effects of Line Fishing (ELF) Project, during which samples of red throat emperor were collected from reefs open and closed to fishing throughout the GBR over a 10 year period (Mapstone *et al.* 2004, Davies *et al*. 2005). Results from the ELF Project and closely related ancillary projects have provided estimates of abundance, biomass, age, growth, natural and total mortality, sex ratios, size and age at maturity and sex change, and spawning season over much broader spatial and temporal scales than the research of Brown *et al.* (1994). Importantly, the structured design of the ELF Project allowed valid comparisons of populations across reefs and regions of the GBR. From these comparisons the ELF Project identified significant and consistent regional variation in many population parameters such as abundance, biomass, age, growth, mortality, and size and age at sex change (Williams 2003, Williams *et al*. 2003, Davies *et al*. 2005).

DPI&F manager Katherine Kelly with a red throat emperor caught on a scientific survey conducted by CRC Reef and DPI&F (picture: CRC Reef).

Research data sets that were available for this assessment, therefore, comprise:

- Fishery-dependent and -independent samples collected from 1988–1992 by DPI&F from reefs open to fishing in the Swains and Capricorn-Bunker regions (Brown *et al*. 1994)
- Fishery-independent samples collected from 1990–1994 from reefs open and closed to fishing in the Townsville region as part of a James Cook University (JCU) research project (G. Russ unpublished data)

- Fishery-independent samples collected from 1995–2004 as part of CRC Reef ELF Project. Samples were collected from reefs open and closed to fishing in three regions of the GBR (Mapstone *et al.* 2004, Davies *et al.* 2005)
- Fishery-independent samples collected in September 2002 from open reefs in the Capricorn-Bunker region as part of a CRC Reef Research Centre project (Williams 2003)
- Fishery-dependent samples collected from 1998–2000 from reefs open to fishing (Williams 2003, Williams *et al.* 2003).

An FRDC-funded project to investigate survival of released fish has begun but not yet provided results that can be used for this stock assessment.

Numbers of fish from each of the samples used in this assessment are listed in Table 2. The ELF Project experimental design is listed in Table 3.

Table 2: Numbers of fish measured in fishery-independent research studies, 1988–2004. The number of fish whose lengths were measured is followed by the number that were aged, in parentheses. Numbers are classified by the regions into which we have divided the GBR for this assessment (see Section 2.1 below). Otoliths from the ELF Project from 2001–2004 were retained for laboratory analysis but had not yet been aged at the time of this assessment.

Study	**Sampling period**	**Numbers measured in each region**					
		Cairns North	*Towns-ville*	*Mackay*	*Storm Cay*	*Swains*	*Cap.-Bunker*
Brown *et al.* (1994)	Oct 1988						12 (11)
	Nov 1988					8 (8)	20 (16)
	Aug 1989	2 (1)				142 (60)	
	Sep 1989		18 (6)				
	Nov 1989			61 (34)			
	Jan 1990			65 (52)			
	Sep 1990						17 (17)
	May 1991						55 (52)
	Jun 1991						1 (1)
	Jul 1991						16 (16)
	Aug 1991						47 (47)
	Sep 1991						58 (56)
	Oct 1991						65 (65)
	Nov 1991						5 (5)
	Dec 1991						35 (19)
	Feb 1992						77 (54)
	Apr 1992						110 (67)
	May 1992						53 (46)
	Sep 1992						72 (72)
	Oct 1992						142 (75)
	Nov 1992						76 (69)
	Dec 1992						42 (42)
Russ (unpub. data)	Jun-Jul 1990		130 (106)				
	Sep-Oct 1990		108 (102)				
	Jun-Jul 1991		159 (146)				
	Sep-Oct 1991		139 (130)				
	Aug 1992		75 (72)				
	Oct 1992		67 (65)				
	Mar 1994		173 (169)				
	Apr 1994		122 (119)				
	May 1994		250 (245)				
ELF	Nov 1995		197 (197)				
	Dec 1995			360 (331)			
	Jan 1996				230 (231)		
	Oct 1996		40 (40)				
	Nov 1996		93 (94)	270 (266)	46 (46)		
	Dec 1996				142 (138)		
	May 1997		133 (0)	141 (1)	143 (0)		
	Aug 1997		79 (6)	76 (0)	91 (3)		
	Oct 1997		231 (200)				

	Nov 1997		194 (180)			
	Dec 1997			164 (145)		
	Jan 1998			37 (34)		
	Apr 1998	35 (11)	68 (0)	47 (0)		
	Oct 1998	133 (122)	118 (114)			
	Nov 1998		122 (113)	242 (227)		
	Feb 1999	105 (0)	174 (0)			
	May 1999	69 (0)	257 (1)	129 (1)		
	Aug 1999	56 (0)	210 (36)	225 (2)		
	Oct 1999	47 (30)				
	Nov 1999	153 (134)	394 (381)	368 (313)		
	Mar 2000		106 (97)	120 (88)		
	Apr 2000	48 (0)				
	Oct 2000	118 (114)				
	Nov 2000		462 (408)	408 (395)		
	Nov 2001	70 (0)	406 (0)			
	Dec 2001			387 (0)		
Williams (2003)	Sep 2002					92 (92)

Table 3: Experimental design of the ELF Project.
Reefs were opened and closed in different years. Closed years are coded 'C', open year 'O' and pulse-fishing years 'P' (these were fished more heavily than usual). All reefs returned to their original status in 2005. The Project also included six reefs around Lizard Island, but no red throat emperor were collected from them because they were beyond the northern end of the range of red throat emperor on the GBR. See Mapstone et al. (2004) for details.

ELF region	**Reef no.**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Townsville	18039	C	C	C	C	C	C	C	C	C	C	C
	18071	C	C	C	C	C	C	C	C	C	C	C
	18074	C	C	P	C	C	C	C	C	C	C	C
	18041	C	C	C	C	P	C	C	C	C	C	C
	18081	O	O	P	C	C	C	C	C	O	O	O
	18083	O	O	O	O	P	C	C	C	C	C	O
Mackay	20137	C	C	C	C	C	C	C	C	C	C	C
	20142	C	C	C	C	C	C	C	C	C	C	C
	20136	C	C	P	C	C	C	C	C	C	C	C
	20138	C	C	C	C	P	C	C	C	C	C	C
	20296	O	O	P	C	C	C	C	C	O	O	O
	20146	O	O	O	O	P	C	C	C	C	C	O
Storm Cay	21131	C	C	C	C	C	C	C	C	C	C	C
	21132	C	C	C	C	C	C	C	C	C	C	C
	21130	C	C	P	C	C	C	C	C	C	C	C
	21133	C	C	C	C	P	C	C	C	C	C	C
	21124	O	O	P	C	C	C	C	C	O	O	O
	21139	O	O	O	O	P	C	C	C	C	C	O

1.5.4 Monitoring history

Commercial catches were recorded by the Queensland Fish Board (QFB) from 1936–1981, although only records from 1946–1981 were available for this assessment. Official records were not kept from mid-1981 to the end of 1987. The QFB data provide annual total catches from the commercial sector, including recreational anglers who sold catch, categorised by port of landing. The QFB data may underestimate the total catches, as fish destined for overseas or interstate were not required to be marketed through the QFB. There was also an unknown level of illegal marketing of fish in Queensland outside the QFB.

The DPI&F Commercial Fisheries Information System (CFISH) collects data from Queensland's commercial fishers through a compulsory logbook program that began in 1988. The CFISH database provides daily records of both catch and effort at a 30-minute location grid resolution. DPI&F has enforced a 6-minute location resolution since July 2004.

The DPI&F Recreational Fisheries Information System (RFISH) collects data from Queensland's recreational fishers through a voluntary telephone survey and fishing diary program (Higgs 2001). These surveys have been conducted for the 1997, 1999 and 2002 calendar years. In addition, the National Recreational and Indigenous Fishing Survey was conducted from May 2000 to April 2001 (Henry and Lyle 2003). The primary purpose of these surveys was to estimate total annual catches, but the raw data can also provide catch per unit effort measurements.

Logbook data from charter operators have been kept by DPI&F since 1992, but have been compulsory since 1996. The logbooks include daily catch and effort data at the same resolution as the CFISH data.

The Australian National Sportfishing Association (ANSA) has been involved in a long-term tagging program for a wide range of species. Tagging of red throat emperor commenced in the early 1990s, and since then there have been few recaptures; thus information from this tagging program is limited.

Underwater visual surveys of demersal reef fish populations were carried out as part of the DPI&F Long Term Monitoring Program and ELF Project from 1999–2002. Very low numbers of red throat emperor were recorded in these surveys, because it is generally a diver-averse species and difficult to survey by this method, and much of the population lives at depths greater than the 12 m limit of these surveys.

1.6 Objectives

Concerns have been raised about the long-term sustainability of red throat emperor on the GBR due to uncertainties about its current status and levels of sustainable harvest. The recent introduction of a TACC for red throat emperor emphasises the importance of collating existing information to assess the current status and estimate sustainable harvest levels in the fishery.

The objectives of this stock assessment for red throat emperor, therefore, are to:

- Summarise the available data and information sources that can be used in this and future assessments.
- Summarise the biology of red throat emperor and the history of the fishery.
- Present the best possible information on the current state of the fishery.
- Provide informed comment on the sustainability of the current TACC.
- Present projections of future outcomes under different TACC levels.
- Provide recommendations for future assessment and monitoring.

2. Biological data

2.1 Regional variation

Significant variation among regions of the Great Barrier Reef has been observed in a number of population parameters for red throat emperor including abundance, biomass, age, growth, mortality, and size and age at sex change (Williams 2003, Williams *et al.* 2003, Davies *et al.* 2005). These regional patterns in population biology have been found to be relatively consistent over time (Williams 2003, Davies *et al.* 2005).

For this assessment the GBR has been divided into six distinct regions, shown in Figure 3, together with commercial catch totals as a guide to abundance: Cairns North, Townsville, Mackay, Storm Cay, Swains and Capricorn-Bunker. Biological data are available from five of these regions; lack of data from the remaining region, Cairns North, was dealt with by combining it with the Townsville region. In this assessment we have estimated region-specific biological parameters where sufficient data were available.

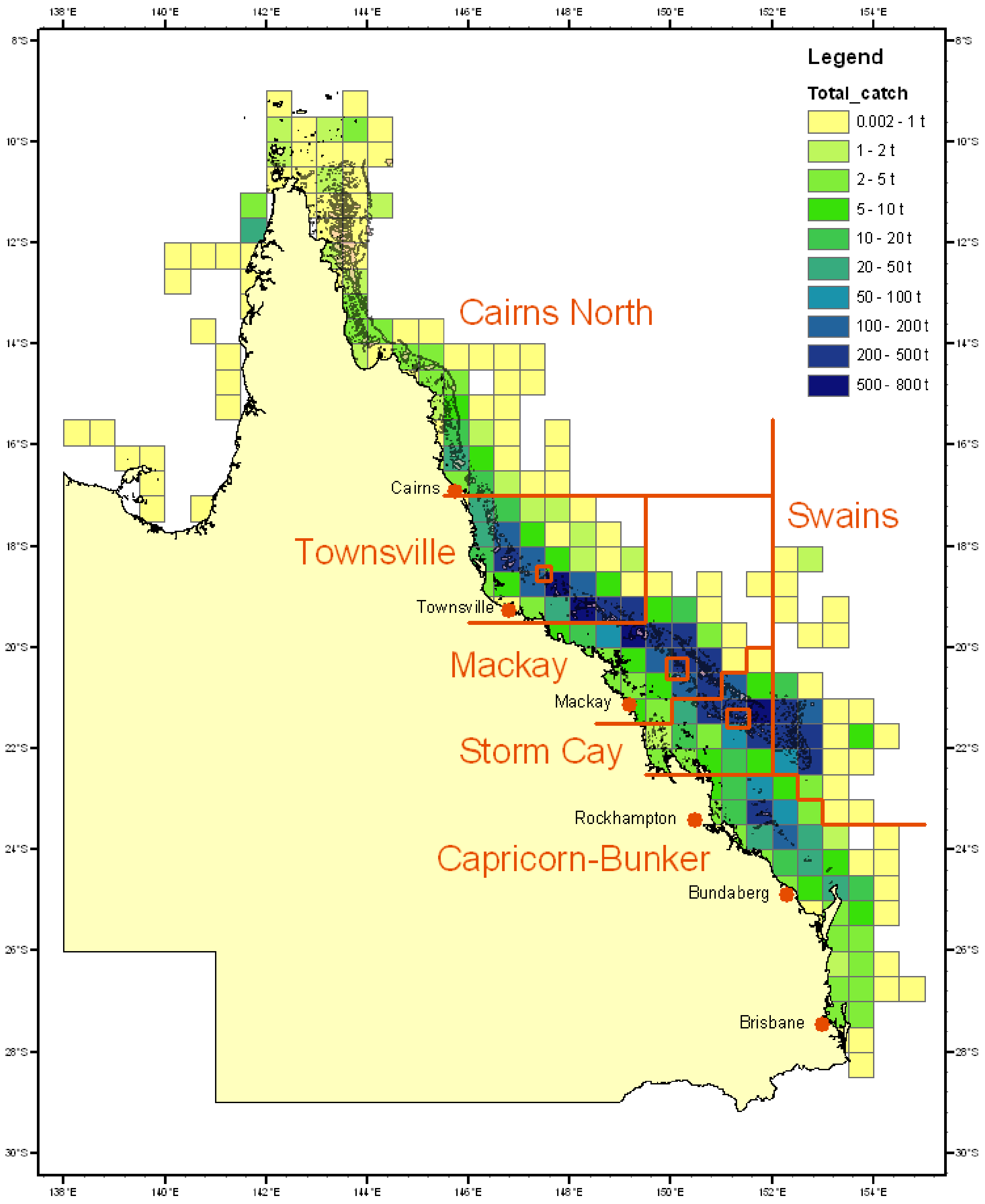

Figure 3: Spatial distribution of commercial catches of red throat emperor in Queensland. Totals over all years (1988–2004), from CFISH logbook data on a 30-minute latitude–longitude grid. The red lines divide the Great Barrier Reef into the six regions used in the assessment: from north to south, Cairns North, Townsville, Mackay, Storm Cay, Swains, and Capricorn-Bunker. The red rectangles are ELF Project sampling areas in the Townsville, Mackay and Storm Cay regions. Catches off Cape York and in the Gulf of Carpentaria are thought to be species misidentifications.

2.2 Length and weight relationships

2.2.1 Fork length, total length and standard length

Linear regression models were fitted to fork length (FL, mm) and total length (TL, mm) data from the ELF Project and Brown *et al*. (1994) (see Table 2 for sample numbers available from the different studies; the Russ data set did not include total length). Data were pooled across both data sets and regressions fitted to data from five regions of the GBR. There were insufficient data to fit meaningful regressions for the Cairns North region. We suggest that data from the Townsville region would be the best proxy for the Cairns North region due to the proximity of the two regions. The fitted models were used to predict FL from TL and TL from FL for each of the five regions separately (Table 4). Regression parameters varied significantly among regions ($P < 0.02$ for both FL to TL and TL to FL).

Table 4: Linear regression models for predicting fork length (FL) from total length (TL) and TL from FL for red throat emperor from five regions of the GBR.
The ± figure provides a standard error of prediction from the regression, which is the approximate error that can be expected in making predictions from this regression (composed almost entirely of the regression's residual standard error as opposed to standard errors of the parameter estimators). The column labelled N is the sample size and that labelled R^2 is the percentage variation explained by the regression. The final row is for all regions combined. 27 outliers were removed before fitting these models.

Region	***N***	R^2	**Linear model (FL to TL)**	**Linear model (TL to FL)**
Townsville	676	99.4%	$\mathrm{TL} = 10.8 + 1.0581 \times \mathrm{FL} \pm 4.7$	$\mathrm{FL} = -7.8 + 0.9397 \times \mathrm{TL} \pm 4.5$
Mackay	397	99.4%	$\mathrm{TL} = 14.0 + 1.0477 \times \mathrm{FL} \pm 4.7$	$\mathrm{FL} = -11.3 + 0.9497 \times \mathrm{TL} \pm 4.5$
Storm Cay	688	99.0%	$\mathrm{TL} = 9.6 + 1.0575 \times \mathrm{FL} \pm 4.7$	$\mathrm{FL} = -5.3 + 0.9370 \times \mathrm{TL} \pm 4.5$
Swains	773	99.2%	$\mathrm{TL} = 12.9 + 1.0521 \times \mathrm{FL} \pm 4.7$	$\mathrm{FL} = -9.1 + 0.9434 \times \mathrm{TL} \pm 4.5$
Capricorn-Bunker	1089	99.1%	$\mathrm{TL} = 4.4 + 1.0646 \times \mathrm{FL} \pm 4.7$	$\mathrm{FL} = -1.0 + 0.9309 \times \mathrm{TL} \pm 4.5$
Combined	3623	99.4%	$\mathrm{TL} = 3.2 + 1.0732 \times \mathrm{FL} \pm 5.0$	$\mathrm{FL} = -0.6 + 0.9260 \times \mathrm{TL} \pm 4.6$

Linear regressions were also fitted to FL (mm) and standard length (SL, mm) data from Brown *et al*. (1994) and Russ (unpublished data), covering the Townsville, Storm Cay, Swains and Capricorn-Bunker regions (Table 5).

Table 5: Linear regression models for converting fork length (FL) to standard length (SL) and SL to FL for red throat emperor from four regions of the GBR.
The ± figure provides a standard error of prediction from the regression, which is the approximate error that can be expected in making predictions from this regression (composed almost entirely of the regression's residual standard error as opposed to standard errors of the parameter estimators). The column labelled N is the sample size and that labelled R^2 is the percentage variation explained by the regression. The final row is for all regions combined. 26 outliers were removed before fitting these models.

Region	***N***	R^2	**Linear model (FL to SL)**	**Linear model (SL to FL)**
Townsville	1260	97.4%	$\mathrm{SL} = -8.3 + 0.8744 \times \mathrm{FL} \pm 5.7$	$\mathrm{FL} = 17.1 + 1.1228 \times \mathrm{SL} \pm 6.3$
Storm Cay	313	97.8%	$\mathrm{SL} = -10.4 + 0.8744 \times \mathrm{FL} \pm 5.7$	$\mathrm{FL} = 18.5 + 1.1228 \times \mathrm{SL} \pm 6.3$
Swains	162	98.5%	$\mathrm{SL} = -6.8 + 0.8744 \times \mathrm{FL} \pm 5.7$	$\mathrm{FL} = 14.6 + 1.1228 \times \mathrm{SL} \pm 6.3$
Capricorn-Bunker	781	98.9%	$\mathrm{SL} = -2.5 + 0.8744 \times \mathrm{FL} \pm 5.7$	$\mathrm{FL} = 9.0 + 1.1228 \times \mathrm{SL} \pm 6.3$
Combined	2516	98.6%	$\mathrm{SL} = 2.9 + 0.8502 \times \mathrm{FL} \pm 6.2$	$\mathrm{FL} = 2.3 + 1.1594 \times \mathrm{SL} \pm 7.1$

2.2.2 Average total weight

Conversion between numbers and weights of fish is needed for this assessment, especially for recreational catch estimates, where only numbers were recorded in the RFISH surveys. We have calculated the average weight of a legal-sized red throat emperor from the fishery-independent ELF samples described in Section 1.5.3. We used the minimum legal size of

350 mm TL that was in place for most of the monitoring history of the fishery, including all the recreational diary samples. We also restricted the analysis to fish from reefs that were open to fishing.

Using the parameters for the combined regression in Table 4, the 350 mm minimum legal TL translates to 323.5 mm FL. The average total weight of fish of this length or greater from the ELF samples from open reefs was 1.169 kg, and was the figure used to convert between number and weight of fish throughout this assessment.

We note that some logbook records from the charter fishery (13697 of a total of 19085) recorded both weight and numbers of red throat emperor harvested. The average weight from these data was 1.564 kg. Other evidence (Queensland Boating and Fisheries Patrol staff pers. comm., Higgs 1993) also indicates that red throat emperor retained by recreational fishers tend to be considerably larger than minimum legal size. We have refrained from using the average weight of available charter-caught fish because of possible bias in the catches that charter operators choose to weigh; they may choose to weigh only the larger fish.

The matter of the best average weight estimate to use for recreationally and charter-caught red throat emperor can be considered further in future assessments. It is possible that the actual weights of recreational and charter catches may be up to one-third higher than those reported in this assessment. The effects of such a change on the assessment are discussed in Section 7 below.

2.2.3 Fork length and weight

Log-linear regression models were fitted to FL (mm) and total weight (TW, kg) data from the ELF Project, Russ (unpublished data) and Brown *et al.* (1994). Data were pooled across all data sets and regressions fitted to data from five regions of the GBR. There were insufficient data to fit a meaningful regression for the Cairns North region. The fitted relationships were used to predict TW from FL for each of the five regions separately (Table 6 and Figure 4). The relationships differed significantly between regions ($F_{8,\,8356} = 96.7$, $P < 10^{-6}$).

Table 6: Log-linear regression models for converting fork length (FL, in mm) to total weight (TW, in kg) for red throat emperor from five regions of the GBR.
The ± figure provides a standard error of prediction from the regression, which is the approximate error that can be expected in making predictions from this regression (composed almost entirely of the regression's residual standard error as opposed to standard errors of the parameter estimators). The column labelled N is the sample size and that labelled R^2 is the percentage variation explained by the regression. The final row is for all regions combined. 33 outliers were removed before fitting these models.

Region	***N***	***R*²**	**Log-linear model**
Townsville	2436	88.7%	$\log TW = -17.3009 + 2.90730 \times \log FL \pm 0.1043$
Mackay	2895	96.2%	$\log TW = -19.1879 + 3.22232 \times \log FL \pm 0.1043$
Storm Cay	2236	93.9%	$\log TW = -18.9120 + 3.17269 \times \log FL \pm 0.1043$
Swains	52	98.5%	$\log TW = -18.6492 + 3.14651 \times \log FL \pm 0.1053$
Capricorn-Bunker	747	97.5%	$\log TW = -18.1905 + 3.06820 \times \log FL \pm 0.1044$
Combined	8366	94.9%	$\log TW = -18.2500 + 3.06507 \times \log FL \pm 0.1090$

The slopes of the regressions were greater than three in all regions except Townsville, which suggests that red throat emperor become relatively deeper in the body as they grow older. The regression's residual standard error is 0.1043; this is the estimate of by how much a fish's weight typically differs from the mean weight-at-length (about ±10%).

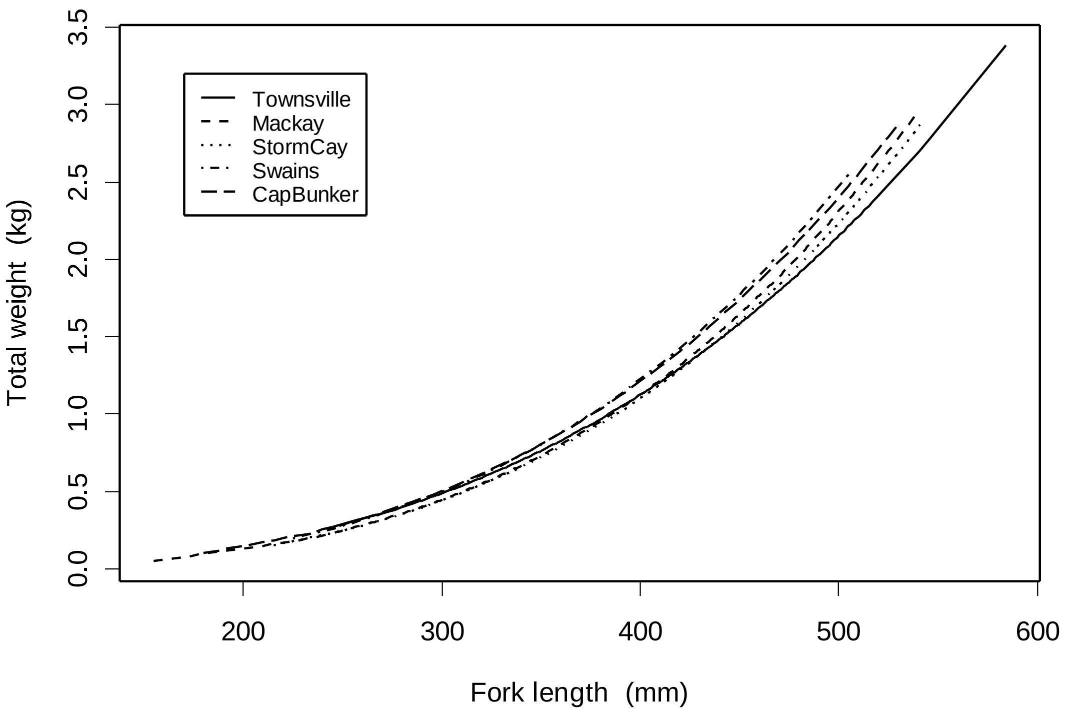

Figure 4: Curves for converting fork length to total weight for red throat emperor from five regions of the GBR..

A log-linear regression model was also fitted to TW (kg) and cleaned (gilled and gutted) weight (CW, kg) data from Russ (unpublished data) for the Townsville region. The ratio of cleaned weight to total weight was found to depend on the size of fish. The relationship between TW and CW was

$$\log CW = -0.1226 + 1.0382 \times \log TW (\pm 0.0458)$$

(N = 219, R^2 = 97.8%). The geometric mean total weight was 1.2635 kg, corresponding to a cleaned weight of 1.1277 kg which was 89.3% of the total weight.

2.3 Growth

A separate von Bertalanffy growth curve (VBGF) was fitted to length-at-age data for five regions of the GBR. Data from three sources (ELF Project, Russ unpublished data, Brown *et al.* 1994) were combined. Only scientifically-collected data were used; fishery-dependent samples were excluded due to concerns over (a) biases in the size of fish sampled by fishers, and (b) whether the annulus was laid down by the date the fish was caught, especially if the capture date was subject to uncertainty. Except for the spring ELF samples which occasionally carried over into January, data from the months of January, February and March were excluded (560 fish out of a total of 8070) because this appears to be the time of year when opaque increments are deposited in red throat emperor otoliths (Williams 2003 pp. 26–29, Williams *et al.* 2005).

The form of the VBGF used to model length-at-age data was

$$L_{tg} = L_{\infty g}\left(1 - e^{-K_g (t - t_{0g})}\right)$$

where

L_{tg} is the length at age t in region g

$L_{\infty g}$ is the mean asymptotic fork length in region g

K_g is the rate at which L_∞ is approached in region g

t_{0g} is the age at which the sampled fish have a theoretical length of zero in region g.

Age was measured in years, composed of an integer part being the number of annuli observed, and a fractional part being the time of year (starting from zero at the beginning of January). The growth curves were fitted by non-linear least squares.

The curves differed between regions at a high level of statistical significance (residual sums of squares analysis, $F_{12,\,6249} = 43.38$, $P < 10^{-6}$). Growth parameter estimates are listed in Table 7. The fitted growth curves are plotted in Figure 5.

Table 7: Von Bertalanffy growth parameters for each region.
From pooled data from the ELF Project, Russ (unpublished data) and Brown et al. (1994). A common standard error was fitted to all regions and gives the estimated standard deviation of lengths around the fitted mean length; it does not relate to the standard errors of the parameter estimates.

Region	**Sample size**	**L_∞(mm)**	**k(yr^{-1})**	**t_0(yr)**	**Standard error (mm)**
Townsville	2098	459.3 ± 2.1	0.37053 ± 0.023	-0.360 ± 0.26	31.2
Mackay	1861	538.6 ± 9.1	0.18367 ± 0.012	-1.686 ± 0.22	31.2
Storm Cay	1528	489.4 ± 4.0	0.25485 ± 0.013	-0.759 ± 0.19	31.2
Swains	68	574.7 ± 68.7	0.17280 ± 0.063	-1.543 ± 0.90	31.2
Capricorn-Bunker	709	516.8 ± 9.7	0.24146 ± 0.017	-1.243 ± 0.17	31.2

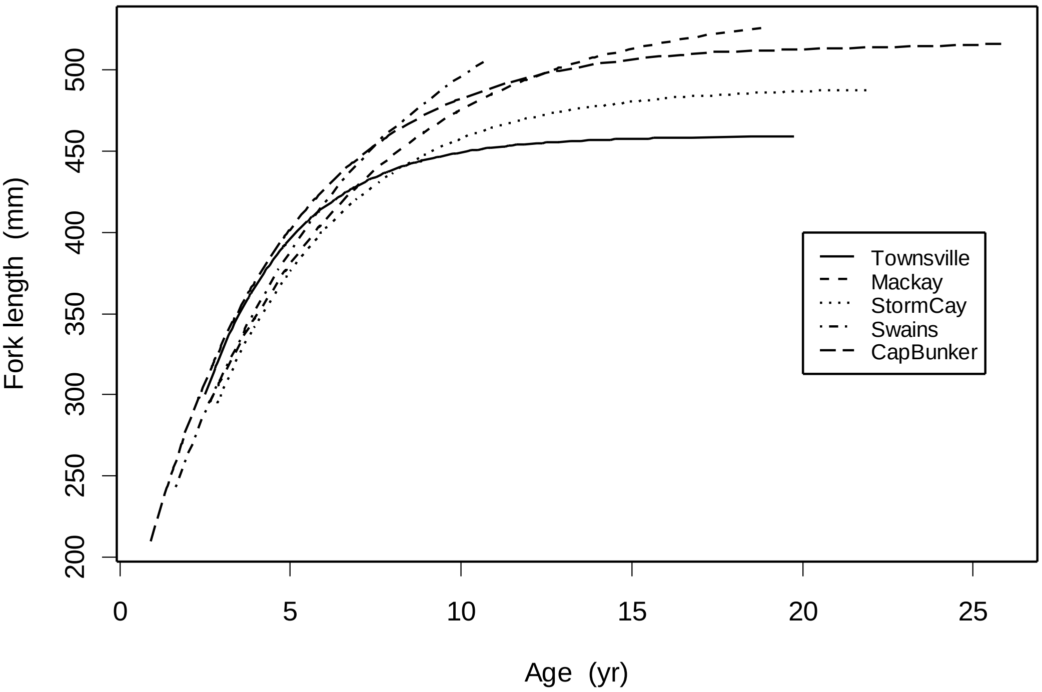

Figure 5: Fitted growth curve for red throat emperor for each region.
The estimated standard deviation of lengths around the fitted mean length is 31.2 mm (Table 7).

2.4 Natural mortality

No reliable estimates of instantaneous natural mortality rates (M) of red throat emperor were available prior to the ELF Project. The ELF age-frequency data have been incorporated into the population dynamics model in Section 6, which estimated a single value $M = 0.51$ yr^{-1} ± 0.02 yr^{-1} for the population over the whole GBR. The figure of 0.02 yr^{-1} is the formal standard error from the model, but does not take into account deviation from model assumptions. In reality the uncertainty may be somewhat greater than indicated by the model.

It is also probable that the value of M for old fish (e.g. > 10 yr) is less than that for younger fish (towards which the model is weighted, due to large numbers of younger fish in the population). There were insufficient data to estimate a separate M for old fish.

The estimate of 0.51 yr^{-1} falls between the extremes of estimates calculated by Williams (2003) which were 0.29 yr^{-1} (Townsville region), 1.12 yr^{-1} (Mackay), and 0.71 yr^{-1} (Storm Cay). The model in Section 6 explains the wide range of apparent values of M by different age dependencies of availability of red throat emperor to fishing in each region.

2.5 Maturity

The proportion of female fish that were mature at each age was estimated from data from the ELF Project and Williams (2003). Maturity proportions at the same age were assumed to be the same over all regions.

The proportion mature was assumed to be zero at age zero: of the ten fish of age zero that were collected, none were mature. The proportions mature at ages greater than zero were estimated by a generalised linear model (GLM) using a binomial distribution and logit link. The analysis was performed in the statistical package *R* (R Development Core Team 2005).

The parameter estimates from the GLM are listed in Table 8, and the observed and fitted maturity proportions in Table 9.

Table 8: Parameter estimates for the generalised linear model fitted to maturity proportions of female fish.
The proportion mature for ages greater than zero is assumed to take the form $\exp(\alpha + \beta a) / \{1 + \exp(\alpha + \beta a)\}$, *where* a *denotes age in years.*

Parameter	Estimate	Standard error
α	0.1740	0.4438
$\beta\,(\text{yr}^{-1})$	0.9302	0.1476

Table 9: Observed and fitted maturity proportions for female fish using the parameter estimates from Table 8.
All fish aged zero were assumed to be immature. The fitted maturity proportions were used in the assessment.

Age	Number mature	Number immature	Observed maturity proportion	Fitted maturity proportion
0	0	10	0.0000	0.0000
1	9	2	0.8182	0.7510
2	157	15	0.9128	0.8844
3	260	24	0.9155	0.9509
4	447	6	0.9868	0.9801
5	252	1	0.9960	0.9920
6	95	0	1.0000	0.9968
7	52	0	1.0000	0.9988
8	36	0	1.0000	0.9995
9	31	0	1.0000	0.9998
10	27	0	1.0000	0.9999
11	14	0	1.0000	1.0000
12	13	0	1.0000	1.0000
13	13	0	1.0000	1.0000
14	10	0	1.0000	1.0000
15	3	0	1.0000	1.0000
16	2	0	1.0000	1.0000
17	1	0	1.0000	1.0000
18	1	0	1.0000	1.0000
19	2	0	1.0000	1.0000
20	1	0	1.0000	1.0000

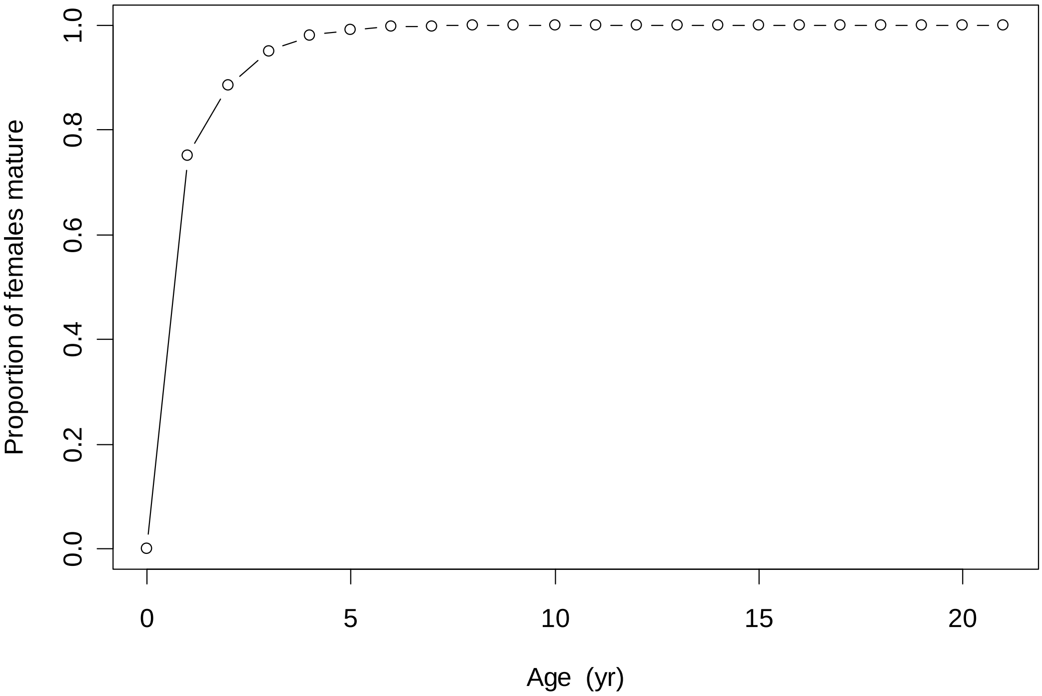

Figure 6: Fitted maturity proportions for female fish used in the assessment.
Using the parameter estimates from Table 8. All fish aged zero were assumed to be immature. Maturity proportions at age are assumed to be the same across all regions.

2.6 Sex change

The proportion of fish that were female at each age was estimated from the same data as for maturity, namely the ELF Project and Williams (2003). Proportions of female fish at the same age were assumed to be the same over all regions.

There appeared to be a proportion of approximately 40% of fish that remained female into old age. This phenomenon suggests that protogyny may not be the only, or even dominant, sexual strategy of red throat emperor (see Williams 2003). The proportion of fish remaining female was included as an extra parameter; hence the analysis was more complicated than the one for maturity. The analysis was undertaken as a maximum likelihood problem, using a binomial distribution for the number of fish that were female at each age. The assumed functional form for the proportion of female fish was

$$p = p_\infty + (1 - p_\infty)\exp\{-\gamma(a - a_0)\} / [1 + \exp(-\gamma(a - a_0)\}],$$

where p is the proportion of female fish, a denotes fish age in years, and p_∞, a_0 and γ are parameters to be estimated: p_∞ is the proportion of fish that remain female into old age, a_0 is the age at which half the fish that are to change their sex have done so, and γ is a slope parameter determining how rapidly the population's sex profile changes with age.

Parameter estimates from the maximum likelihood formulation are listed in Table 10, and the observed and fitted proportions of female fish in Table 11.

There is some suggestion in Table 11 that the proportion of fish that are female may increase into old age, for example through sex-selective mortality. The model has not allowed the fitted proportion to increase due to small numbers of old fish sampled and lack of biological evidence for this effect.

The stock assessment model embodied the assumption that there were always enough male fish to fertilise eggs produced by the female fish. The model's stock recruitment relation involved only the number of eggs produced, and didn't consider numbers of male fish.

Table 10: Parameter estimates for the maximum likelihood binomial model fitted to the proportions of fish that were female.
The proportion female is assumed to take the form $p_\infty + (1 - p_\infty)\exp\{-\gamma(a - a_0)\} / [1 + \exp(-\gamma(a - a_0)\}]$*, where a denotes age in years.*

Parameter	Estimate	Standard error
p_∞	0.4029	0.0218
a_0 (yr)	4.8304	0.0940
γ(yr^{-1})	1.6158	0.1433

Table 11: Observed and fitted proportions of fish that are female, using the parameter estimates from Table 10.
The fitted proportions were used in the assessment. The ± figures shown for the observed female proportion are rough standard errors.

Age	**Number female**	**Number male**	**Observed female proportion**	**Fitted female proportion**
0	10	0	1.0000	0.9998
1	17	0	1.0000	0.9988
2	183	2	0.9892±0.0076	0.9939
3	284	9	0.9693±0.0101	0.9705
4	453	61	0.8813±0.0143	0.8763
5	253	131	0.6589±0.0242	0.6608
6	95	107	0.4703±0.0351	0.4813
7	52	70	0.4262±0.0448	0.4203
8	36	69	0.3429±0.0463	0.4065
9	31	61	0.3370±0.0493	0.4036
10	27	31	0.4655±0.0655	0.4031
11	14	22	0.3889±0.0813	0.4029
12	13	22	0.3714±0.0817	0.4029
13	13	11	0.5417±0.1017	0.4029
14	10	5	0.6667±0.1217	0.4029
15	3	1	0.7500±0.2165	0.4029
16	2	1	0.6667±0.2722	0.4029
17	1	0	1.0000	0.4029
18	1	1	0.5000±0.3536	0.4029
19	2	1	0.6667±0.2722	0.4029
20	1	0	1.0000	0.4029

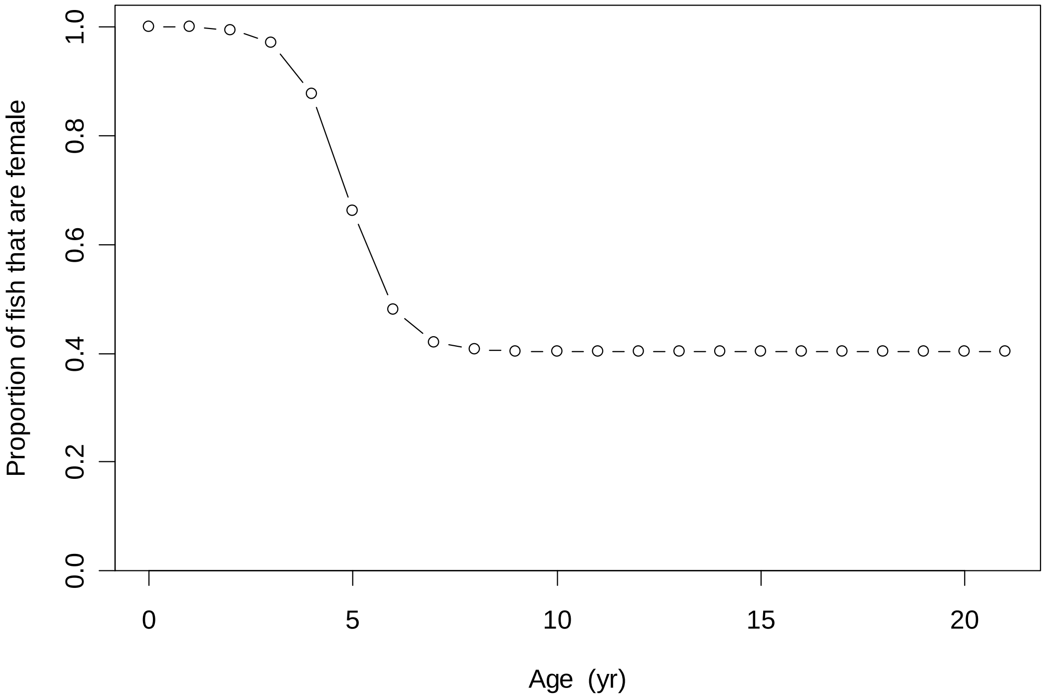

Figure 7: Fitted proportions of fish that are female.
Using the parameter estimates from Table 10. Proportions at age are assumed to be the same across all regions.

2.7 Fecundity

No information is available on the fecundity for red throat emperor or any other emperor. For this assessment we assumed that the number of eggs produced by a female red throat emperor was proportional to its weight, and that all eggs have the same probability of fertilisation and subsequent survival, irrespective of size and age of the parents.

2.8 Age structure

Plots of all sizable age-frequency samples mentioned in Section 1.5.3 are combined with the results of the age-structured population dynamic model of Section 6, and are shown in Figure 32 below (p. 73). They are especially remarkable for the differences they show in age structure between different regions. The ages with the highest frequencies are 5–8 years in the Townsville, Mackay and Storm Cay regions, and only 2 years in the Capricorn-Bunker region.

Data for all years combined are plotted in Figure 33 below (p. 81). For the Townsville, Mackay and Storm Cay regions these plots show the difference in age structures between reefs that are open to fishing and reefs that are closed: older fish are clearly less common on the open reefs.

3. Fishery data

3.1 Commercial sector

3.1.1 Queensland logbook (CFISH) data

Commercial data for calendar years 1988–2004 were taken from the CFISH database. Catch data were ignored from 1988 to 1990 because it took time to introduce the logbook system to fishing operators and much of the catch is known not to have been recorded in those years (Mark Elmer, pers. comm.).

The majority of the catch came from the GBR between Townsville and Capricorn-Bunker reefs (see Figure 3). Commercial logbooks record only harvested fish and not fish that were released. The catch from fisheries other than the line fishery was very small: a total of 15 t over the period 1988–2004, mainly from the trawl fishery, with a maximum of 4.4 t in 1991.

Line fishery data only are used to analyse historical catches and catch rates in this assessment.

Some of the logbook records are converted from fillet or trunk weight to whole weight, using species or species-group standard conversion factors within the CFISH database.

The commercial sector of the fishery has passed through several growth phases. The peak involvement occurred in 1997 with 587 licensed operations catching either red throat emperor or unspecified emperor species; following management intervention, 310 operations were involved in 2004. An Investment Warning for the fishery was issued in 1997. The fishery has a high turnover of vessel involvement, with 1297 different operations reporting catches of red throat emperor between 1988 and 2004; the number of commercial operations by year, split into pre-existing versus first-year licensees, is plotted in Figure 8. The effort level in the fishery has grown over time, although effort targeted specifically at red throat emperor is difficult to establish because of the multi-species nature of the fishery and the fact that red throat emperor are often not the target species.

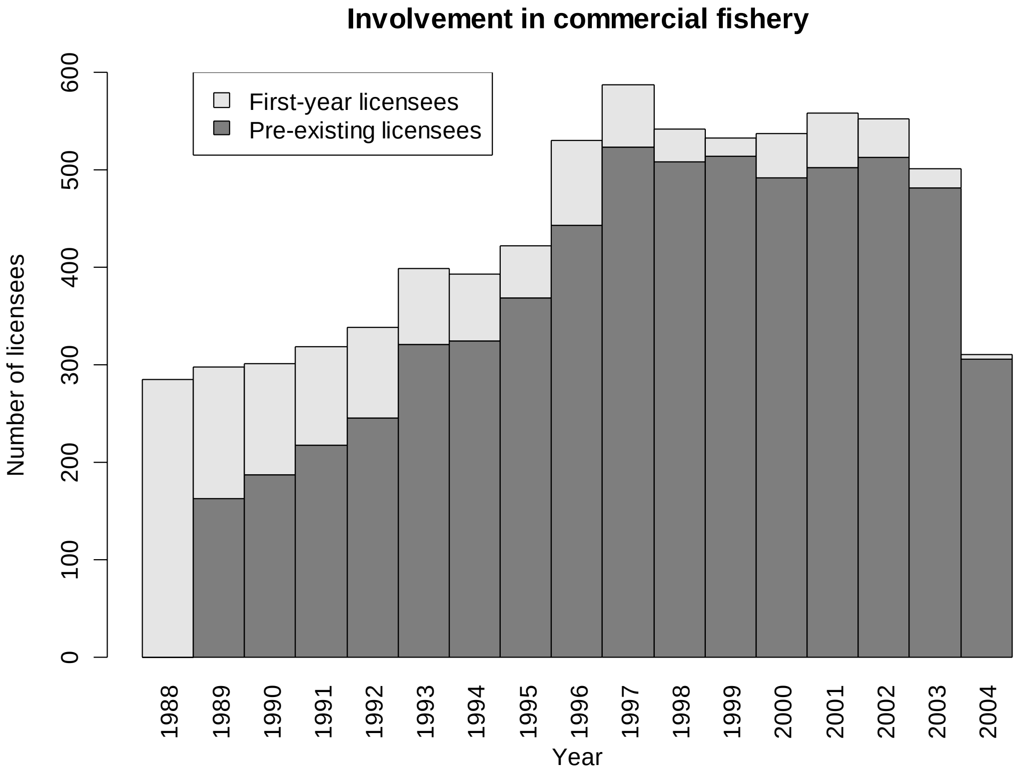

Figure 8: Number of commercial licensees reporting catches of either red throat emperor or unspecified emperor species.
For the commercial sector of the reef line fishery, 1988–2004. All licensees were classified as first-year in 1988 because this was the first year of the database.

Some catches of emperor in the CFISH database were recorded as ‘Emperor—unspecified’, some of which could have been red throat emperor (Figure 9). Total recorded catches are listed in Table 12, classified by whether the same vessel also reported red throat emperor. Table 12 shows that 99.2% of unspecified emperor was reported by vessels that also reported red throat emperor in any year, and 52.9% was by vessels that also reported red throat emperor on the same day. These statistics indicate that operators distinguish red throat emperor from other emperor species, and support the hypothesis that the number of red throat emperor recorded as ‘unspecified’ is low and may well occur when small numbers are caught among other emperor species.

Unspecified emperor catches, therefore, were excluded from this assessment.

About 2% of the catch data had no 30-minute grid square associated with it. Catches from unknown locations were spread across regions in the same proportions as catches from known regions in the same year.

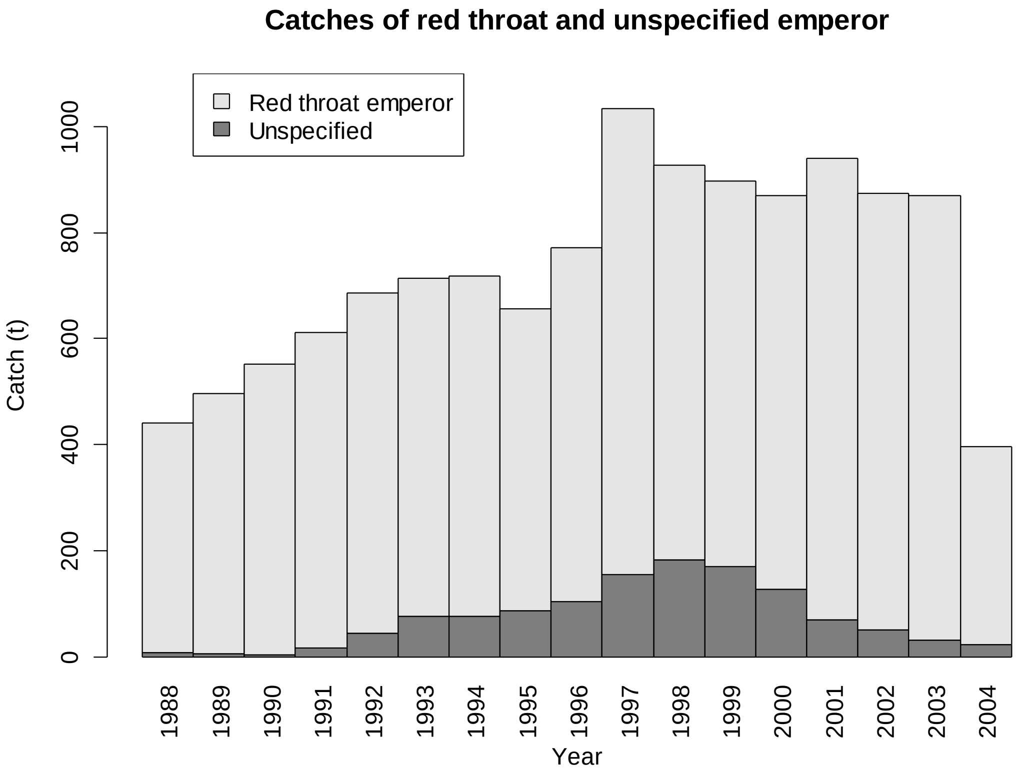

Figure 9: Commercial catches (t) of red throat emperor and unspecified emperor from logbook data (CFISH database).

Table 12: Catches (t) of unspecified emperor from the CFISH database 1988–2004, classified according to whether the same vessel reported red throat emperor.

Category	Unspecified emperor (t)	Red throat emperor (t)
Total reported catch	1228	11 227
Total from operators that also reported red throat emperor:		
In any year	1218	
In the same year	1104	
In the same month	892	
On the same day	649	

3.1.2 Historic Queensland Fish Board data

QFB catch returns, which have been discussed in Section 1.5.4, were aggregated over financial years (i.e., July to June). To fit the calendar-year nature of this assessment, they were assumed to apply to the calendar year corresponding to the second half of the data-collection year (e.g., 1980–1981 is assumed to apply to calendar year 1981).

The QFB data also showed species confusion with categories for ‘Sweet lip’ (red throat emperor) and ‘Emperor’ (unspecified emperor). The total unspecified emperor catch over all years 1946–1981 was 1267 t, which is about 38% of the total red throat emperor catch of 3298 t. This compares to a figure of about 11% for the CFISH data, indicating that the majority of unspecified emperor in the historical catch records may have been red throat emperor.

Species identification also appears inconsistent from year to year, especially in the Mackay, Storm Cay and Swains regions (it was not possible to distinguish these regions in the QFB data, because data were classified only by port of landing). These records are plotted in Figure

10. They show a growth phase in the fishery from 1970 to 1975 in which large catches of unspecified emperor were recorded. This is followed by a period of stable catches with a much smaller weight of unspecified emperor. Figure 10 strongly suggests that most of the unspecified catch from 1970–1975 was red throat emperor.

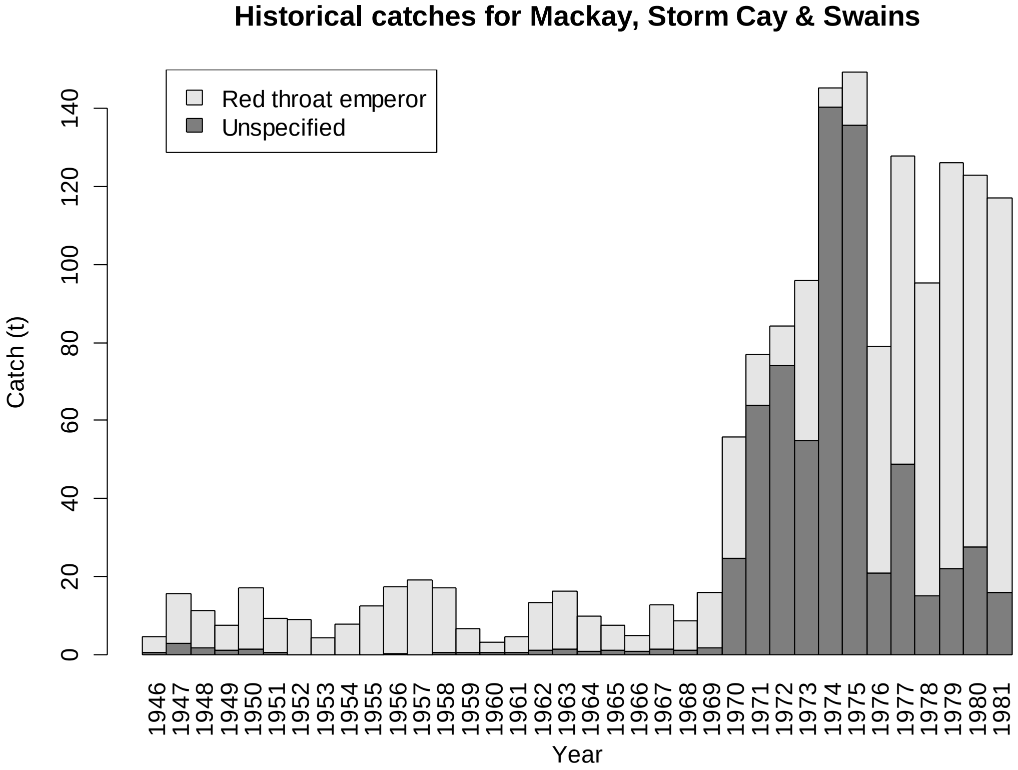

Figure 10: Historical catches of red throat emperor and unspecified emperor from the Mackay, Storm Cay and Swains regions combined (Queensland Fish Board returns).

The unspecified emperor records in the QFB data were assumed to be mainly red throat emperor, and were added to the red throat emperor catch for analysis. The QFB and CFISH data sets appear to be qualitatively different, with operators filling in CFISH logbooks taking much more care to distinguish emperor species than is the case for the QFB data.

As remarked above, it was impossible to distinguish the Mackay, Storm Cay and Swains regions in the QFB data, because data were categorised only by port of landing. Data from the three regions combined were split into individual regions using catch weight fractions by region from the 1991 CFISH data.

3.1.3 Time series of catches

Catch sizes for 1982–1990 were interpolated linearly from the average of 1980 and 1981, and the average of 1991 and 1992 commercial catches. The resulting time series of catches by year and region is shown in Figure 11. Annual total commercial catch sizes are listed in Table 13.

Figure 11 shows a much larger catch in the Townsville region in 1997 than in prior years. Fishers have ascribed this to the effect of Cyclone Justin which stayed around the Queensland east coast for several weeks in March 1997 and appears to have had a profound effect on the availability of both red throat emperor and coral trout (CRC Reef Stakeholder Workshop participants, pers. comm. 2004).

Cyclone Justin, although a relatively weak tropical cyclone, was extremely large and had a long duration (17 days, 7–24 March 1997). The United States Navy Typhoon Havens Handbook (Naval Meteorology and Oceanography Command 2003) states, ‘According to

BOM ([Australian Government] Bureau of Meteorology) … during its first week, Justin was a large storm, covering a major portion of the Coral Sea. It followed a slow and erratic path before cooler sea surface temperatures (SST), caused by the mixing of the top oceanic layer and persistent cloud cover, weakened it. The mixing and cloud cover caused the SST to fall by 7.2°F (4°C) or more. Justin then moved northeast over warmer water and intensified to a severe Category 3 while off southeast Papua New Guinea near 12°S 155°W on 17 March. Justin then moved southwestward and made landfall as a low Category 2 tropical cyclone just north of Cairns on the Queensland coast on 22 March. The storm moved approximately 70 nautical miles inland before re-curving southeastward and exiting the coast north of Townsville. The final warning was issued when Justin was just east of Townsville.'

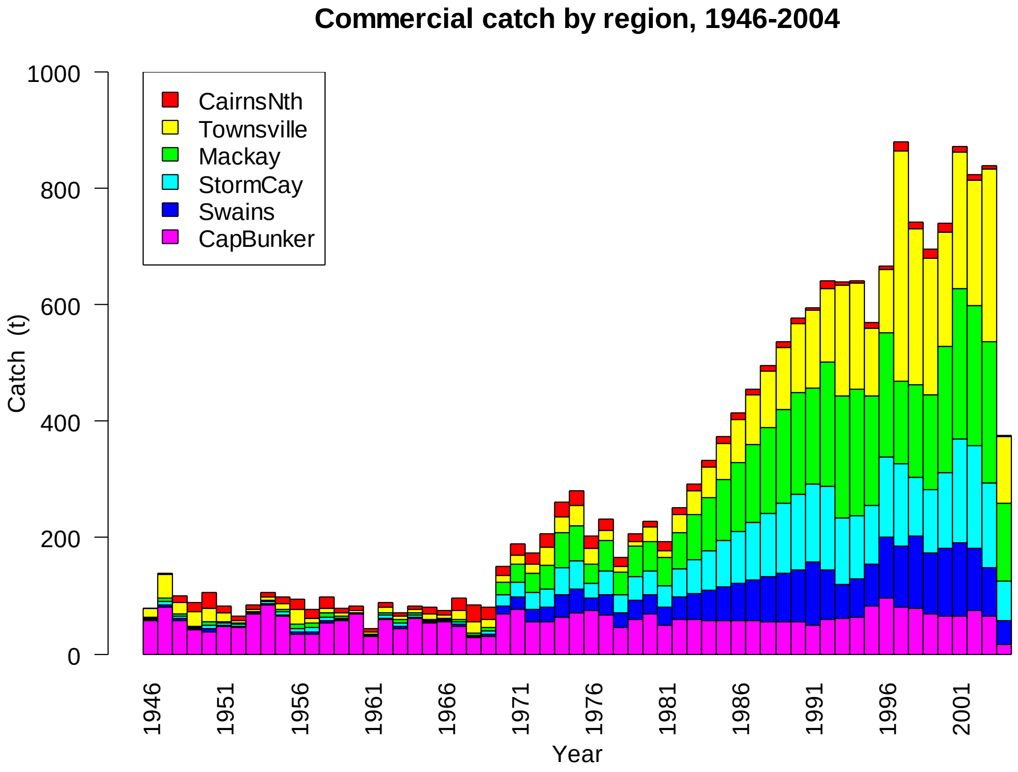

Figure 11: Time series of commercial catches of red throat emperor.
From 1946–2004, by region, as used for the assessment. Unknown locations in the commercial logbook data were dealt with by spreading their catches across regions in the same proportions as catches from known regions in that year. Catches from 1982–1990 have been interpolated from those before and after.

Table 13: Time series of total commercial catches by year.

Catches from 1946–1981 are from Queensland Fish Board records, and those from 1991–2004 are from the CFISH logbook database. Catches from 1982–1990 have been interpolated from the average of 1980 and 1981, and the average of 1991 and 1992 catches. (The assessment used catches by both year and region.)

Year	Catch (t)	Year	Catch (t)	Year	Catch (t)	Year	Catch (t)
1946	78.2	1961	44.7	1976	202.9	1991	591.4
1947	139.1	1962	88.2	1977	232.1	1992	598.3
1948	100.1	1963	70.3	1978	165.1	1993	622.4
1949	88.5	1964	82.9	1979	206.0	1994	623.4
1950	105.1	1965	80.1	1980	228.5	1995	545.4
1951	82.1	1966	74.0	1981	192.8	1996	648.1
1952	65.0	1967	96.0	1982	249.0	1997	854.2
1953	84.7	1968	83.7	1983	287.5	1998	719.9
1954	106.3	1969	80.4	1984	325.9	1999	670.7
1955	98.9	1970	149.6	1985	364.3	2000	714.7
1956	94.8	1971	189.2	1986	402.7	2001	860.3
1957	76.1	1972	173.0	1987	441.2	2002	810.5
1958	97.6	1973	206.5	1988	479.6	2003	823.9
1959	78.6	1974	261.1	1989	518.0	2004	369.9
1960	82.1	1975	280.8	1990	556.4		

3.1.4 Seasonal patterns in red throat emperor catch and effort

Although few data have been published on the spawning activities of red throat emperor, there is at least anecdotal evidence that they spawn over the full moon from July to November (Slade and Williams 2002). Of 23 very large catches (over 1000 kg per day of trip) recorded in the CFISH logbook data base, four (17%) were outside the nominal spawning season and only three (13%) occurred within dates which would now be covered by seasonal closures under the *Fisheries (Coral Reef Fin Fish) Management Plan 2003*.

There is a general trend for larger commercial catches of red throat emperor during the spawning months (Figure 12). However, there is no clear monthly trend in CPUE during the year. One explanation for this pattern might be that commercial fishers target other species but fish heavily for red throat emperor whenever they are 'biting', even during spawning months.

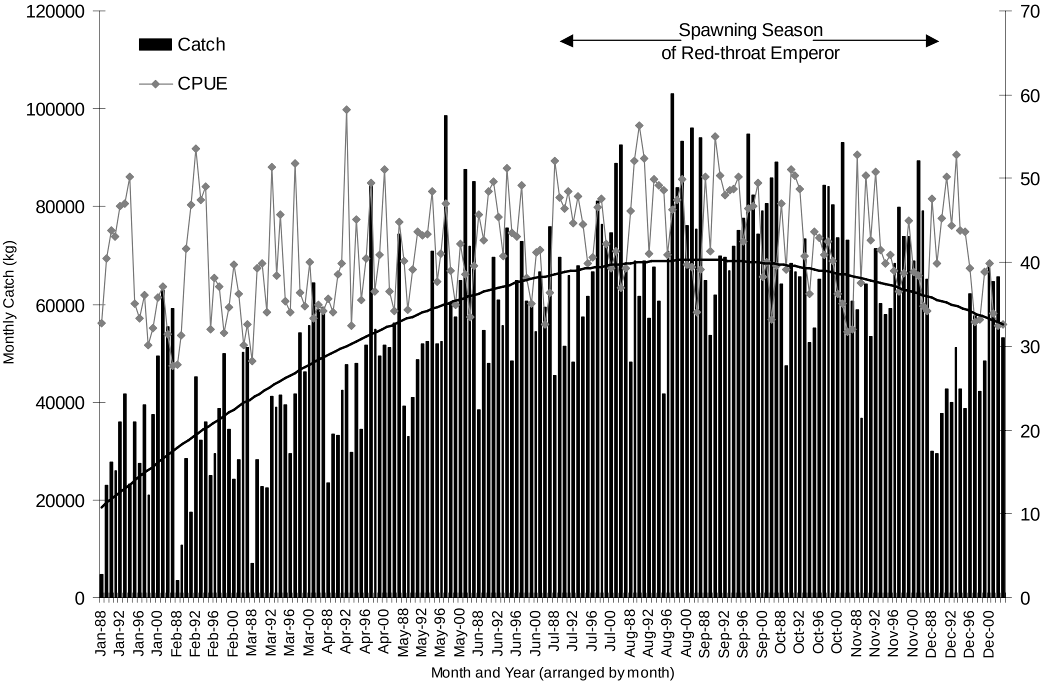

Figure 12: Commercial catch and raw catch-per-unit-effort (CPUE) arranged by month from 1988 to 2003.
The catch trendline is a quadratic and spawning season is marked (CFISH database).

3.2 Recreational and charter sectors

3.2.1 Components

Non-commercial fishers fall into three main components, the ‘self drive’ recreational and tourist fishers, fishers employing the charter boat industry to access the fishery, and indigenous subsistence fishers. The first component consists mostly of Queensland residents who access the fishery through private means. The second component contains interstate and international tourists who hire charter fishing operators to access the fishery, although the ratio of the number of these visitors to the number Queensland resident fishers who hire charter boats is unknown.

3.2.2 Conversion of numbers to weights

Recreational catches were recorded as numbers of fish, which required conversion to weights for comparison to commercial data and input to population dynamic models. Catch numbers were scaled by the average fish weight of 1.169 kg calculated in Section 2.2.2.

3.2.3 Recreational fishing survey data

Recreational fishers, particularly in the Townsville, Mackay and Capricorn-Bunker regions, deliberately target red throat emperor (Blamey and Hundloe 1993, Higgs 1993). In a study of two Townsville fishing clubs, Higgs (1993) found that red throat emperor represented 14.7% of the number of fish caught and noted a decline in the CPUE of red throat emperor from the 1960s to the 1990s, although this may have been due to a change in fishing practices of the clubs, targeting other deep water snappers.

A 1990–1991 survey by Blamey and Hundloe (1993) examined the economic regions of Cairns (Far North Statistical Division), Townsville (Northern SD), Mackay (Mackay SD) and Rockhampton (Fitzroy plus Wide Bay – Burnett SD) by telephone and boat ramp surveys. These regions correspond approximately to our Cairns North, Townsville, Mackay and Capricorn-Bunker regions, but classify fishers by place of residence or boat launching rather than where they fished; boats launched in the Mackay and Rockhampton SDs could have fished in the Swains. Respondents provided data on total fish numbers caught. These authors found 890 ‘Sweetlip Emperor’, including red throat emperor, were caught by the 453 respondents. Some 4% of boat ramp respondents targeted sweetlip, all of which were fishing within the GBR. In this survey the highest catch of sweetlip was made in the Rockhampton region, where this species group accounted for 62% of all fish caught, and was the target of 10% of the fishers. Many of these fish may have been grass sweetlip (*Lethrinus laticaudis*), which is a common target species in this region. As this study targeted boat ramps it is not possible to extrapolate the survey data on its own, to give a total state-wide catch.

The 2000–2001 National Recreational and Indigenous Fishing Survey (NRIFS) (Henry and Lyle 2003) provided a comprehensive data set for recreational and indigenous fishing activities in Australia. The survey estimated that 438 518 (±73 679) emperor were harvested by recreational fishers in Queensland from May 2000 to April 2001, and a further 9268 by indigenous fishers. The ‘Emperor’ category in the National survey included lethrinid species other than red throat emperor. Although the survey also considered overseas visitors fishing, only the Australian residents’ catch has been used in this assessment because no species catch information was available for international visitor fishers, and concentrating on Australian anglers gave a reduced potential of overlap with the charter boat logbook data.

The 1997, 1999 and 2002 RFISH diary surveys estimated the number of sweetlip (all Lethrinidae species combined) harvested in Queensland as 719 000 (±36 000), 861 000 (±67 000) and 638 000 (±57 000) respectively. These diary surveys were divided into areas of angler residence. In the 1997 survey the largest proportion of the catch was reported by residents of the Northern Statistical Division (21%), next was the Far North SD (16%), then the Fitzroy and Mackay SDs (11% each) (Higgs 1999). We have estimated the catches made in each of our regions by analysing the RFISH raw data (see Section 3.2.4 below).

Both the RFISH and National surveys included charter catches by Queensland residents. However, as noted in Section 3.2.1, the charter sector contains overseas residents, whose catch is additional to the diary surveys.

In the National survey, recreational fishers caught emperor predominantly by line (99.9%) but also by dive (0.07%) and in pots/traps (0.01%), and 94.5% were caught from boats. All emperor caught by indigenous fishers in the National survey were caught by line.

The reason for the discrepancy between the RFISH catch estimates and the much lower National survey estimate is unknown.

3.2.4 Analysis of RFISH raw data

Raw data from the RFISH surveys contained information on

- location of catches
- species composition
- released fish.

A summary analysis of these data is presented in Table 14. This shows a different regional pattern to both the commercial and charter catches (see Section 3.1.3 above and Section 3.2.5 below). Most of the catches come from the Townsville and Capricorn-Bunker regions, while those from the Storm Cay and Swains regions are small. Table 14 uses the recorded information on location of catches, as opposed to the Statistical Division based on places of residence of fishers; each reef on which red throat emperor were caught was checked and classified into one of the regions used for this assessment.

The effect of Cyclone Justin in 1997 (see Section 3.1.3) is evident again in Table 14. The Cairns North and Townsville regions make a much greater contribution to the total catch in 1997 than in other years (the *Region %* column in Table 14), while the Mackay, Swains and Capricorn-Bunker regions contribute relatively less. This effect appears to be specific to red throat emperor as opposed to other emperor species (mainly grass sweetlip *Lethrinus* *laticaudis*, spangled emperor *L. nebulosus* and reticulated emperor *L. semicinctus*) (see the *Red throat %* column in Table 14).

The release rate of red throat emperor was not found to vary significantly with either region or year (generalised linear model with quasi-binomial distribution, omitting Storm Cay region due to low catch numbers: region: $F_{4,\,8} = 3.26$, $P \approx 0.11$; year: $F_{2,\,8} = 0.21$, $P \approx 0.8$).

Numbers of red throat emperor caught over the whole of Queensland were converted to numbers of red throat emperor within each region using the percentages (*Red throat %*) in Table 14. Numbers were then converted to weights using the average weight of 1.169 kg discussed in Sections 2.2.2 and 3.2.2. The final estimated numbers and weights of red throat emperor harvested by Queensland recreational fishers are listed in Table 15 and plotted in Figure 13.

Table 14: Raw data from RFISH surveys, with information on location, species composition and releases.
Harvests and releases are expressed as numbers of fish as recorded in diaries. The 'Red throat %' column is the proportion of emperor that was red throat in the particular year and region. The 'Region %' column is the proportion of red throat emperor catch that came from a particular region in the relevant year. The 'Release %' column is the proportion of the total number of red throat caught that was released in the particular year and region. Catches from the Gulf of Carpentaria are included in the Cairns North region and assumed not to be emperor other than red throat (source: RFISH database).

Year	**Emperor harvested**	**Red throat harvested**	**Red throat %**	**Region %**	**Red throat released**	**Release %**
Cairns North region						
1997	239	86	36.0	12.3	75	46.6
1999	157	36	22.9	6.3	24	40.0
2002	49	23	46.9	3.3	21	47.7
Overall	445	145	32.6	7.4	120	45.3
Townsville region						
1997	483	418	86.5	59.5	207	33.1
1999	328	177	54.0	31.0	119	40.2
2002	84	37	44.0	5.3	41	52.6
Overall	895	632	70.6	32.1	367	36.7
Mackay region						
1997	365	81	22.2	11.5	130	61.6
1999	313	76	24.3	13.3	65	46.1
2002	214	117	54.7	16.9	118	50.2
Overall	892	274	30.7	13.9	313	53.3
Storm Cay region						
1997	39	7	17.9	1.0	6	46.2
1999	36	6	16.7	1.1	8	57.1
2002	0	0	–	0.0	0	–
Overall	75	13	17.3	0.7	14	51.9
Swains region						
1997	45	9	20.0	1.3	21	70.0
1999	61	59	96.7	10.3	35	37.2
2002	81	65	80.2	9.4	30	31.6
Overall	187	133	71.1	6.8	86	39.3
Capricorn-Bunker region						
1997	242	101	41.7	14.4	106	51.2
1999	462	217	47.0	38.0	191	46.8
2002	847	451	53.2	65.1	479	51.5
Overall	1551	769	49.6	39.1	776	50.2
All regions combined						
Overall	8090	3932	48.6	–	3352	46.0

Table 15: Estimates of emperor and red throat emperor harvested each year by recreational fishers in Queensland.
The 2000–2001 estimate includes 9,268 fish harvested by indigenous fishers. The proportion of emperor that was red throat has been estimated from RFISH raw data from fishing diaries (Table 14). Overall numbers from the three RFISH surveys combined were used for the 2000–2001 survey. Numbers of red throat emperor have been converted to weights using the average fish weight of 1.169 kg calculated from ELF sample data (see Section 2.2.2).

Year	Reported category	Number harvested in category	Region	Number of red throat harvested	Weight of red throat harvested (t)
1997	Sweetlip (Lethrinidae) (RFISH)	719 000 (± 36 000)	Whole of Queensland	357 200	417.4
			Cairns North	43 800	51.1
			Townsville	212 700	248.5
			Mackay	41 200	48.2
			Storm Cay	3600	4.2
			Swains	4600	5.4
			Cap-Bunker	51 400	60.1
1999	Sweetlip (Lethrinidae) (RFISH)	861 000 (± 67 000)	Whole of Queensland	362 300	423.4
			Cairns North	22 800	26.7
			Townsville	112 300	131.2
			Mackay	48 200	56.3
			Storm Cay	3800	4.4
			Swains	37 400	43.7
			Cap-Bunker	137 700	160.9
2000–2001	Emperors (not Red Emp.) (Henry and Lyle 2003)	447 786 (± 73 679)	Whole of Queensland	217 600	254.3
			Cairns North	16 100	18.8
			Townsville	70 000	81.8
			Mackay	30 300	35.4
			Storm Cay	1400	1.7
			Swains	14 700	17.2
			Cap-Bunker	85 100	99.5
2002	Sweetlip (Lethrinidae) (RFISH)	638 000 (± 57 000)	Whole of Queensland	346 800	405.2
			Cairns North	11 500	13.4
			Townsville	18 500	21.6
			Mackay	58 500	68.4
			Storm Cay	0	0.0
			Swains	32 500	38.0
			Cap-Bunker	225 700	263.7

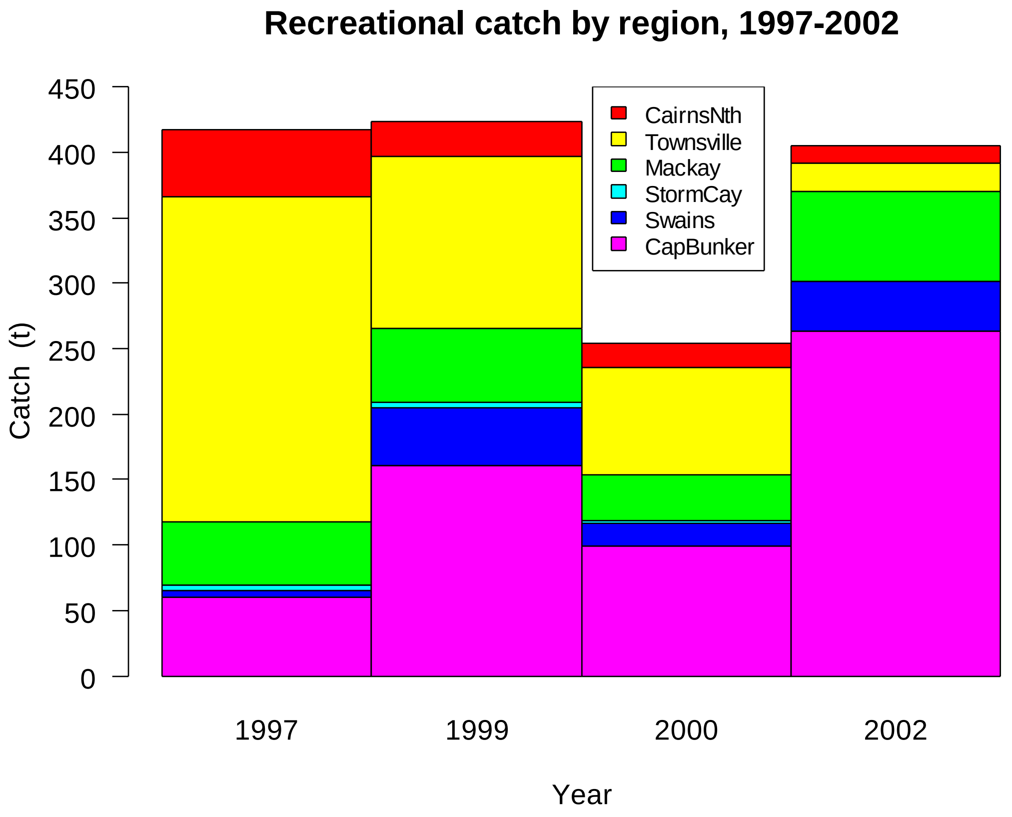

Figure 13: Estimates of emperor and red throat emperor harvested each year by recreational fishers in Queensland.
(Numbers listed in Table 15).

3.2.5 Charter logbook data

Charter boat data were expressed mainly as catch numbers; these were converted to weights where necessary using the factor of 1.169 kg as discussed in Section 3.2.2.

The charter sector grew rapidly until 2003 when 231 operators reported catches of either red throat emperor or unspecified emperor species. Only 123 operators were involved in 2004 (see comments in Section 1.5.1). A total of 974 different operators reported catch between 1992 and 2004: Figure 14 shows the number of operators involved each year, classified into first-year licensees and pre-existing licensees in order to show the turnover in the fishery.

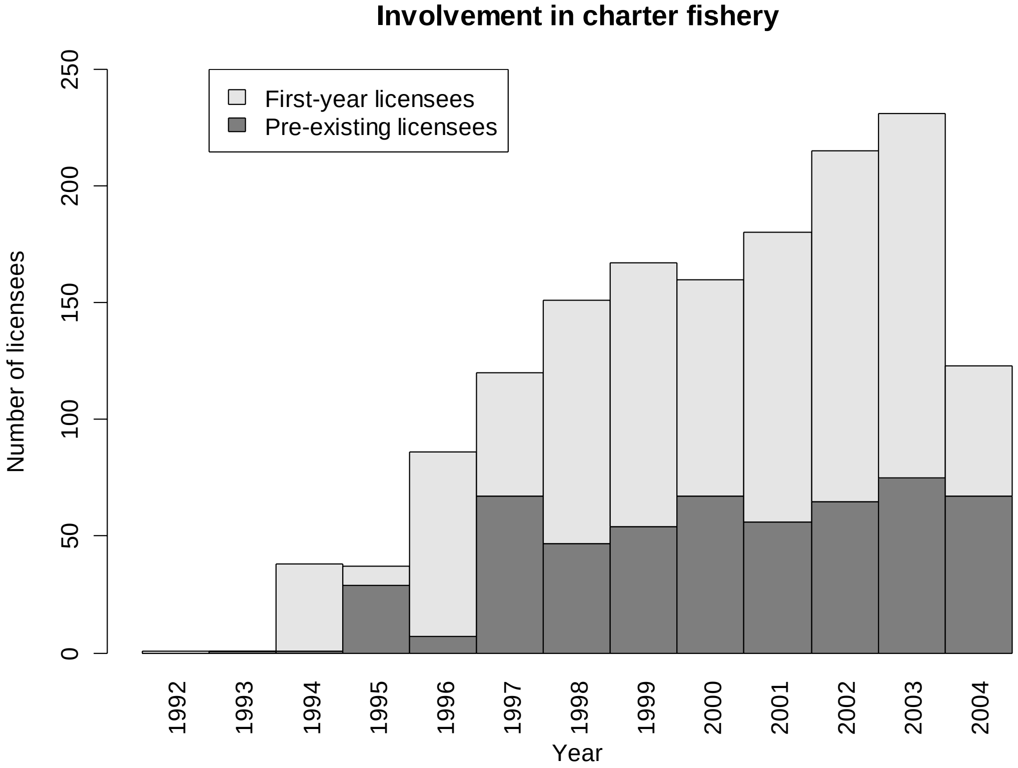

Figure 14: Number of charter licensees reporting catches of either red throat emperor or unspecified emperor species.
From 1988–2004, (Charter logbooks were voluntary before 1996) (source: CFISH database).

Figure 15 shows the total harvest (defined as retained catch) reported by charter operators in each year. Logbooks were voluntary from 1992–1995; the actual total charter catches in those years were probably greater than the reported catches.

As for the other sectors, species identification is an issue in the charter sector, with the total unspecified emperor catch being 41.3% of the total red throat emperor catch. Total recorded catches are listed in Table 16, classified by whether the same operator also reported red throat emperor. Table 16 shows that:

- Only 36.5% of unspecified emperor was reported by vessels that also reported red throat emperor in any year.
- 3.9% was reported by vessels that reported red throat emperor in the same month.
- 1.4% was reported by vessels that also reported red throat emperor on the same day.

Also,

- 98.6% of unspecified emperor came from 30-minute grid squares in which more than six red throat emperor were caught (this was the 10th percentile of the distribution over grid squares)
- 81.0% came from grid squares in which a thousand or more red throat emperor were caught.

These statistics suggest that some operators tend not to distinguish red throat emperor from other emperor species, and that therefore much of the ‘unspecified’ emperor is in fact red throat emperor.

Unspecified emperor catches in the charter data were added to the red throat emperor catches for this assessment. Annual catches are plotted in Figure 16 and listed in Table 17. About 2% of the catch data had no 30-minute grid square associated with it. As with the commercial logbook data (see Section 3.1.1), a year’s catch from unknown locations was spread across regions in the same proportions as the catch from known regions in that year.

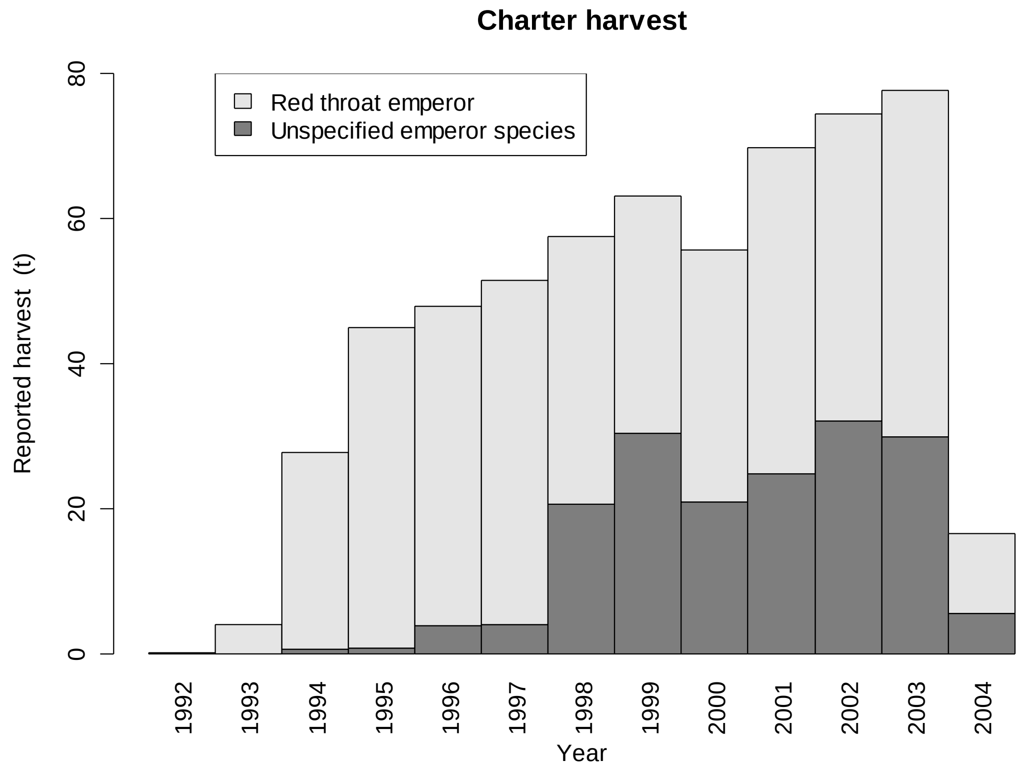

Figure 15: Reported charter catches of red throat emperor, 1992–2004.
Charter logbooks were voluntary before 1996, so the full harvest is not recorded from 1992–1995. Numbers of fish have been converted to weights using the average fish weight of 1.169 kg calculated in Section 2.2.2 (source: CFISH database).

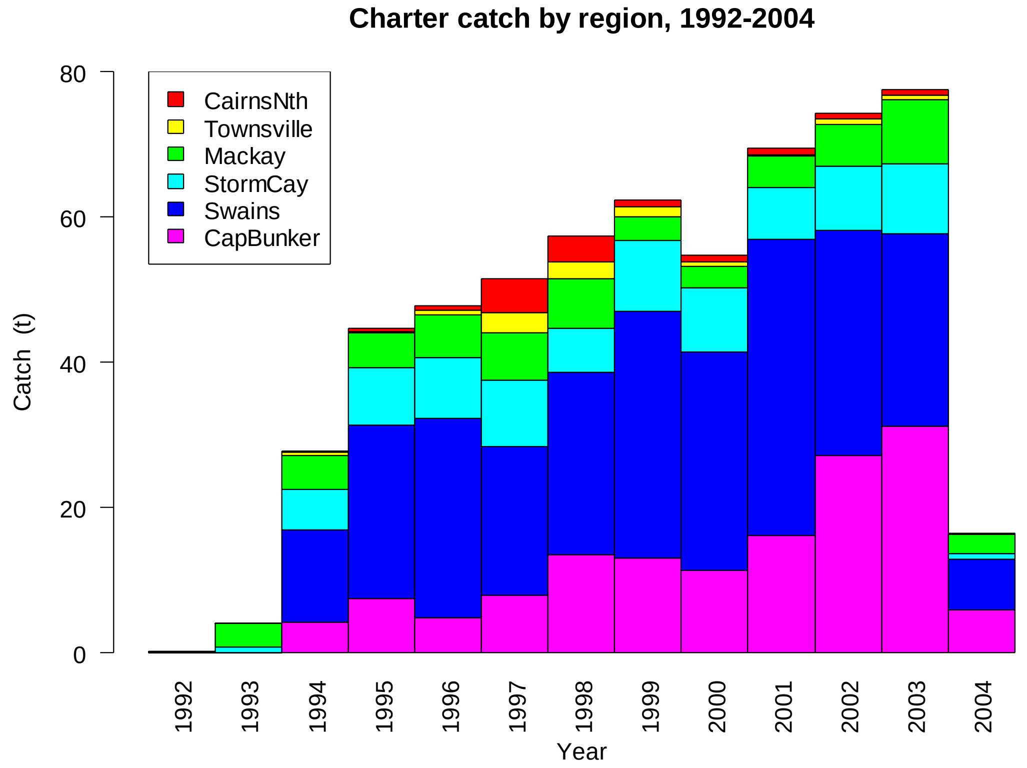

Figure 16: Time series of charter catches of red throat emperor.
From 1992–2004, by region, as used for the assessment. Catches are a combination of both red throat emperor and unspecified emperor. Unknown locations were dealt with by spreading their catches across regions in the same proportions as catches from known

regions in that year. Numbers of fish have been converted to weights using the average fish weight of 1.169 kg calculated in Section 2.2.2. Charter logbooks were voluntary before 1996, and the recorded catch is probably an underestimate of the total charter catch from 1992–1995 (source: CFISH database).

Table 16: Charter boat catches of unspecified emperor.
From the CFISH database 1988–2004. Classified according to whether red throat emperor was reported by the same vessel or in the same 30-minute grid square. Numbers of fish have been converted to weights using the average fish weight of 1.169 kg calculated in Section 2.2.2.

Category	**Unspecified emperor (t)**	**Red throat emperor (t)**
Total reported catch	172.8	418.1
Total from vessels that also reported red throat emperor:		
In any year	63.1	
In the same year	44.8	
In the same month	6.7	
On the same day	2.4	
Total reported catch from identified grid squares, excluding Gulf of Carpentaria	136.0	325.2
Total from grid squares in which the reported red throat emperor catches was:		
At least one fish	134.8	
Greater than six fish (the 10th percentile of non-zero red throat emperor catches)	134.1	
At least 1000 fish	110.2	

Table 17: Charter boat logbook catches by year.
Numbers have been converted to weights using the average fish weight of 1.169 kg calculated in Section 2.2.2. Logbooks were voluntary from 1992–1995, and the resulting catches are probably underestimates of the total catch. Total catches from 1996–2004 in the final column were used for the assessment (source: CFISH database).

Year	**Red throat emperor (t)**	**Unspecified emperor (t)**	**Total (t)**
1992	0.03	0	0.03
1993	4.0	0	4.0
1994	27.2	0.5	27.8
1995	44.3	0.7	45.0
1996	44.1	3.7	47.8
1997	47.6	3.9	51.5
1998	36.9	20.6	57.5
1999	32.8	30.4	63.2
2000	34.8	20.8	55.7
2001	45.1	24.7	69.8
2002	42.3	32.1	74.4
2003	47.9	29.9	77.8
2004	11.0	5.5	16.5

3.2.6 Seasonal patterns in red throat emperor catch and effort for the charter sector

The seasonal charter catch follows the same general trends as the commercial catch, but the CPUE is very low and variable in non-spawning months (Figure 17). Charter boats do not appear to target red throat emperor in the non-spawning season, but do occasionally catch small numbers of them.

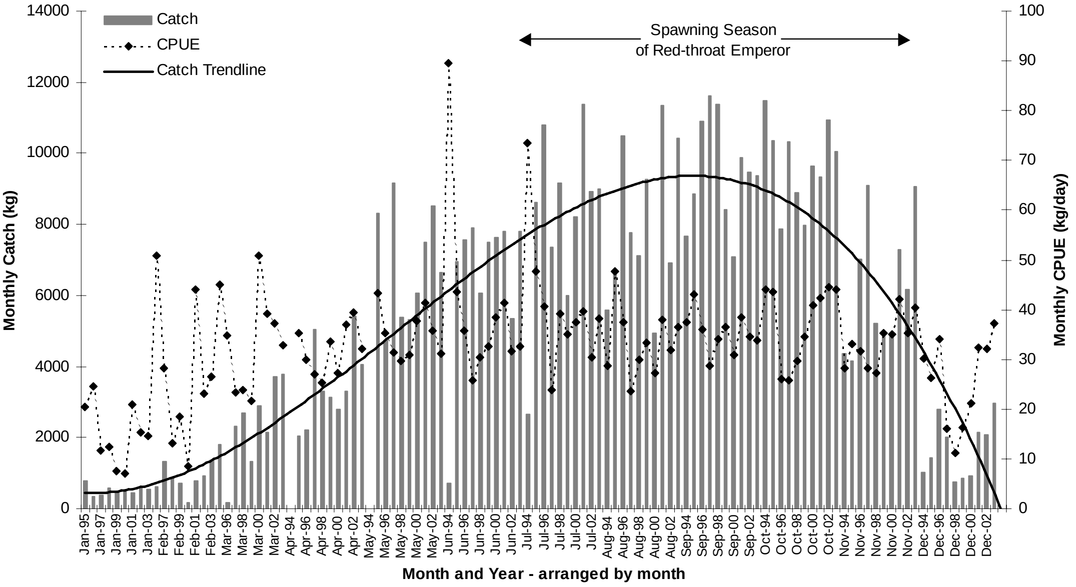

Figure 17: Graph of charter boat red throat emperor catch and raw CPUE. Arranged in months to show seasonal change in catch and CPUE. Catch trendline (cubic) and spawning season for red throat emperor are marked (source: CFISH database).

3.3 Released fish and post-release survival

A major difference between recreational and charter boat catches is the proportion of fish that are released. Charter boats reported that only 7.4% of the red throat emperor caught were released between 1997 and 2003. In 2004, 11.1% were released; in that year the minimum legal size increased from 350 mm to 380 mm TL (see Table 1). In contrast, the three RFISH diary surveys estimated release rates between 43.6% and 49.9% for red throat emperor, with an overall rate of 46.3%. The National survey (Henry and Lyle 2003) found a release rate of 51.1% for all emperor over the whole of Australia (including other emperor species and the Western Australian fishery). The release rate of red throat emperor in Queensland may also have changed in 2004 with the change in minimum legal size.

For the commercial sector, preliminary estimates of release rates are: by number, 12±2% standard error before the size limit change, increasing to 28±4% after the change; by weight the estimates are 7±2% and 16±3% respectively (D. Welch, DPI&F / CRC Reef, pers. comm.).

As remarked in Section 1.5.3, an FRDC-funded project on post-release survival of reef fish, including red throat emperor, is under way, but results are not yet available.

In this assessment it is assumed that all released fish survive. The results will not be relatively insensitive to this assumption if release and survival rates have changed little since the 1980s (the period of a steep increase in total catch size). This assumption can be revisited in future assessments when accurate comparisons are able to be made between pre- and post-2004 release rates, and when data on post-release survival are available.

3.4 Total catch

3.4.1 Catch components

Total catches for the fishery were composed of all three sectors:

- commercial catch
- recreational catch
- charter catch.

The charter catch was included in addition to the recreational catch (see discussion in Section 3.2.3); the total catches from the fishery were assumed to be the sum of all three sectors.

Recreational and charter catches required extrapolation backwards in time to make full use of the commercial catch data, for which a time series was available since 1946 (see Section 3.1.3). The recreational catch was available for only four years between 1997 and 2002, while the charter catch was available from 1996–2004.

3.4.2 Extrapolation and interpolation of recreational catch

Recreational catches were available for 1997, 1999, 2000 and 2002; the National Recreational and Indigenous Fishing Survey from May 2000 to April 2001 was assumed to apply to 2000 because this assessment is based on calendar years and the bulk of the catch would have been taken in calendar year 2000.

Estimation of catches for the years 1991–1996, 1998, 2001 and 2003–2004 was based on the standardised commercial catch per unit effort (CPUE) derived in Section 4.1 below, in the same manner as the estimation of recreational spotted mackerel catches undertaken by Begg *et al.* (2005, pp. 86–87):

- For years 1997, 1999, 2000 and 2002, recreational catch was divided by CPUE to produce a standardised effort.
- This effort was then averaged over the years, and the average effort was assumed to apply to the years for which recreational catches were unavailable.
- Finally, the average effort was multiplied by the CPUE in the years 1991–1996, 1998, 2001 and 2003–2004 to produce a catch estimate.

Each region was analysed separately.

In addition, the following sequential approach was used to estimate catches for 1946–1990:

1. Total recreational catch in years 1946–1981, for all regions combined, was first taken to be proportional to the commercial catch. The ratio of the total recreational catch to the total commercial catch over the years 1997, 1999, 2000 and 2002 was multiplied by historical commercial catches to provide recreational catch estimates for 1946–81.

2. These estimates were then multiplied by a historical recreational factor which was set equal to 2: the recreational sector in this historical period was assumed to be more important, relative to the commercial sector, than it was in 1997, 1999, 2000 and 2002. The value of 2 was decided upon after discussions with ReefMAC members who indicated that the recreational sector was quite large in the 1970s and 1980s, and therefore did not grow at the same rate as the commercial sector between 1981 and 1991.

3. Catches for 1982–1990 were interpolated linearly in the same way as for the commercial data (see Section 3.1.3).

4. Catch estimates were split into regions in the same proportions as the estimated catches over the period 1991–1996. This period was chosen because it pre-dated Cyclone Justin which had a big effect on the fishery in 1997 (see Section 3.1.3).

The resulting recreational catch estimates are plotted in Figure 18. The total catches over all regions combined are listed in Table 18.

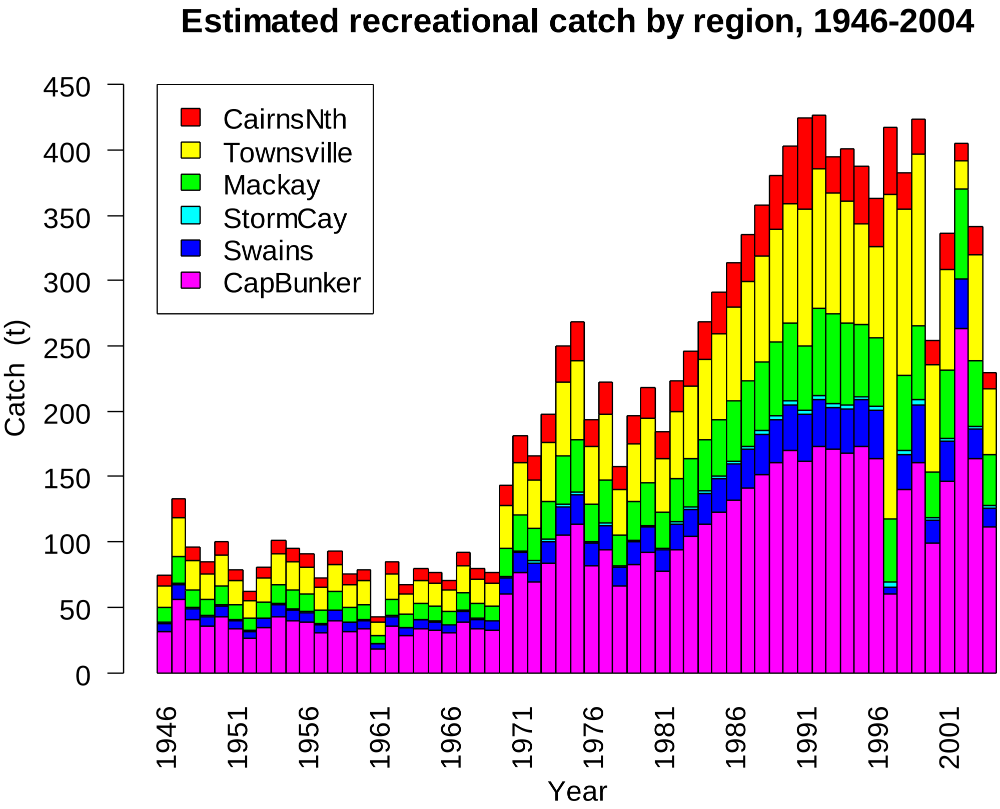

Figure 18: Estimated recreational catch by region for all years 1946–2004. Years 1991–1996, 1998, 2001 and 2003–2004 have been estimated using standardised commercial catch per unit effort, 1946–1981 from commercial catch data, and 1982–1990 have been interpolated from years before and after.

Table 18: Time series of recreational catches for all regions combined. 1946–2004, used for the assessment. Years 1991–1996, 1998, 2001 and 2003–2004 have been estimated using standardised commercial catch per unit effort, 1946–1981 from commercial catch data, and 1982–1990 have been interpolated from years before and after.

Year	Catch (t)	Year	Catch (t)	Year	Catch (t)	Year	Catch (t)
1946	74.7	1961	42.8	1976	193.9	1991	424.5
1947	132.9	1962	84.3	1977	221.8	1992	426.1
1948	95.7	1963	67.2	1978	157.7	1993	395.0
1949	84.6	1964	79.3	1979	196.8	1994	400.6
1950	100.4	1965	76.6	1980	218.4	1995	387.8
1951	78.4	1966	70.8	1981	184.2	1996	363.1
1952	62.1	1967	91.8	1982	223.7	1997	417.4
1953	81.0	1968	80.0	1983	246.1	1998	381.9
1954	101.6	1969	76.9	1984	268.5	1999	423.4
1955	94.5	1970	143.0	1985	290.9	2000	254.3
1956	90.6	1971	180.8	1986	313.3	2001	335.8
1957	72.7	1972	165.4	1987	335.7	2002	405.2
1958	93.3	1973	197.3	1988	358.1	2003	341.3
1959	75.1	1974	249.5	1989	380.5	2004	229.5
1960	78.5	1975	268.3	1990	402.9		

3.4.3 *Extrapolation of charter catch*

The charter sector has evidently grown more rapidly than either the commercial or recreational sector (see Figure 11, Figure 16 and Figure 18). The following exponential curve was fitted to the log of charter catch from 1995 to 2003:

$$\log(\text{catch}) = -125.1584 + 0.0681054 \times \text{year} \pm 0.0654,$$

with an R^2 value of 91.2%. The standard error of 0.0654 applies to the predicted catch for 1999; standard errors for other years are larger: that for 1995 and 2003 is 0.0728, for 1970 is 0.2413, and the standard error for 1946 is 0.4294. The estimated catches for the early years are very small and have very little effect on the overall stock assessment; therefore large standard errors on them are not a major concern.

Predictions of log-catch were made from the above regression and exponentiated to provide estimates of total charter catches back to 1946. The total charter catches were split into regions in the same proportions as the recorded charter catches for the period 1995–96, which was chosen to pre-date Cyclone Justin in 1997. Charter logbooks were still voluntary in 1995, but the recorded catch was very close to the 1996 level, providing confidence that an almost complete coverage of the red throat emperor charter sector had been attained by 1995.

The estimated charter catch by region for each year 1946–2004 is plotted in Figure 19. The estimated catch for all regions combined is listed in Table 19.

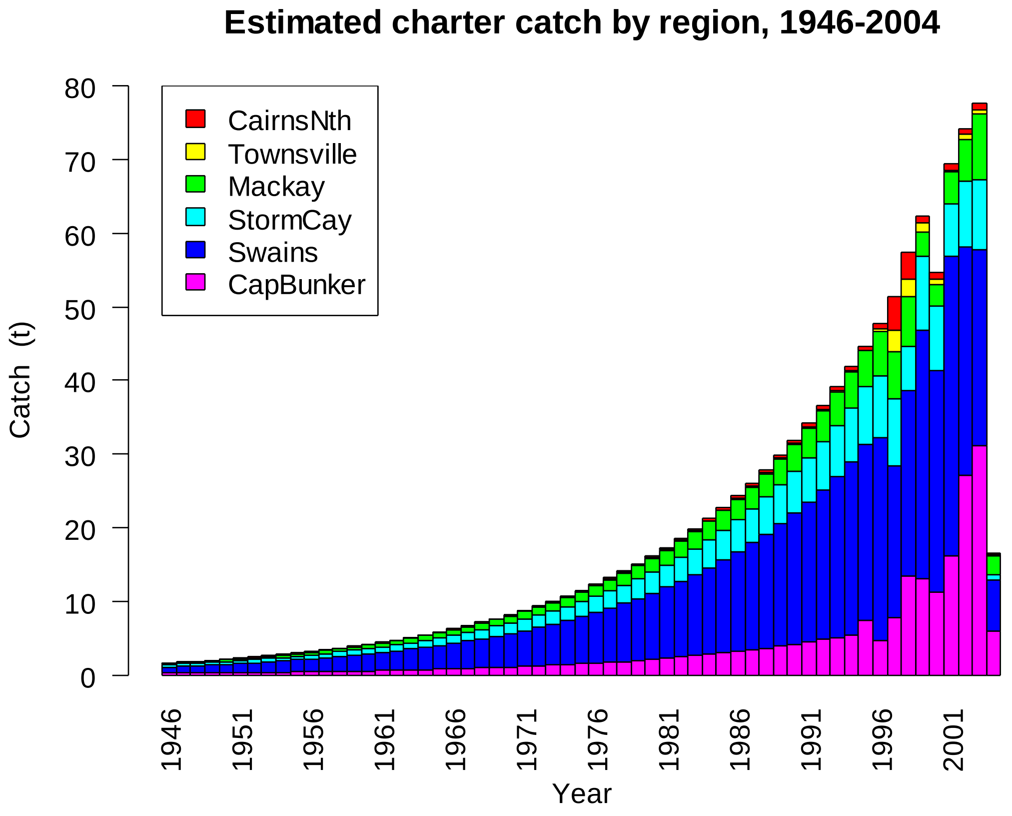

Figure 19: Estimated charter catch by region for years 1946–2004.
Catches for 1946–1994 were extrapolated by fitting an exponential curve to the catches from 1995–2003, and using the split into regions from 1995–1996.

Table 19: Estimated charter catch for all regions combined.
1946–2004 used in the assessment. Catches for 1946–1994 were extrapolated by fitting an exponential curve to the catches from 1995–2003.

Year	Catch (t)	Year	Catch (t)	Year	Catch (t)	Year	Catch (t)
1946	1.6	1961	4.4	1976	12.3	1991	34.2
1947	1.7	1962	4.7	1977	13.2	1992	36.6
1948	1.8	1963	5.1	1978	14.1	1993	39.2
1949	2.0	1964	5.4	1979	15.1	1994	41.9
1950	2.1	1965	5.8	1980	16.2	1995	44.7
1951	2.2	1966	6.2	1981	17.3	1996	47.7
1952	2.4	1967	6.7	1982	18.5	1997	51.4
1953	2.6	1968	7.1	1983	19.8	1998	57.4
1954	2.8	1969	7.6	1984	21.2	1999	62.4
1955	2.9	1970	8.2	1985	22.7	2000	54.7
1956	3.2	1971	8.8	1986	24.3	2001	69.5
1957	3.4	1972	9.4	1987	26.0	2002	74.2
1958	3.6	1973	10.0	1988	27.9	2003	77.6
1959	3.9	1974	10.7	1989	29.8	2004	16.4
1960	4.1	1975	11.5	1990	31.9		

3.4.4 Time series of total catch

Catches from the three sectors (commercial, recreational and charter) were added together to produce total catches of red throat emperor by region and year. This is plotted in Figure 20, and the totals for each year are listed in Table 20.

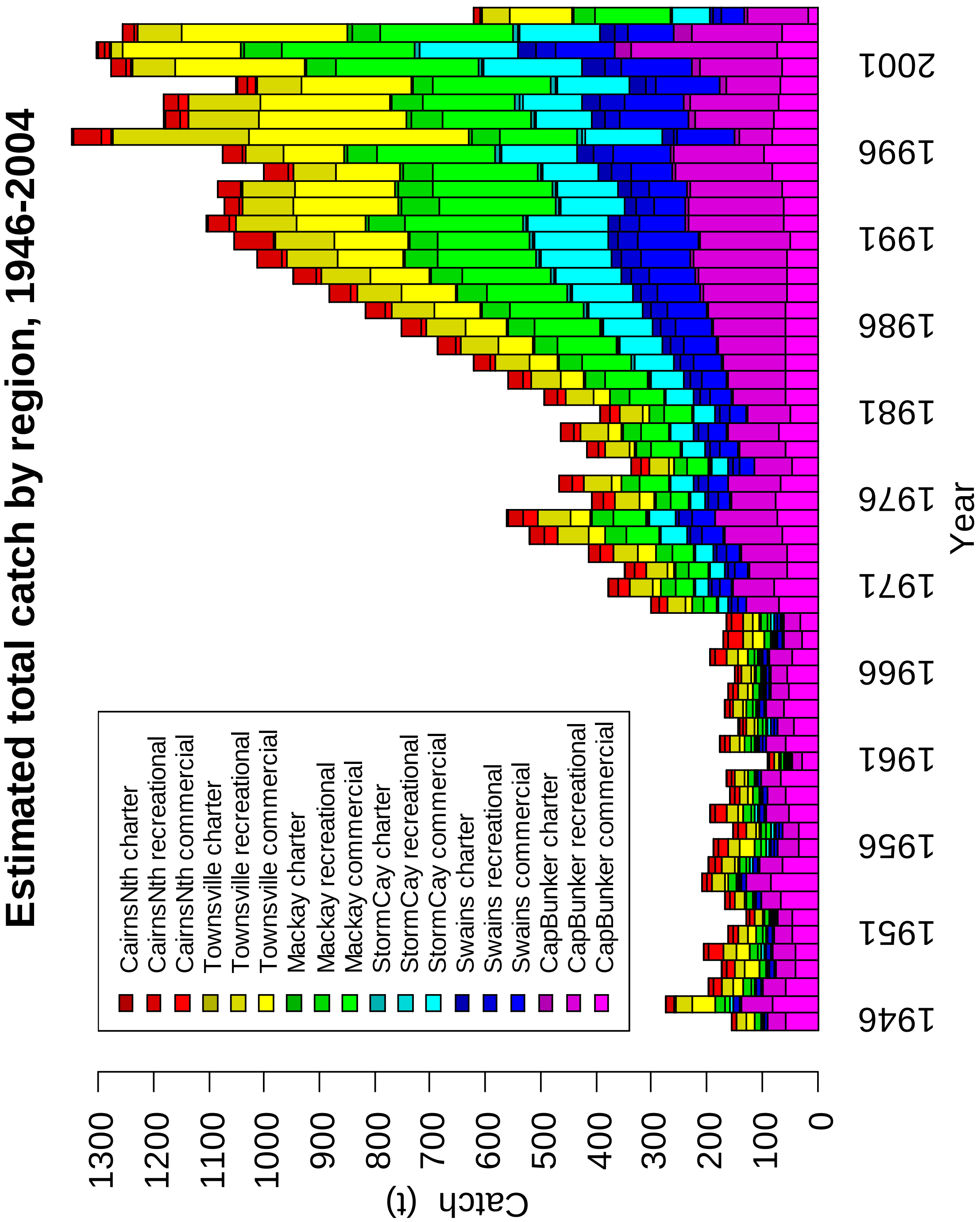

Figure 20: Estimated catch by region of all sectors, 1946–2004, used for the assessment.

Table 20: Estimated total catch for all regions and sectors combined.
Catches comprise the sums of the values listed in Table 13, Table 18 and Table 19 for the commercial, recreational and charter sectors.

Year	Catch (t)	Year	Catch (t)	Year	Catch (t)	Year	Catch (t)
1946	154.4	1961	91.9	1976	409.1	1991	1054.3
1947	273.7	1962	177.2	1977	467.1	1992	1103.3
1948	197.6	1963	142.6	1978	336.9	1993	1073.5
1949	175.1	1964	167.6	1979	417.9	1994	1083.8
1950	207.6	1965	162.5	1980	463.0	1995	1001.1
1951	162.7	1966	151.0	1981	394.3	1996	1076.4
1952	129.5	1967	194.5	1982	493.6	1997	1349.0
1953	168.3	1968	170.8	1983	558.0	1998	1182.4
1954	210.7	1969	164.9	1984	622.6	1999	1181.5
1955	196.4	1970	300.7	1985	687.2	2000	1049.9
1956	188.6	1971	378.7	1986	752.0	2001	1277.4
1957	152.1	1972	347.8	1987	816.8	2002	1302.4
1958	194.5	1973	413.8	1988	881.8	2003	1257.1
1959	157.5	1974	521.3	1989	946.9	2004	620.6
1960	164.7	1975	560.6	1990	1012.2		

3.5 Caveats

The following caveats apply to the data sets analysed:

1. Logbook data from commercial and charter sectors have not been checked by fisheries observers or processor scrutiny programs. This is being addressed in the *Fisheries (Coral Reef Fin Fish) Management Plan 2003.* As of 1 July 2004, first buyers must lodge a return detailing purchases, which can be reconciled against landing data for audit purposes. Also from 1 July 2004, all fish taken commercially must be tagged for audit purposes through the product handling chain.
2. Commercial logbooks do not record targeting information. Fishers report their fishing effort as simply the days on which red throat emperor were caught.
3. Logbook records are converted from fillet or trunk weight to whole weight by species or species group standard conversion factors within the CFISH database.
4. Not all data recorded in the database(s) are identified to species or species categories; for example 'Emperor—unspecified' refers to general lethrinid species.
5. Recreational, indigenous and charter boat records have been converted from number of fish to weight of fish harvested, using scientific catch data collected by the ELF Project. This is based on the average weight of a red throat emperor caught by a typical commercial operator, but it is possible that it underestimates the size of the recreational and charter harvests (see Section 2.2.2).
6. Catch data, including research data, are subject to gear selectivity and methodology bias.
7. A change in fishing behaviour occurred after commercial catch quotas were introduced in 2004. CPUE estimates after 2003 have been excluded from this assessment.

4. Standardisation of catch and effort data

4.1 Commercial sector data

Catch and effort data were analysed to provide a measure of abundance of red throat emperor in each year and region by means of a standardised catch rate or catch-per-unit-effort (CPUE).

A unit of effort was defined to be one day's fishing by a boat, including all of its dories. Data were not available to resolve effort down to the dory level.

The CFISH data contained a field for the number of days' duration of the trip. Most of the records (98.9%) were a single day's duration, but some trips were longer than one day. The longer trips were dealt with by allowing second and subsequent days to constitute less than, or more than, a single unit of effort. A second or subsequent day could constitute less than a full unit of effort if the boat was still at sea but not actively fishing for all of that day, and could constitute more than one unit of effort if, for example, a boat travelled a long way from land where red throat emperor were more plentiful. A parameter was included in the model to allow for the effective fishing effort expended on a second or subsequent day.

Location was resolved down to 30-minute grid squares.

Catch and effort data were analysed by a log-linear model. The analysis was performed in the statistical package *R* (R Development Core Team 2005). A separate analysis was performed for each region. The *R* code generating the log-linear model object for each grid square was:

```
lme(log(Catch.kg) ~ offset(log(TripDays)) +
I(1/(TripDays+1)) + fYear + fMonth + Lunar1 + Lunar2 +
fCatchGrid, random = ~ 1 | fBoatMark)
```

The terms can be explained as follows:

- `log(Catch.kg)`: log of catch by a boat over a trip (98.9% of which were single-day trips)
- `offset(log(TripDays))`: term to convert log-catch into log-CPUE, having the effect of dividing the catch by the number of days; `TripDays` denotes the duration of the fishing trip
- `I(1/(TripDays+1))`: term to allow CPUE to depend on duration of trip, allowing (approximately) the first day of a trip to constitute a full unit of effort, but subsequent days to constitute less (or potentially more) than a full unit of effort
- `fYear`: effect of year, as a 14-level factor covering the years 1991–2004 (data for 2004 were later excluded from subsequent analysis)
- `fMonth`: effect of month, as a 12-level factor
- `Lunar1`: measure of brightness of the moon
- `Lunar2`: relative brightness of the moon, displaced seven days (approximately a quarter of a lunar cycle): the combination of `LunarPhase1` and `LunarPhase2` in the model closely approximates a sinusoidal curve with amplitude and phase as parameters
- `fCatchGrid`: effect of location, as a factor with one level for each 30-minute grid square
- `random = ~ 1 | fBoatMark`: random effects term for fishing vessel, which accounts as best we can for the different capabilities of different boats (e.g. numbers of dories, degree to which different boats target red throat emperor, etc.).

The coefficients of the `fYear` factor, when exponentiated, provided the standardised CPUE for each year in each grid square. Standardised CPUE was defined to equal 1 in 1991.

Standardised effort can then be defined as catch divided by standardised CPUE; this was used in Section 3.4.2 and in the 'Overall' results shown below. Catch and standardised effort can be summed over all regions, and a CPUE for all regions combined can be defined by dividing the summed catch by the summed standardised effort.

Standardised commercial CPUE by region is plotted in Figure 21 and listed in Table 21.

The Cairns North, Townsville, Storm Cay and Swains regions all show a substantial downward trend since 1991. Standardised CPUE in 2003 was 31% of the 1991 level for the Cairns North region, 78% for Townsville and Storm Cay, and 62% for the Swains. CPUE in 2003 was very close the 1991 levels for the Mackay and Capricorn-Bunker regions. The 2003 Mackay level, however, was 75% of the 1992 level. Capricorn-Bunker CPUE declined to 84% of the 1991 level in 1999, and had fully recovered by 2003; this recovery may be related to reduced catch sizes in that region in 1997–2001 after the peak in 1996 (Figure 20).

Cyclone Justin in 1997 obviously constituted an exceptional event, dramatically raising catch rates in the Townsville region. It appears to have reduced catch rates in the Storm Cay, Swains and Capricorn-Bunker regions, although the age-structured model explains this fall by a period of several years of below-average recruitment (see Section 6.2 below). We checked daily CPUE around March 1997, and a sharp increase in CPUE in the Townsville region corresponded exactly to the dates when Cyclone Justin was present. CPUE stayed high in the Townsville region for several years afterwards.

The low values of CPUE in 2004 occurred at a time of major upheaval in the fishery, and are almost certainly related to fishers' targeting behaviour rather than low abundance of red throat emperor. Reef fish quota holders stated to us that, with the introduction of quotas from July 2004, they were 'banking' their red throat emperor quotas to use later in the quota year when they had either filled their quotas on other reef fish species or had difficulty finding those species (CRC Reef Stakeholder Workshop participants, pers. comm. 2004).

CPUE values for 2004 were therefore excluded from the assessment.

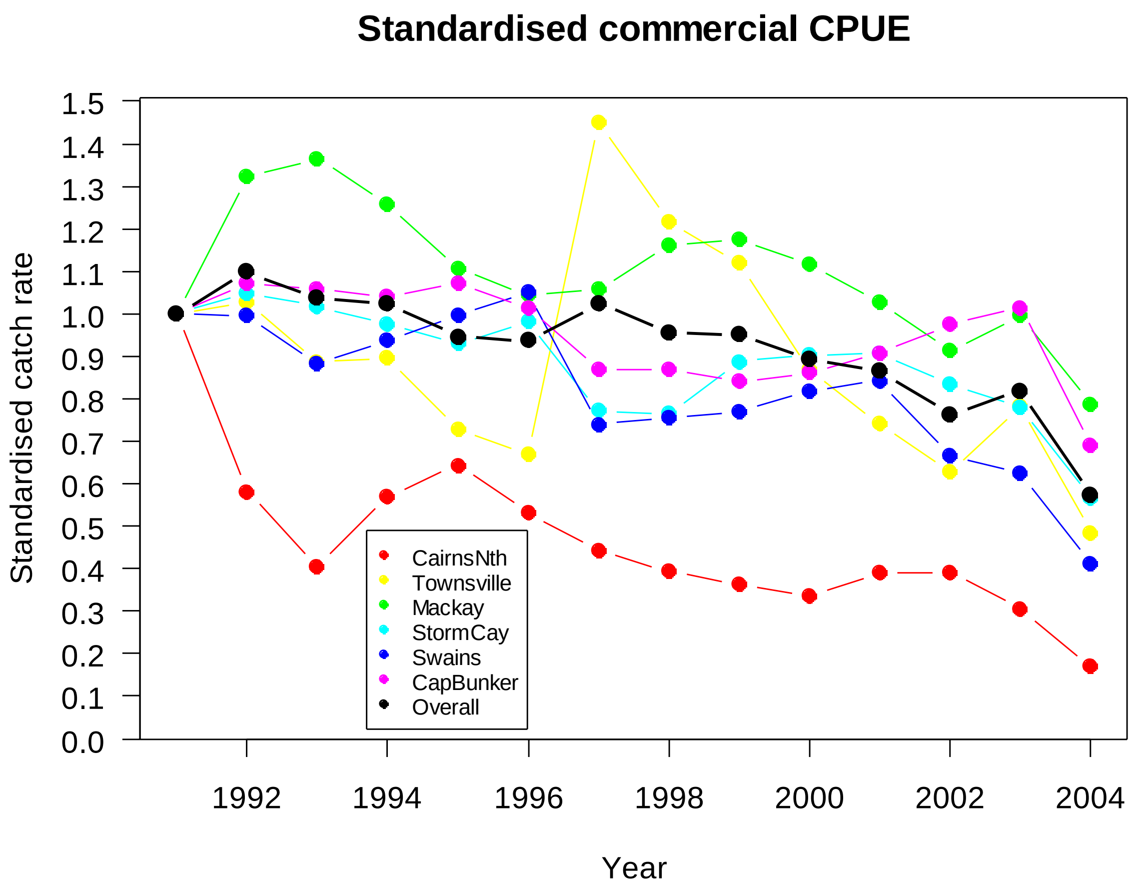

Figure 21: Standardised commercial catch per unit effort by region.
Scaled to a level of 1 in 1991, together with an overall curve formed by weighting the regions by catch size. Low catch rates in 2004 probably relate to targeting rather than abundance of red throat emperor, and were excluded from further analysis (source: CFISH database).

Table 21: Values of standardised commercial catch per unit effort used in the assessment. Standardised to a level of 1 in 1991. The 'Overall' CPUE was formed by weighting the regions by catch size. Low catch rates in 2004 probably relate to targeting rather than abundance of red throat emperor.

Year	CairnsNth	Townsville	Mackay	StormCay	Swains	CapBunker	Overall
1991	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1992	0.581	1.027	1.323	1.049	0.996	1.073	1.098
1993	0.405	0.887	1.365	1.018	0.883	1.059	1.036
1994	0.570	0.896	1.258	0.974	0.938	1.039	1.024
1995	0.643	0.729	1.105	0.930	0.997	1.071	0.946
1996	0.531	0.669	1.044	0.981	1.050	1.012	0.936
1997	0.444	1.450	1.057	0.772	0.740	0.868	1.024
1998	0.394	1.215	1.162	0.764	0.754	0.868	0.956
1999	0.363	1.118	1.175	0.887	0.769	0.840	0.951
2000	0.335	0.868	1.115	0.902	0.818	0.861	0.893
2001	0.392	0.742	1.028	0.907	0.842	0.908	0.864
2002	0.391	0.628	0.912	0.836	0.667	0.975	0.763
2003	0.305	0.781	0.995	0.779	0.624	1.015	0.819
2004	0.170	0.483	0.786	0.567	0.412	0.689	0.572

4.2 Recreational sector data

Catch and effort data for the non-charter recreational sector were available for only the three RFISH survey years, 1997, 1999 and 2002. Therefore they contained little information on long-term catch-rate trends in the fishery, but because 1997, the year of Cyclone Justin, was one of those years, it was thought worthwhile to attempt an analysis of RFISH raw data to estimate recreational CPUE.

A unit of effort was defined to be a fishing trip by one person.

Location was resolved only to the level of Region (six of which embrace the whole GBR). Location was specified in the RFISH raw data as a place name rather than a grid square; usually the reef name was given, but sometimes only the nearest town.

Catch and effort data were analysed by a log-linear model similar to that used for the commercial data. A single analysis was performed for the entire set of RFISH diary data. Fishing trips were included where any emperor, nannygai, red emperor or coral trout were caught. Catches analysed included released fish. The *R* code generating the log-linear model object was:

```
lme(log(Rte+1) ~ Region * fYear, random = ~ 1 | fLogNo)
```

The terms can be explained as:

- `log(Rte+1)`: log of number of red throat emperor caught, including those released, plus one fish
- `Region * fYear`: compound term including the effects of region, year and the interaction between region and year
- `random = ~ 1 | fLogNo`: random effects term for fisher’s diary number (fisher ID).

The coefficients of the `Region * fYear` term, when exponentiated, provided the standardised CPUE for each year in each region. Standardised CPUE was defined to equal 1 in 2002; this year was chosen because it was distant from 1997 which was atypical, being the year of Cyclone Justin.

Terms involving month and lunar phase were initially included in the model but were not significant.

The resulting standardised recreational CPUE by region is plotted in Figure 22. The results confirm those from the commercial CPUE; in particular, 1997 catch rates are higher than the other years in the Townsville and Cairns North regions and lower in the Capricorn-Bunker region. Values for the Storm Cay and Swains regions are based on relatively few records and are subject to high uncertainty.

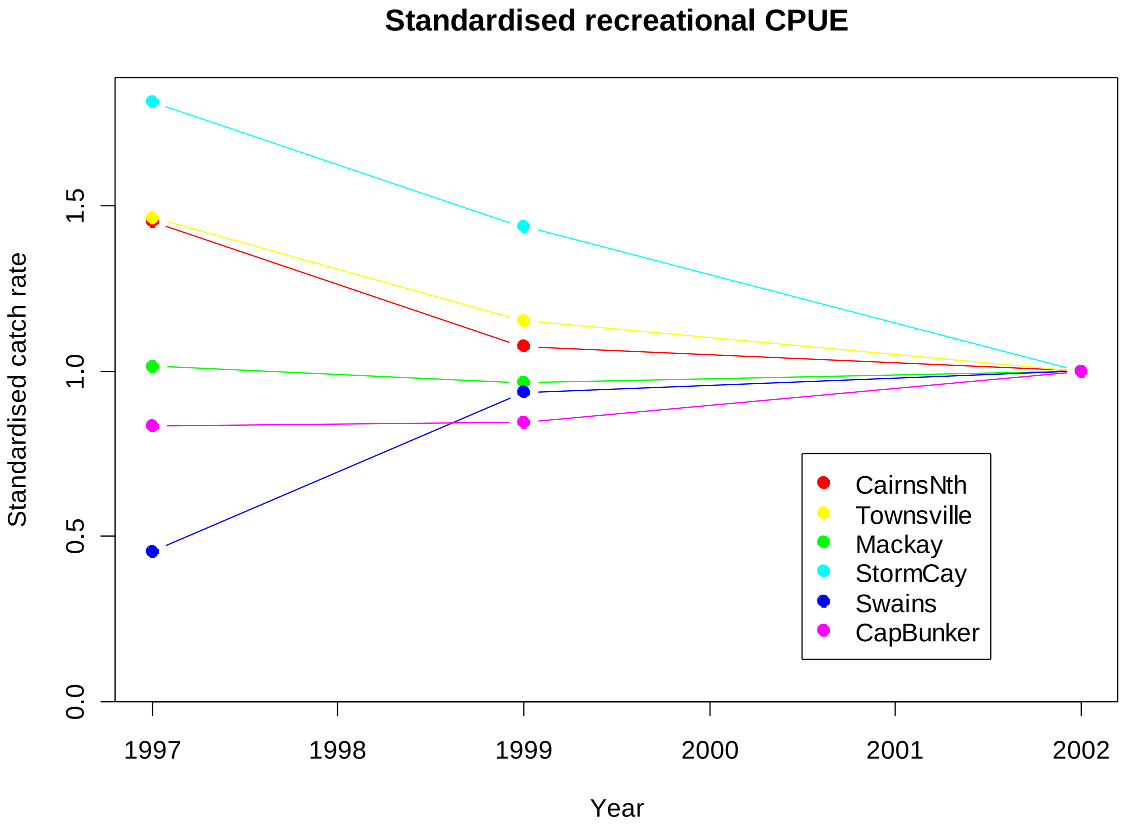

Figure 22: Standardised recreational catch per unit effort by region.
Scaled to a catch rate of 1 in 2002. Values for the Storm Cay and Swains regions are based on relatively few records and are subject to high uncertainty (source: RFISH database).

4.3 Charter sector

Sufficient charter data were available for a catch per unit effort analysis from 1994 to 2004 (see analysis of catch records in Section 3.2.5). The model was identical to that used for the commercial data (see Section 4.1).

The standardised charter vessel CPUE by region is plotted in Figure 23. The curves are remarkable for being flat, showing almost no trend except for very high catch rates in Townsville in 1997, most likely as a result of Cyclone Justin.

The commercial CPUE estimates were used as an index of relative abundance of red throat emperor for the assessment because we believe that targeting behaviour of charter boats may be correlated with availability of different species. Charter operators may target certain species when they are available, and avoid them when they are scarce. In times of low abundance of red throat emperor, charter operators may well pursue other species instead. Commercial operators, on the other hand, have skills, equipment and marketing connections applicable to certain target species, and will not always find it worthwhile to target other species when their preferred species are scarce.

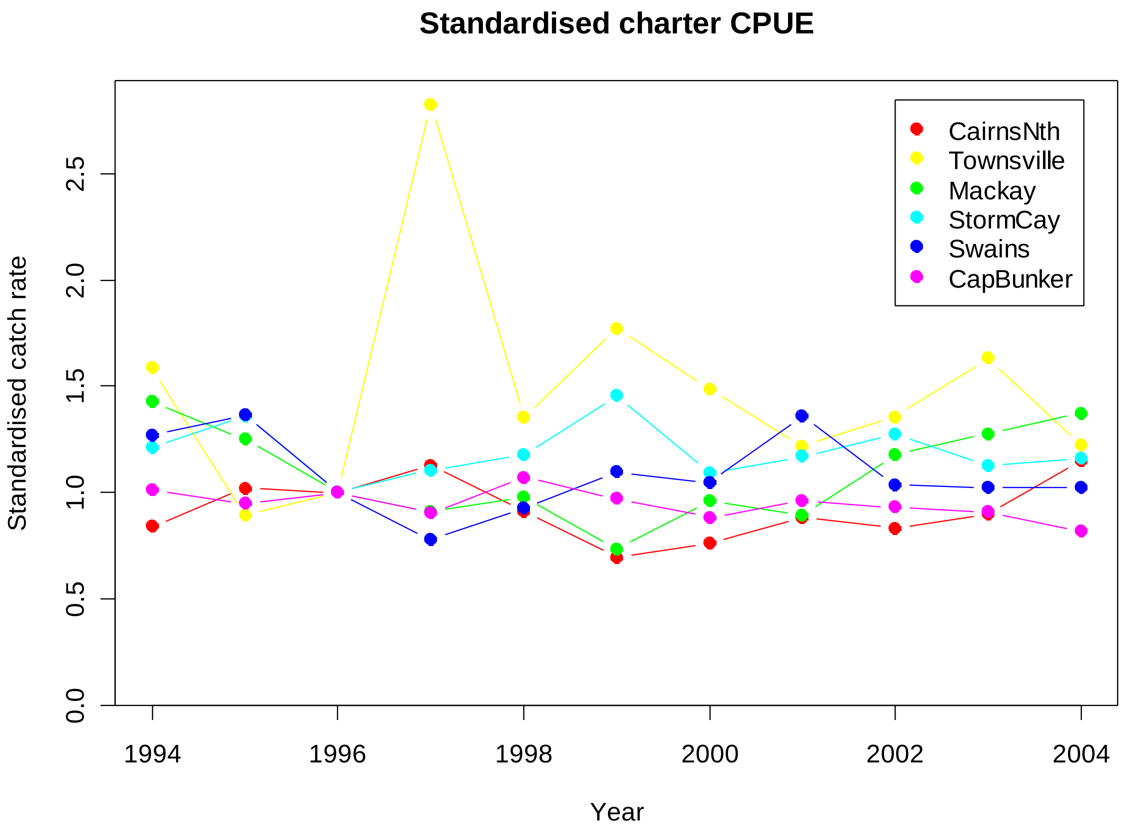

Figure 23: Standardised charter vessel catch per unit effort by region. Scaled to a catch rate of 1 in 1996 (source: RFISH database).

5. Surplus production population dynamic model

5.1 Methods

5.1.1 Description of the basic surplus production model

Surplus production models are widely used in fisheries stock assessments. It was considered advantageous to apply this model in addition to the more detailed age-structured model (Section 6 below) in order to compare the results of the two models and possibly gain insight from where the results of the two models disagree.

Surplus production models use catch and abundance (CPUE) data only, without considering age structure of the catch (Haddon, 2001, Ch. 10). Given the surplus production model's simplicity, it was considered worthwhile to fit it to the red throat emperor catch and CPUE data, and contrast the results to those of the age-structured model presented in Section 6 below.

The Schaefer form of the surplus production model is used here (Haddon, 2001, pp. 288–9):

$$B_{t+1} = B_t + rB_t\,(1 - B_t / K) - C_t,$$

where B_t is the biomass at the beginning of year t, C_t is the total catch from all sectors in year t, and r (the population replenishment rate) and K (the maximum population biomass or 'carrying capacity') are parameters that are estimated. The catch rate or CPUE, I_t, is assumed indicative of the exploitable biomass, and the trend in I_t is matched to the trend in B_t for the years in which both I_t and B_t are available. The parameter r is a combined effect of growth, natural mortality and recruitment, while K depends on both the size distribution and number of animals in the population prior to exploitation.

The basic surplus production model used for this assessment estimates only two parameters, r and K. Variants of the surplus production model can include catchability (q; see below) and initial biomass (B_1, also discussed below).

To fit the model, B_t was taken to be deterministic (i.e., subject to no random error), and I_t was assumed to be subject to lognormal errors. The model was fitted by minimising the following sum of squares:

$$\sum_t [\log I_t - \log\{q(B_t + B_{t+1})/2\}]^2\ ,$$

where q is the catchability, estimated by

$$q = \prod_t I_t \Big/ \prod_t \frac{B_t + B_{t+1}}{2}\ .$$

The quantity $(B_t + B_{t+1}) / 2$ is an approximation to the midyear biomass which is recommended by Haddon (2001, p. 293).

5.1.2 Application to the red throat emperor fishery

The red throat emperor population and fishery is regional in nature; hence we considered it prudent to model each of the regions separately. The equations described above were applied to each region to produce a biomass time series by year and region. The population replenishment rate r was assumed to be the same for all regions, while a separate carrying capacity K was included for each region. We note that the case of region-specific r parameters would be biologically interesting, but available data do not permit their accurate estimation.

The initial biomass B_1 was generated for each region assuming that the population was in equilibrium with an annual catch given by the average of the total catches from 1946 to 1969, a period when catches were relatively stable prior to increasing levels.

As noted in Section 4.1, the 2004 CPUE was excluded from analysis because of concern that it represented changed targeting behaviour of fishers rather than abundance of fish.

It was also necessary to include a special parameter to fit the increase in exploitable biomass in the Townsville region in 1997, associated with Cyclone Justin. The cyclone was assumed to have switched unexploitable biomass to exploitable biomass, which then remained exploitable and also constituted additional breeding stock.

The model was coded in the statistical package *R* (R Development Core Team 2005).

5.1.3 Model assumptions

The major assumptions of the surplus production model applied to red throat emperor were:

1. Commercial CPUE is an accurate index of abundance.
2. The biomass dynamics of the populations follow the Schaefer functional form described in Section 5.1.1.
3. The effect of Cyclone Justin was to switch unexploitable biomass to exploitable biomass in the Townsville region in 1997; this biomass remained exploitable in subsequent years and also constituted additional breeding stock. The assumption is supported by the age structure of the samples collected from Townsville in 1997, which contained many more young fish (2, 3 and 4 years old) than samples collected from Townsville in other years. These cohorts could also be seen in the samples from subsequent years.

Further assumptions arising from the regional model are:

4. The population growth rate *r* is the same over all regions of the GBR.
5. There is no more than a moderate amount of mixing of red throat emperor between regions. This assumption is supported by the different age distributions observed on reefs open to fishing and reefs closed to fishing in the same region (see Section 6.2.2 below).

5.2 Results

The model produced an estimate of the population replenishment rate *r* which appears a little too low to be realistic ($r = 0.12\ \mathrm{yr}^{-1}$). This rate is the rate at which the population biomass would increase if fishing were terminated after first reducing the population to a small fraction of its virgin size; a figure of 12% per year increase in population biomass under these circumstances implies a low rate of population recovery.

To provide an apparently more reasonable value of *r*, the model was also run with *r* set to its upper 95% confidence limit of $0.30\ \mathrm{yr}^{-1}$. This confidence limit was generated by profile likelihood; the difference between the log-likelihoods of this value of *r* and the maximum likelihood value was set to 1.92 which is half the 95th percentile of the χ^2_1 distribution, in accord with maximum likelihood theory. The model was allowed to freely estimate all other parameters when *r* was fixed.

The results are quite pessimistic. Parameter estimates for both models are listed in Table 22. The estimated maximum sustainable yield (MSY) is only $760\ \mathrm{t\,yr}^{-1}$ for the maximum likelihood solution, and $964\ \mathrm{t\,yr}^{-1}$ for the solution with $r = 0.30\ \mathrm{yr}^{-1}$. These figures include both the commercial and recreational harvests. It is generally considered wise to set the total allowable catch somewhat lower than the estimated MSY, in order to provide a margin of safety over statistical error in the estimates and lack of exact fit of the model.

Trajectories of catch rate, exploitable biomass and harvest rate are plotted in Figure 24, Figure 25 and Figure 26 respectively for the model in which *r* is estimated, and Figure 28, Figure 29 and Figure 30 for the model in which *r* is fixed to $0.30\ \mathrm{yr}^{-1}$. They show large declines in both catch rate and biomass since the 1970s, with biomass down to about 40% of virgin in the northernmost regions of Townsville and Cairns North. Estimated recent harvest rates are well below their peaks, but this apparently has still not resulted in a substantial recovery in the biomass (right-hand sides of Figure 25 and Figure 29).

Figure 27 and Figure 31 show steady-state yield curves for the fishery; the curves show the annual yields that would result if effort were held constant for many consecutive years. The observed year-by-year catch and standardised effort points are superimposed. Many of the observed catch–effort points have catches above the estimated MSY (top of the parabolic curve), and effort levels above the levels associated with MSY (where the curve is a maximum). These figures show the red throat emperor fishery as over-exploited up to 2003 in all areas except possibly Capricorn-Bunker.

Standard errors for the maximum likelihood estimates are high; this is mainly because the r and K parameters are correlated (higher r and lower K give very similar log-likelihood).

Table 22: Parameter estimates from the surplus production model.

Parameter	***Estimate***	***Standard error***
	***r* estimated by maximum likelihood**	
r, replenishment rate (yr^{-1})	0.12	0.0970
B_{97} / B_{96} for Townsville	2.1486	0.2131
K Cairns North (t)	1003.6	523.2
K Townsville (t)	3427.4	1079.8
K Mackay (t)	6912.9	4071.8
K Storm Cay (t)	3602.4	1996.9
K Swains (t)	3186.3	1480.2
K Capricorn-Bunker (t)	7213.4	4753.2
MSY = $\Sigma\, r\, K / 4$ (t yr^{-1})	760.4	224.2
	***r* fixed to its upper 95% confidence limit**	
r, replenishment rate (yr^{-1})	0.30	–
B_{97} / B_{96} for Townsville	2.3978	0.2458
K Cairns North (t)	523.0	3.9
K Townsville (t)	2299.1	126.0
K Mackay (t)	3281.5	391.9
K Storm Cay (t)	1757.2	135.6
K Swains (t)	1720.8	83.2
K Capricorn-Bunker (t)	3274.1	584.0
MSY = $\Sigma\, r\, K / 4$ (t yr^{-1})	964.2	55.0

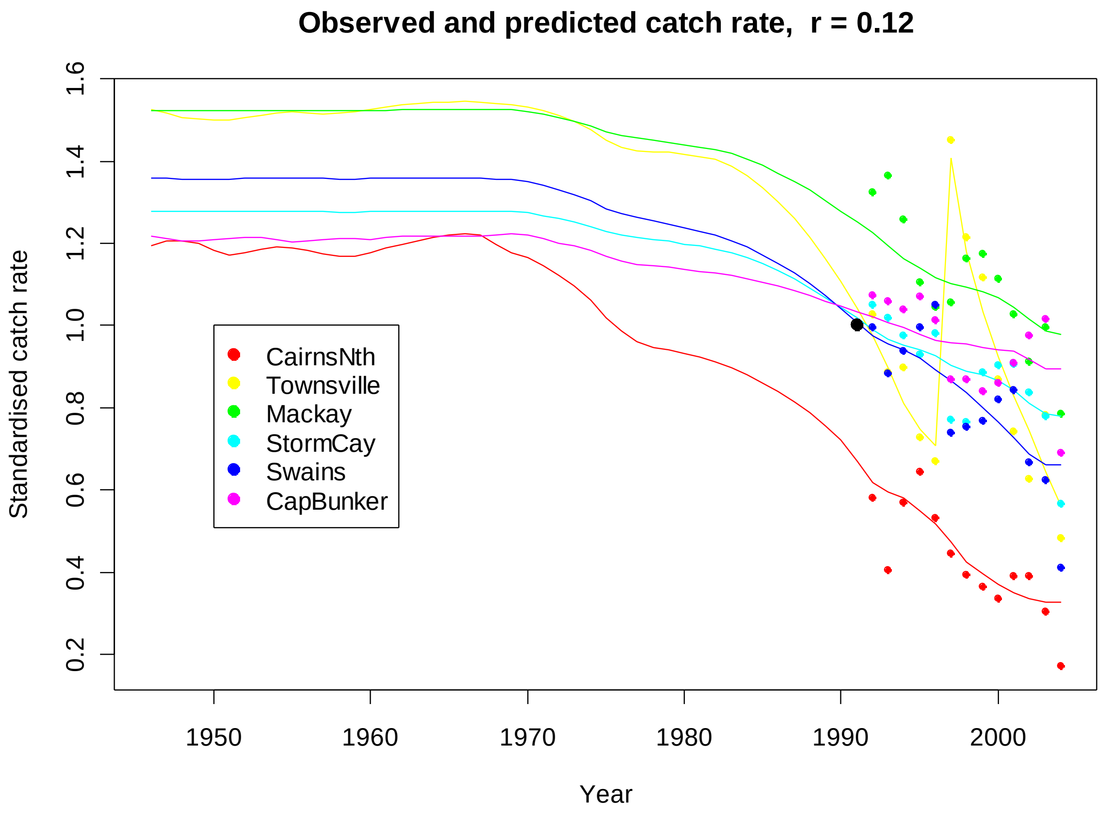

Figure 24: Catch rates from the surplus production model with r = 0.12 yr^{-1}, the maximum-likelihood estimate. The points plotted are the observed values.

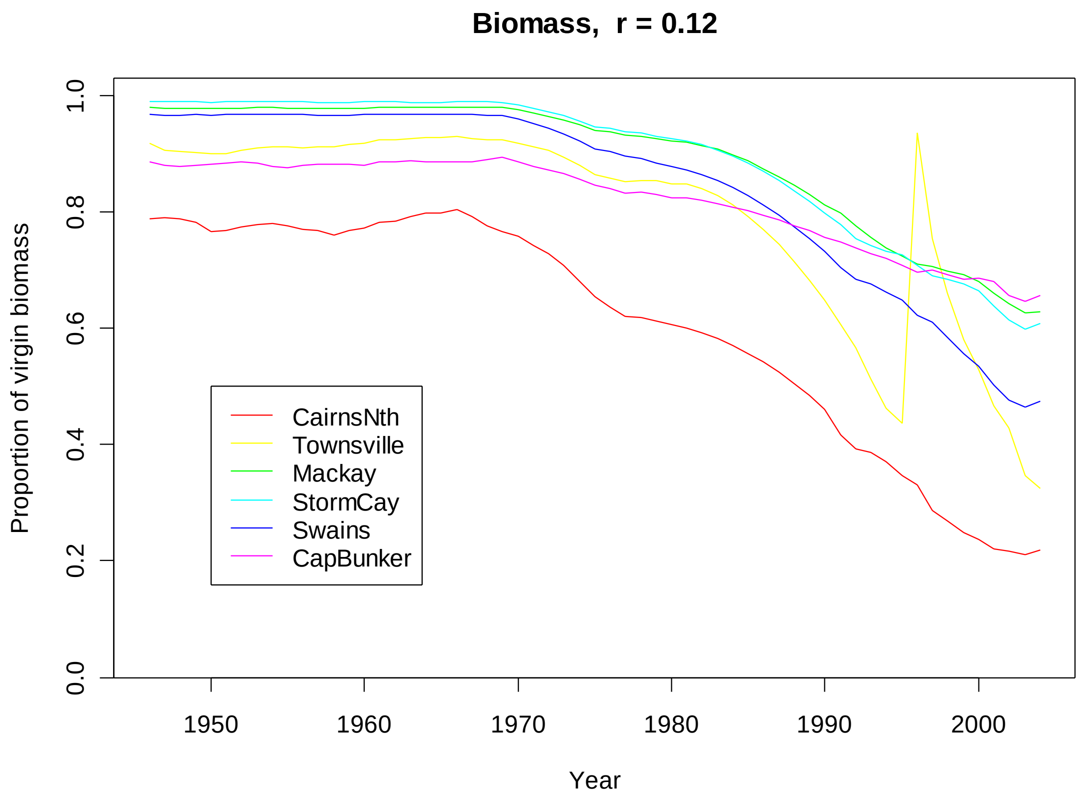

Figure 25: Biomass trend from the surplus production model with r = *0.12 yr^{-1}, the maximum-likelihood estimate.*

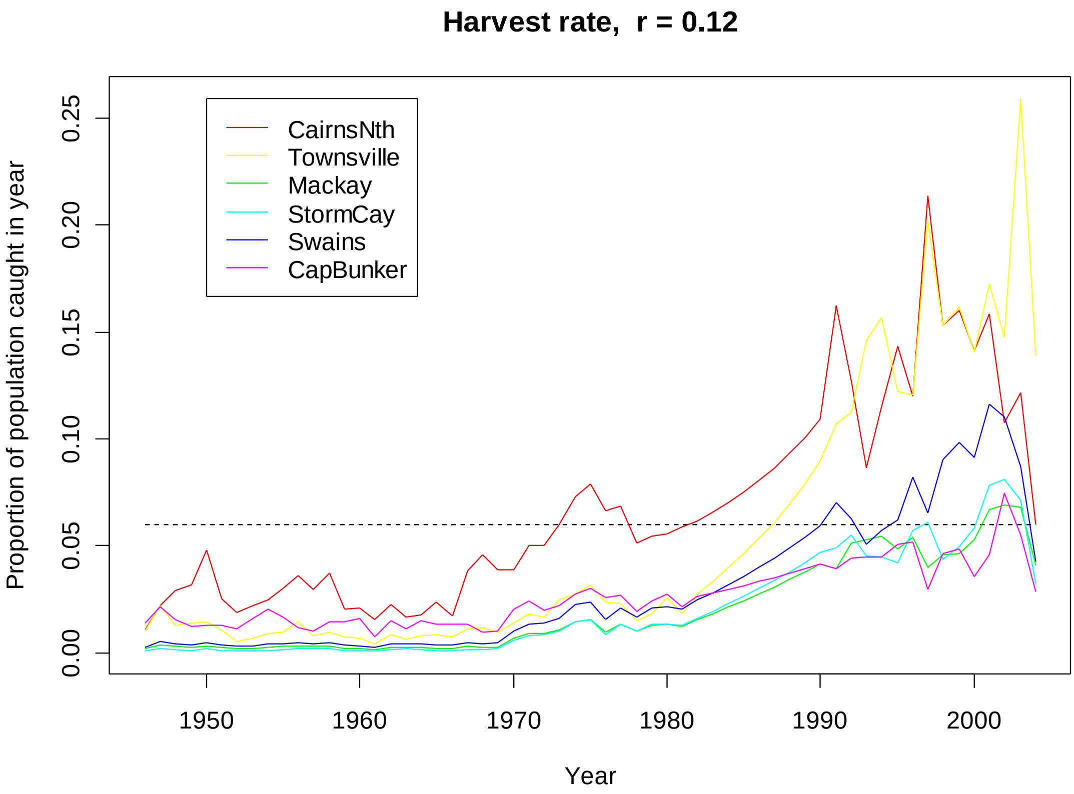

Figure 26: Harvest rate (proportion of population that is caught in each year) from the surplus production model with r = *0 .12* yr^{-1}*, the maximum-likelihood estimate.*

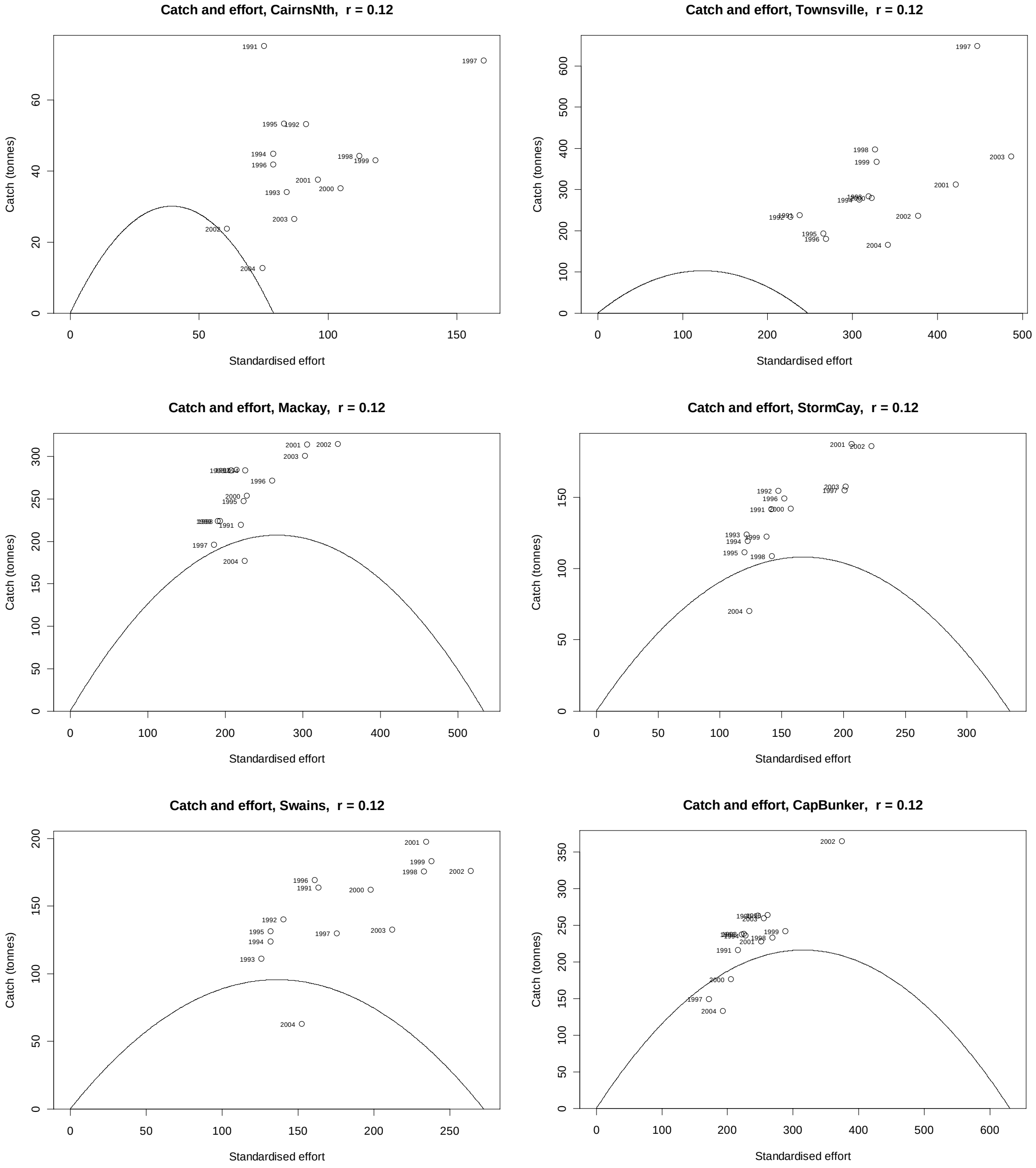

Figure 27: Catch, effort and steady-state yield from the surplus production model with $r = 0.12\ yr^{-1}$*, the maximum-likelihood estimate.*

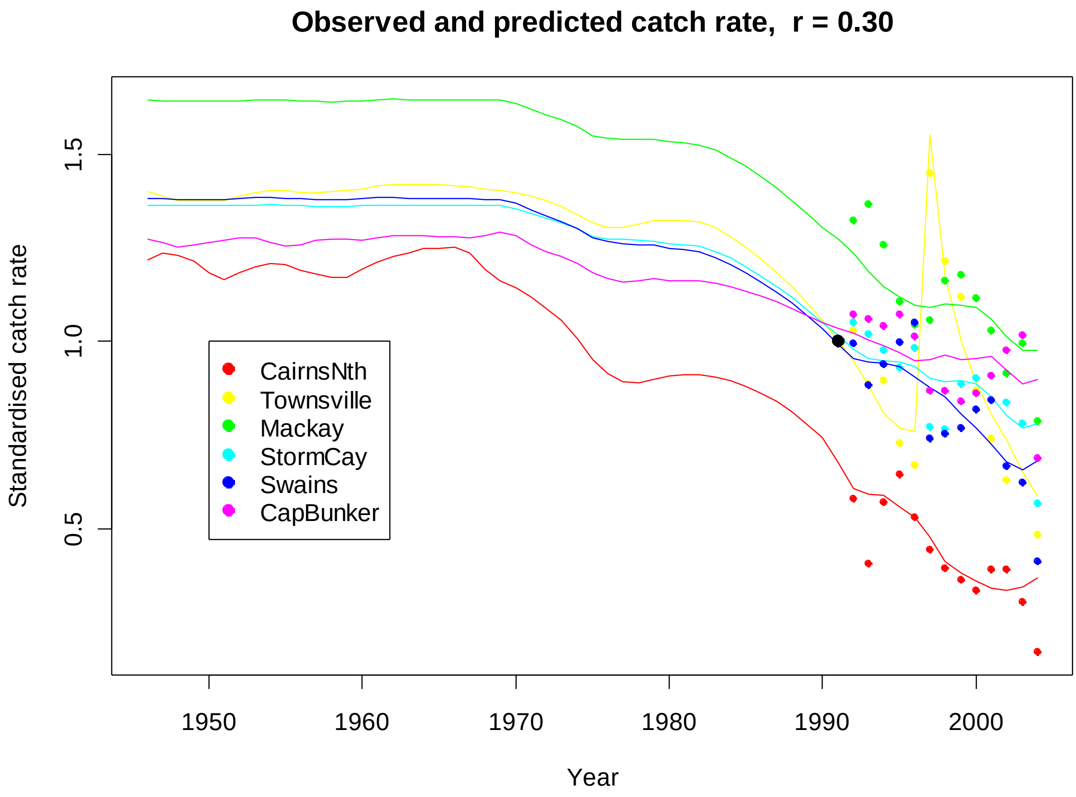

Figure 28: Catch rates from the surplus production model with r *= 0.30 yr*$^{-1}$*, the upper 95% confidence limit.*

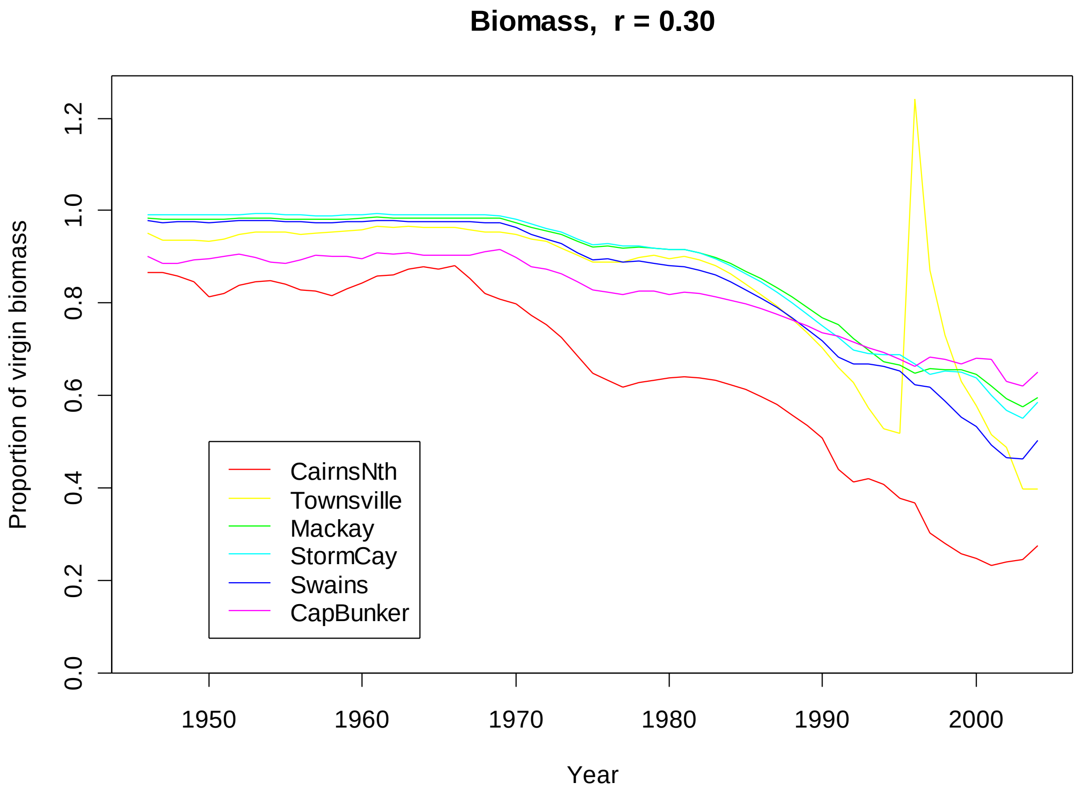

Figure 29: Biomass trend from the surplus production model with r *= 0.30 yr*$^{-1}$*, the upper 95% confidence limit.*

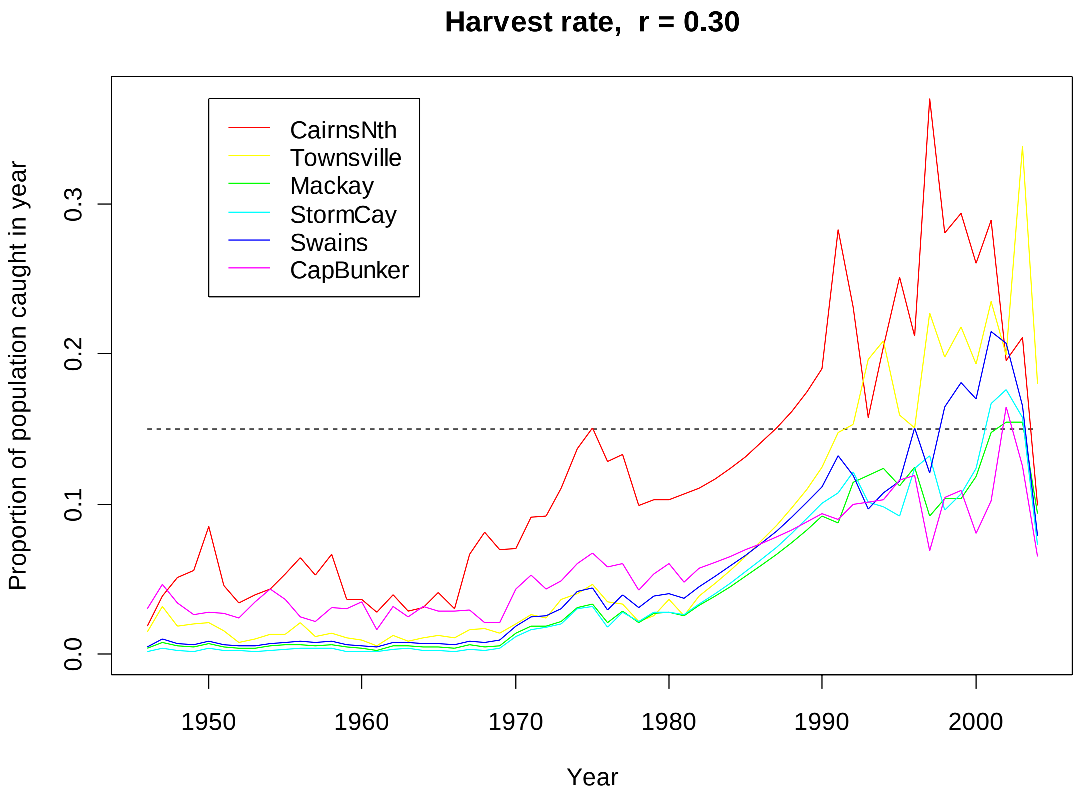

Figure 30: Harvest rate (proportion of population that is caught in each year) from the surplus production model with r = *0.30 yr*$^{-1}$*, the upper 95% confidence limit.*

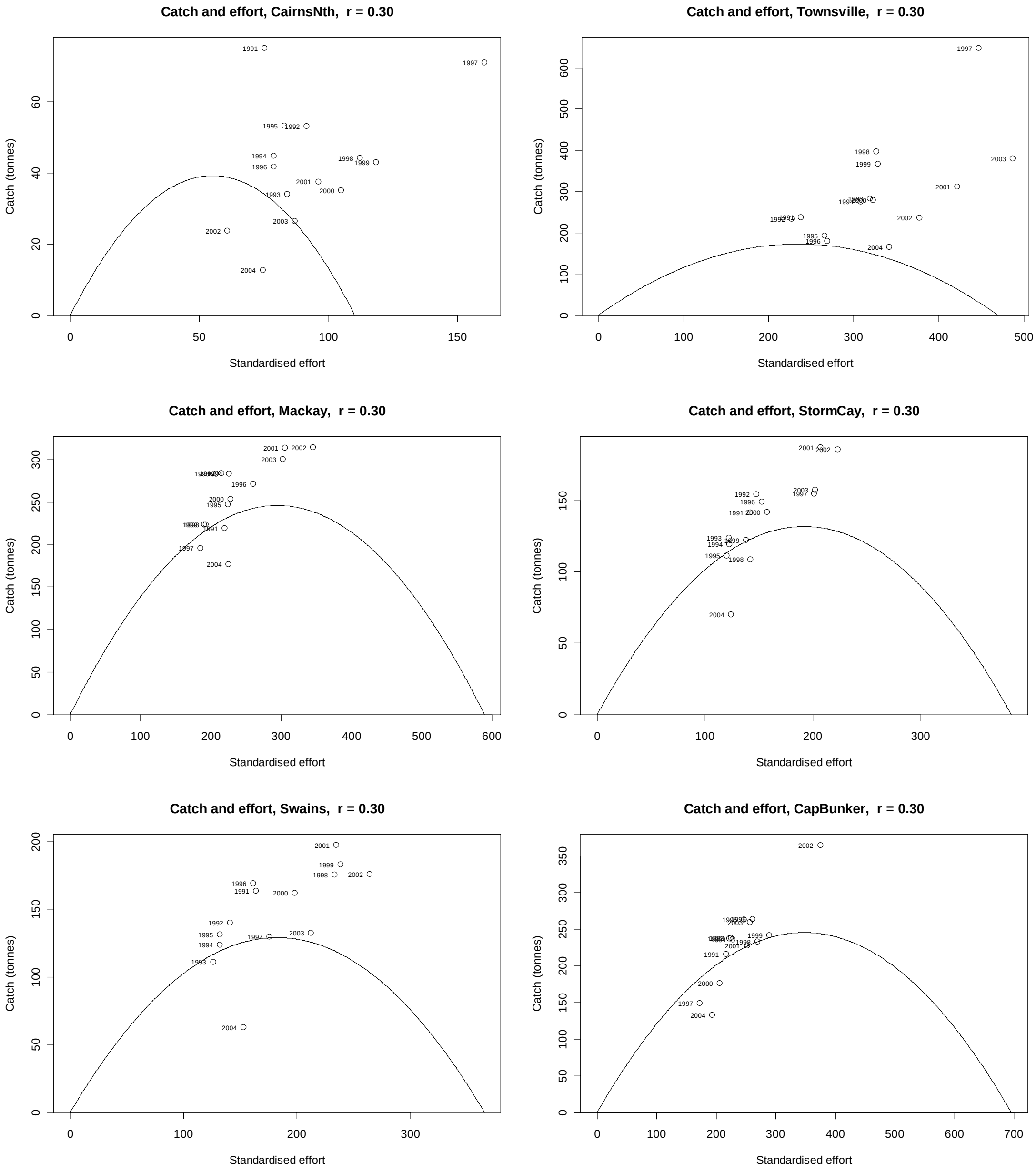

Figure 31: Catch, effort and steady-state yield from the surplus production model with r = *0.30* yr^{-1}*, the upper 95% confidence limit.*

6. Age-structured population dynamic model

6.1 Methods

6.1.1 Model description

Age-structured models make use of information on ages of fish that are caught. They attempt to track year-to-year population numbers from each year-class or recruitment pulse as the fish in it become older. A big advantage of the models is that they can take account of

- year-to-year variation in strength of recruitment
- scientifically-derived ages at maturity, and
- age- or size-dependent gear-selectivity or availability to the fishery.

These capabilities can be used to gauge the effect of fishing on the population more accurately than can be done with a surplus production model. Age-structured models can also test management measures such as size limits.

The age-structured model used for red throat emperor tracks the number of fish in each age-class (0–21 yr which was the oldest age recorded in the ageing data) present in the population in each year and region. It also included an age- and region-dependent vulnerability function whereby more fish became vulnerable to exploitation as they aged.

The term 'vulnerability' in the fishery refers to the product of (a) availability of fish to fishing and (b) selectivity of the particular fishing gear used. Both availability and selectivity would be expected to vary with age, but only availability would be expected to vary between regions; selectivity should be the same over all regions. The model does not need to distinguish availability from selectivity; it combines the two into a single effect called vulnerability.

The model and notation are similar but not identical to those of Haddon (2001, Ch. 11), and are generalised to multiple regions: $N_{a\,y\,g}$ is the number of fish of age a in the population at the beginning of year y in region g. In the next year, $y + 1$, for $a \geq 1$, the number of fish of age a in region g is given by

$$N_{a\,y+1\,g} = N_{a-1\,y\,g}\,(1 - S_{a-1\,g}\,U_{y\,g})\,e^{-M},$$

where $S_{a\,g}$ is the proportion of fish of age a in region g that are vulnerable to fishing, $U_{y\,g}$ is the harvest rate (probability that a vulnerable fish is caught) in year y and region g, and M is the instantaneous rate of natural mortality, assumed constant over all ages and regions and measured in yr^{-1}. The final age group is the 'plus group' of all fish aged 21 yr or more. Strictly speaking, the model is a 'pulse fishery' whereby all the catch is taken in the middle of the year and $N_{a\,y\,g}$ is defined for the middle of the year, just before the catch is taken.

Vulnerability to fishing follows a Richards (1959) curve, written here as:

$$S_{a\,g} = 1 \,/\, [1 + \exp\{-(\log 19)\,(a - x_{50\,g}) \,/\, (x_{50\,g} - x_{05\,g})\}]^{\gamma},$$

where $x_{05\,g}$ and $x_{50\,g}$ are the 5% and 50% points on a logistic curve, and γ (constant over all regions) is the power to which this curve is raised to give vulnerability in region g. The parameter γ can be viewed as a measure of the asymmetry of the vulnerability functions; $\gamma = 1$ corresponds to a logistic function which is symmetrical about $a = x_{50\,g}$. The Richards equation can be inverted according to the formula

$$a = x_{50\,g} + \{(x_{50\,g} - x_{05\,g}) \,/\, \log 19\}\, \log\{S_{a\,g}^{\,1/\gamma} \,/\, (1 - S_{a\,g}^{\,1/\gamma})\},$$

from which the ages at 5% and 50% vulnerability, denoted $a_{05\,g}$ and $a_{50\,g}$, can be found by setting $S_{a\,g} = 0.05$ and 0.50 respectively. In implementation, the model was reparameterised to use the parameters $a_{05\,\mathrm{diff}\,g}$ and $a_{50\,g}$, where $a_{05\,\mathrm{diff}\,g} = a_{50\,g} - a_{05\,g}$, in place of $x_{05\,g}$ and $x_{50\,g}$.

Recruitment of zero-year-old fish is assumed to follow a Beverton-Holt stock-recruitment relationship (Haddon, 2001, pp. 251–254), with stochastic lognormal variation and adapted to use egg production instead of stock size:

$$N_{0\,y+1\,g} = \text{recres}_y\, \alpha_g\, e_{y\,g} \,/\, (1 + \beta_g\, e_{y\,g}),$$

where

- recres_y is a 'recruitment residual' whose log is a normal variable with zero mean and variance σ^2_{rec}
- $e_{y\,g}$ is the relative number of eggs produced in year y and region g: $e_{y\,g} = \Sigma_a\, (N_{a\,y\,g}\, \text{fem}_a\, \text{mat}_a\, f_a)$ where fem_a is the proportion of fish that are female at age a (see Section 2.6), mat_a is the proportion of females that are mature by age a (see Section 2.5) and f_a is relative fecundity at age (see Section 2.7)
- the parameters α and β are given by

  $$\alpha_g = r_{\max}\, N_{0\,g} \,/\, e_{0\,g}$$

  and

  $$\beta_g = (r_{\max} - 1) \,/\, e_{0\,g}$$
- $N_{0\,g}$ is the virgin recruitment in region g
- $e_{0\,g}$ is the virgin relative number of eggs produced in region g.

The parameters $N_{0\,g}$, $r_{\max}$ and σ^2_{rec} have to be estimated. The recruitment residuals recres_y are also estimated for individual years for which there are sufficient data.

The parameter $r_{\max}$, in the absence of fishing, is identical to the parameter denoted $\hat{\alpha}$ by Myers *et al.* (1999), described by them as 'the number of spawners produced by each spawner over its lifetime at very low spawner abundance'. Myers *et al.* (1999) centre their discussion on the parameter $\tilde{\alpha}$, 'the number of spawners produced by each spawner per year', which is related to $r_{\max}$ by $\tilde{\alpha} = r_{\max}\,(1 - e^{-M})$. The parameter $r_{\max}$ is related to the more widely-used 'steepness' parameter h by $h = r_{\max} \,/\, (4 + r_{\max})$; steepness is defined as the proportion of virgin recruitment that takes place when the spawning population size (or egg production) is reduced to 20% of its virgin level.

Myers *et al.* (1999) find that $\tilde{\alpha}$ usually ranges between 1 and 7, giving a range for $r_{\max}$ between $1 \,/\, (1 - e^{-M})$ and $7 \,/\, (1 - e^{-M})$.

The recres_y parameters could, in principle, be estimated separately for each region–year combination, rather than, as the model did, making one parameter cover all regions in a particular year. This would put 95 recres_y parameters into the model instead of only 19. It was judged that estimation of 95 of these parameters would have poor precision given the available data (most samples sizes under 100 fish on reefs open to fishing, and many under 200 on closed reefs). Therefore the number of recres_y parameters was restricted to 19 so that they could be estimated more accurately.

Another difficulty with the inclusion of all 95 parameters was that data were not available from some region–year combinations. Parameters relying on these data for their estimation would have to be either estimated with especially poor precision or set to zero. Inferring them from data from other regions was believed to be preferable to these two options, and this is essentially what the model did by having one parameter cover all regions in a particular year.

The parameter $r_{\max}$ was also assumed to take the same value over all regions, but was still impossible to estimate (see Section 6.2.1 below).

The $N_{0\,g}$ parameters varied between regions in order to handle differences in adult fish abundance between regions.

Because age-frequency samples were available from both open and closed reefs, a parameter was included to represent the ratio of effective instantaneous fishing mortality on reefs closed to fishing to that on reefs open to fishing. This parameter could be nonzero if fish move between open and closed reefs, or if some fishers infringe the regulations by fishing on closed reefs.

Each of the five different patterns of whether particular reefs were open or closed to fishing in particular years of the ELF Project was modelled separately (Table 3), as was an 'always open' population. This resulted in six different patterns in all, which were denoted 'Open', 'Closed', 'Mixed1', 'Mixed2', 'Mixed3' and 'Mixed4'. The Mixed1 pattern was the third row in each region in Table 3, Mixed2 was the fourth row, etc. For the purpose of matching age frequencies, the Open, Mixed3 and Mixed4 patterns were aggregated into a group of 'Open' reefs, and the Closed, Mixed1 and Mixed2 patterns were aggregated into 'Closed' reefs.

Cyclone Justin in 1997 was modelled by introducing a different vulnerability function for the Townsville region in 1997, with separate a_{05} and a_{50} parameters but the same value of γ. Fish that became vulnerable in 1997 were assumed to remain vulnerable for life, while those that were left were assumed to become vulnerable according to the pre-existing age-dependent pattern. Therefore, taking 1998 as an example, for the Townsville region (which is region 1)

$$S_{a\,1\,1998} = S_{a-1\,1\,1997} + \{(S_{a\,1} - S_{a-1\,1}) / (1 - S_{a-1\,1})\}\ (1 - S_{a-1\,1997})\ (a \geq 1),$$

$$S_{a\,1\,1999} = S_{a-2\,1\,1997} + \{(S_{a\,1} - S_{a-2\,1}) / (1 - S_{a-2\,1})\}\ (1 - S_{a-2\,1997})\ (a \geq 2),$$

etc.

The model uses catch data in the form of weights, necessitating an age-weight relationship, which is given by the length-weight relationship derived in Section 2.2.3 above, together with the growth curve derived in Section 2.3 above.

Because there were minimal scientific data for the Cairns North region, it was combined with the Townsville region.

6.1.2 Model parameters

Table 23 lists the parameters explicitly estimated by the model. In addition to these parameters, the model also implicitly estimated the following parameters:

σ^2_{rec}, the variance of the log-recruitment residuals;

q_g, the catchability parameter for region g, which was set to $(\Pi_y\ \text{cpue}_{y\,g}) \,/\, (\Pi_y\ B_{y\,g})$, where $\text{cpue}_{y\,g}$ is the catch per unit effort in year y and $B_{y\,g}$ is the midyear biomass in year y, taken midway through the year's fishing;

$N_{a\ 1946\ g}$, the initial numbers-at-age, which were generated by running the model for a 'warm-up' period of 20 years, beginning from the virgin state (determined by $N_{0\,g}$ and M), with a constant catch equal to the average of the years 1946–1969, a period of stable catches prior to substantial growth of the fishery.

Table 23: Parameters estimated by the age-structured model.
Subscripts g and y denote region and year respectively.

Symbol	**Description**
$a_{05\ \text{diff}\ g}$	Difference between ages at 5% and 50% vulnerability (g = 1, …, 5) (yr)
$a_{50\,g}$	Age at 50% vulnerability (g = 1, …, 5) (yr)
$a_{05\ \text{diff}\ 1\ 1997}$	Difference between ages at 5% and 50% vulnerability for Townsville region in 1997 (a 'Cyclone Justin' parameter) (yr)
$a_{50\ 1\ 1997}$	Ages at 50% vulnerability for Townsville region in 1997 (a 'Cyclone Justin' parameter) (yr)
γ	Asymmetry parameter in the Richards age-dependent vulnerability curve
M	Instantaneous natural mortality rate (yr^{-1})
Ffac	Ratio of effective fishing mortality on closed reefs to that on open reefs
$r_{\max}$	Ratio of the number of recruits per spawner at low population sizes to that at virgin population size
$N_{0\,g}$	Virgin recruitment numbers (g = 1, …, 5)
log recres$_y$	Annual deviations from the Beverton-Holt stock-recruitment relation in recruitment of zero-year-old fish (y = 1980, …, 1998)

6.1.3 Input data and model fitting

The model was fitted by matching the expected to the observed CPUE and age structures. CPUE from 1991 to 2003 was used, and age compositions from 1988–1992 and 1994–2002.

CPUE was assumed to follow a lognormal distribution, giving rise to the log-likelihood

$$L_{\text{cpue}} = -n_{\text{cpue}} \log \sigma_{\text{cpue}} - \Sigma_{y,\,g} (\log \text{cpue}_{y\,g} - \log \text{pred.cpue}_{y\,g})^2 \,/\, (2\sigma_{\text{cpue}}^2),$$

where n_{cpue} is the number of year-region combinations of CPUE data, $\text{pred.cpue}_{y\,g}$ is the CPUE predicted by the model in year y and region g, and σ_{cpue} is the standard deviation of log $\text{cpue}_{y\,g}$.

Age composition in year y, region g and status b (open or closed) was measured by the cumulative distribution function, $\text{cdf}_{y\,g\,b}(a)$, which was the proportion by weight of fish in the catch of age $\leq a$. The difference between predicted and observed distribution functions was assumed to follow a normal distribution, giving the log-likelihood

$$L_{\text{age}} = -n_{\text{age}} \log \sigma_{\text{age}} - \Sigma_{y,\,g,\,b} \left(\Sigma_a \{\text{cdf}_{y\,g\,b}(a) - \text{pred.cdf}_{y\,g\,b}(a)\}^2 / A_{y\,g\,b}\right) / \, (2\sigma_{\text{age}}^2)\,,$$

where

n_{age} is the effective total number of degrees of freedom of age categories over all year-region-status combinations for which age-frequency data are available (the sum over (y, g, b) is over those combinations);

$A_{y\,g\,b}$ is the number of fish aged in year y, region g and status b; it is included in the formula to account for the greater variability in $\text{cdf}_{y\,g\,b}(a)$ when sample size is small;

pred.cdf_y is the age composition in year y predicted by the model; and

σ_{age} is the standard deviation of the normal distribution.

Some constant terms have been omitted from the above log-likelihoods.

In defining the effective number of degrees of freedom n_{age} , it was recognised that small numbers of fish (especially in the oldest age groups) contribute comparatively little information. The contribution of an age-frequency sample from region g to this number was therefore based on the dominant age group in that region. The contribution was defined to be d_g , the largest integer such that the overall age-frequency proportions, taken over all year-status combinations in region g, were all less than or equal to d_g^{-1}. For example, 38.0% of all fish by weight sampled from the Capricorn-Bunker region (region 5) were aged 2 yr, 28.2% were aged 3 yr, and lesser proportions were assigned other ages. The largest proportion, 38.0%, lies between 33.3% (⅓) and 50% (½), thereby giving $d_5 = 2$ degrees of freedom; this agrees with the intuitive number of degrees of freedom that would result from splitting the population into three groups of roughly equal size (one degree of freedom is lost through the requirement that the proportions must sum to 1). Values of d_g are listed in Table 24.

Table 24: Values of the effective number of degrees of freedom, d_g *, contributed by age-frequency samples from each region.*
The proportion of fish by weight in the dominant age category defines the value of d_g *.*

Region	d_g	**Dominant age category**
Townsville	6	8 yr (16.3%)
Mackay	4	5 yr (21.9%)
Storm Cay	6	5 yr (16.3%)
Swains	3	4 yr (27.8%)
Capricorn-Bunker	2	2 yr (38.0%)

The final component of the overall log-likelihood is the log-likelihood from deviations in recruitment from the Beverton-Holt stock-recruitment relation. As stated above, the recruitment residuals were assumed to follow a lognormal distribution; the resulting log-likelihood is

$$L_{\mathrm{rec}} = -n_{\mathrm{rec}} \log \sigma_{\mathrm{rec}} - \Sigma_y (\log \mathrm{recres}_y)^2 / (2\sigma_{\mathrm{rec}}^2), \qquad (1)$$

where n_{rec} is the number of years for which separate recruitment residuals are estimated, and σ_{rec} is the standard deviation of log recres_y .

In order to prevent either σ_{rec} or σ_{cpue} converging to zero (i.e., a perfect fit to either CPUE or the stock-recruitment relation at the expense of other likelihood components), the ratio of these two parameters is fixed. Fixing $\sigma_{\mathrm{rec}} / \sigma_{\mathrm{cpue}} = 4$ allowed adequate variation in both the recruitment residuals and the CPUE fits; model results were not greatly sensitive to the value of this ratio.

The negative sum of the three log-likelihoods was minimised by the *R* routine `optim` using the quasi-Newton method `BFGS` (R Development Core Team 2005). Derivatives of the likelihoods with respect to all the parameters were programmed in *R* to assist in the optimisation.

The *R* code for the age-structured model is listed in full in the Appendix.

6.1.4 Model assumptions

1. The instantaneous natural mortality rate *M* is constant over all years, ages and regions. In reality we recognise that *M* is likely to be lower for old fish than for young fish, but there are insufficient data on old fish to estimate multiple values of *M*.
2. Vulnerability to fishing follows a Richards curve with age, and all fish in the population eventually become vulnerable to exploitation. Differences in age structure between regions are the result of different vulnerability curves. Vulnerability does not change with year, except in the Townsville region in 1997. The asymmetry parameter γ is the same over all the Richards curves.
3. Vulnerable and non-vulnerable fish of the same age have the same capacity to breed.
4. Recruitment to the population follows a Beverton-Holt stock-recruitment relation with stochastic, lognormal variation. The parameter $r_{\max}$ does not depend on region.
5. The relative recruitment strength in a given year is the same over all regions.
6. Movement of fish between open and closed reefs can be represented by a single parameter giving the ratio of effective instantaneous fishing mortality rates between the two.
7. There is little movement of fish between regions. An alternative model was attempted that had a common vulnerability curve over all regions and explained the different age structures in the regions by northward migration of red throat emperor over their lifetimes, following Williams (2003). This model was unable to achieve the magnitude of the observed differences in age structure between regions, and it was impossible to obtain sensible results from it. For example, for the age structure of the Storm Cay region to arise by northward migration, many of the fish aged 5–7 years must come from the Capricorn-Bunker or Swains regions, but those regions are unable to supply enough of these older fish (see Figure 32 below). Similarly, the Townsville region would require a continuous influx of 8-year-old fish, which the Mackay region is unable to supply.
8. Within each region, the time series of standardised commercial CPUE by year is proportional to the time series of midyear exploitable (vulnerable) biomass.
9. Cyclone Justin in 1997 had the effect of altering the vulnerability curve in the Townsville region to a different Richards curve. Fish that became vulnerable in 1997 remained vulnerable for the rest of their lives. Fish that did not become vulnerable in 1997 followed the pre-existing vulnerability curve in subsequent years.

10. Approximating the fishery by a ‘pulse fishing’ model, whereby all fishing takes place in the middle of the year, does not significantly affect the accuracy of the results.
11. The initial state of the fishery in 1946 is accurately approximated by a start from virgin state in 1926 followed by 20 years of annual catches equal to the average catches over the period 1946–1969.
12. Age-frequency samples taken from sampled reefs within a region are representative of the red throat emperor population throughout the region, of which there are five in the GBR.
13. The use of different fishing gear to collect age-frequency samples did not introduce any biases in the sampling.
14. Ages assigned to otoliths are accurate.
15. The estimated effective numbers of degrees of freedom for age-frequency samples are accurate for practical purposes (Table 24).
16. Annual catches were accurately recorded in the QFB and CFISH databases, and approximating catches for 1982–1990 by linear interpolations does not affect the accuracy of the model results.
17. Recreational catches are accurately measured by the telephone / diary survey method used for the RFISH and NRIFS surveys. Extrapolating recreational catches backwards in time from 1997 does not affect the accuracy of the model results.

6.1.5 Management scenarios

The future management scenarios tested were different levels of total catch. Annual catch was assumed to be the same for each year into the future, and levels of 900 t, 1200 t and 1500 t were tried; given a recreational / charter catch of approximately 500 t yr^{-1}, these correspond to TACC levels of about 400 t, 700 t and 1000 t. Catches were assumed to be divided into regions in the same proportions as in 2003.

Variation in recruitment about the Beverton-Holt stock-recruitment relation was assumed to continue to follow the same lognormal distribution for which the parameter σ^2_{rec} was estimated (see Equation (1) above). Recruitment levels after 1998 (the final year for which the model included a parameter) were simulated using random numbers. For comparison, 10 different trajectories were generated for each catch level.

6.1.6 Sensitivity analysis

Sensitivity analysis was performed on three key input variables:

- The instantaneous natural mortality rate *M*: a fixed value of 0.40 yr^{-1} was tried in addition to the model’s best estimate of 0.51 yr^{-1}. In fact the main purpose of this analysis was to test sensitivity of the results to the assumption of the asymmetric Richards vulnerability curve. The lower value of *M* had the effect of forcing the vulnerability curve to be more symmetric.
- The size of historical catches: due to the uncertainty in the size of the historical recreational catch (see stage 2 in Section 3.4.2), a case was run in which the historical catch (over all sectors) in each year up to 1981 was double the base level used in the main analysis. The multiplying factor was then linearly interpolated from its value of 2 in 1981 to a value of 1 1991; from 1991 onwards the base catch level was used. Another case was run in which historical catch was half the base level, and the same interpolation method was used.
- The post-release mortality rate of red throat emperor (see Section 3.3); zero post-release mortality was assumed in the main analysis, and a level of 30% was also tested.

6.1.7 *Size-dependent vulnerability*

The regional vulnerability curves were converted to functions of length instead of age, to determine whether regional differences in vulnerability-at-age could be due simply to different growth curves in the different regions. The data used to make the conversion were:

- the age-dependent vulnerability curves, given by the a_{05} and a_{50} parameters in the model
- the growth curves derived in Section 2.3 (Table 7 and Figure 5).

For the purposes of this comparison, vulnerability-at-length was assumed to follow a logistic distribution:

$$S^*_{L\,g} = 1 / [1 + \exp\{-(\log 19)\,(L - L_{50\,g}) / (L_{50\,g} - L_{05\,g})\}]$$

where $S^*_{L\,g}$ denotes length-dependent vulnerability at length L in region g, and $L_{05\,g}$ and $L_{50\,g}$ are the lengths at 5% and 50% vulnerability respectively. From this the age-dependent vulnerability function is derived as

$$S_{a\,g} = E_{a\,g}(S^*_{L\,g}),$$

where $E_{a\,g}$ denotes the expectation over lengths of fish of age a in region g from the growth curves in Section 2.3. Lengths were assumed to be normally distributed about the mean length-at-age, with the standard deviation given by the standard error column of Table 7.

The parameters $L_{05\,g}$ and $L_{50\,g}$ were obtained from a least-squares fit of the above formula for $S_{a\,g}$ to the model estimates of $S_{a\,g}$, over ages 0–21 yr. The reference time of year was taken as the middle of November, as this is the time when the most samples were collected.

6.2 Results

6.2.1 *Estimability of parameters*

Some of the parameters in the model could not be estimated sensibly given the input data. These parameters were either fixed to constants or made to depend on other parameters; the parameters and their values are listed in Table 25.

Table 25: Model parameters that could not be estimated sensibly, together with the values to which they were fixed and the reason.
Descriptions of the parameters are given in Table 23.

Parameter	Value	Reason
$a_{05\,\text{diff}\,4}$	$a_{05\,\text{diff}\,2}$	Only one age-frequency sample was available from Swains region; Mackay region had the most similar age structure (samples from the neighbouring region, Storm Cay, were composed of older fish).
$a_{50\,4}$	$a_{50\,2}$	As above
$a_{50\,2}$	3.05 yr	Estimated vulnerability in Mackay region increased rapidly from close to 0 at age 2 to close to 1 at age 4; allowing $a_{50\,2}$ to vary freely over-parameterised the vulnerability curve.
$a_{50\,5}$	1.05 yr	Estimated vulnerability in Capricorn-Bunker region increased rapidly from close to 0 at age 0 to close to 1 at age 2; allowing $a_{50\,5}$ to vary freely over-parameterised the vulnerability curve.
γ	10,000	Approached infinity during model convergence.
Ffac	0	Converged to negative value.
$r_{\max}$	$7 / \{1 - \exp(-M)\}$	Approached infinity during model convergence; set to maximum limit recommended by Myers *et al.* (1999).

6.2.2 Results of model fitting

As noted above (Section 6.1.4, assumption 7), an alternative age-structured model, which explained different age structures in the regions by migration rather than regional variation in vulnerability, was incapable of representing the magnitude of the differences, and could not be made to produce sensible results. Results of the model with different vulnerability curves for the different regions are presented here.

Histograms of the observed age-frequencies for open and closed reefs, together with fits from the age-structured model, are plotted in Figure 32. The fits are generally close and show that the model has been able to fit the different age structures in different regions.

Histograms for all years combined are shown in Figure 33; these show the difference in age structure between open and closed reefs.

Older fish are present in relatively higher numbers on reefs that are closed to fishing, implying limited migration of fish between open and closed reefs. If large amounts of movement between reefs occurred, the age distributions on open and closed reefs would tend to be the same.

Parameter estimates, with standard errors derived from the Hessian matrix at the maximum likelihood point, are listed in Table 26. Combined with Table 25, this table shows firstly the vulnerability curve parameters, with the ages at 50% vulnerability to fishing preceded by the difference between the ages at 5% and 50% vulnerability.

The age at 50% vulnerability ranges from about 1 yr in the Capricorn-Bunker region to about 9 yr in the Townsville region, while the difference between ages at 5% and 50% vulnerability ranges from less than 1 yr in Capricorn-Bunker to about 5 yr in Townsville. For the special case of the Townsville region in 1997, the values are lower with an estimated 50%-vulnerability age of about 6½ yr and a 5%-to-50% difference of about 3 yr. The estimated vulnerability to fishing is plotted in Figure 34, and the estimated vulnerability to scientific sampling in Figure 35. Fishing vulnerability is affected by the minimum legal size which was 350 mm. The curves for scientific sampling are not subject to size limits, and all fish caught are assumed to be retained.

The model estimated that red throat emperor become exposed to exploitation very gradually in the Townsville and Storm Cay regions (Figure 35). The ages at 95% vulnerability to scientific sampling were estimated as 18 yr and 13 yr respectively. Populations in other regions become exposed sooner: 95% vulnerability ages were 5 yr for the Mackay and Swains regions, and 2 yr for the Capricorn-Bunker region.

The population's natural mortality rate M is estimated as 0.51 yr^{-1} which is higher than might be expected for a long-lived fish, but is within the bounds of possibility. It is also possible that M is lower than this for older fish (see Section 2.4 above).

In contrast to the surplus production model, the age structured model estimates that the majority of red throat emperor live in the Townsville region, with a virgin recruitment level of 28 million age-zero fish compared to the next best of about 7 million in the Storm Cay region. In arriving at these numbers, the model has taken into account the relevant vulnerability curves, according to which many of the fish in the Townsville region are not available to fishing. The surplus production model does not use age-structure data and does not include terms for age-dependent vulnerability.

The fits to commercial CPUE data (plotted in Figure 36) are not as good those to the age frequency data, and must cast some doubt on the quality of the CPUE data. A diagnostic plot of CPUE residuals against fitted values (Figure 41) also indicates a negative slope, which is evidence of hyperstability. Hyperstability is a problem in which the behaviour of fishers masks changes in abundance of fish, and CPUE can appear relatively constant even though the abundance of fish may be changing dramatically. A negative slope on the plot of CPUE residuals against fitted values shows that observed CPUE is often higher than expected when predicted CPUE (using age-frequency information) is low, and that observed CPUE is often lower than expected when predicted CPUE is high.

The much higher CPUE in 1997 and subsequent years in the Townsville region fits the lower ages of 50% vulnerability (6½ yr v 9 yr) and 95% vulnerability (12 yr v 18 yr) in that year, and is consistent with an influx of new fish that were previously not available to the fishery.

Estimated harvest rates (proportions of exploitable biomass that are harvested each year, plotted in Figure 37) show a steep rise in harvest rates from 4–9% around 1980 to 23–29% around 2002. Harvest rates fell dramatically in 2004, probably due to a combination of the fishery restructure and high fuel prices.

Estimated numbers of recruits to the population appear to be quite variable (Figure 38). According to the model, recruitment had a few low years in the early 1990s, followed by at least a partial recovery. No dependence of recruitment on spawning stock size is apparent, and factors other than stock size appear to dominate recruitment.

Exploitable biomass was estimated as having fallen to about 60% of virgin levels by around 2000, but appears to have recovered to about 70% since then (Figure 39). Egg production appeared only to fall to about 70–80% of virgin levels, aided by the presence of mature fish that had not yet become vulnerable to fishing (Figure 40). Egg production also appears to have recovered since the mid-1990s.

Table 26: Parameter estimates, for the age-structured model.
Standard errors (S.e.) from the log-likelihood Hessian matrix are given. Parameters whose values were fixed are listed in Table 25.

Parameter	**Units**	**Value**	**S.e.**
$a_{05\ \mathrm{diff}\ 1}$	yr	4.8955	0.6453
$a_{05\ \mathrm{diff}\ 2}$	yr	0.8993	0.2265
$a_{05\ \mathrm{diff}\ 3}$	yr	3.9845	0.8560
$a_{05\ \mathrm{diff}\ 5}$	yr	0.2553	0.2554
$a_{50\ 1}$	yr	9.2909	0.8321
$a_{50\ 3}$	yr	6.2456	0.8831
$a_{05\ \mathrm{diff}\ 1\ 1997}$	yr	3.0199	0.8051
$a_{50\ 1\ 1997}$	yr	6.4912	0.8124
M	yr^{-1}	0.5117	0.0160
$N_{0\ 1}$	10^7 fish	2.8159	1.0667
$N_{0\ 2}$	10^7 fish	0.5387	0.1140
$N_{0\ 3}$	10^7 fish	0.6920	0.2836
$N_{0\ 4}$	10^7 fish	0.2979	0.0966
$N_{0\ 5}$	10^7 fish	0.3036	0.0609
log recres_{1980}	–	0.1159	0.3466
log recres_{1981}	–	0.0124	0.3282
log recres_{1982}	–	–0.0477	0.3011
log recres_{1983}	–	–0.1906	0.2867
log recres_{1984}	–	–0.0457	0.2531
log recres_{1985}	–	0.1500	0.2143
log recres_{1986}	–	0.1749	0.1939
log recres_{1987}	–	–0.3674	0.2423
log recres_{1988}	–	–0.2195	0.2052
log recres_{1989}	–	0.3257	0.1336
log recres_{1990}	–	0.0911	0.1454
log recres_{1991}	–	–0.3583	0.1894
log recres_{1992}	–	–0.5875	0.2110
log recres_{1993}	–	–0.3204	0.1792
log recres_{1994}	–	0.1685	0.1394
log recres_{1995}	–	–0.0008	0.1627
log recres_{1996}	–	–0.1356	0.1893
log recres_{1997}	–	–0.1337	0.2037
log recres_{1998}	–	–0.3469	0.2435

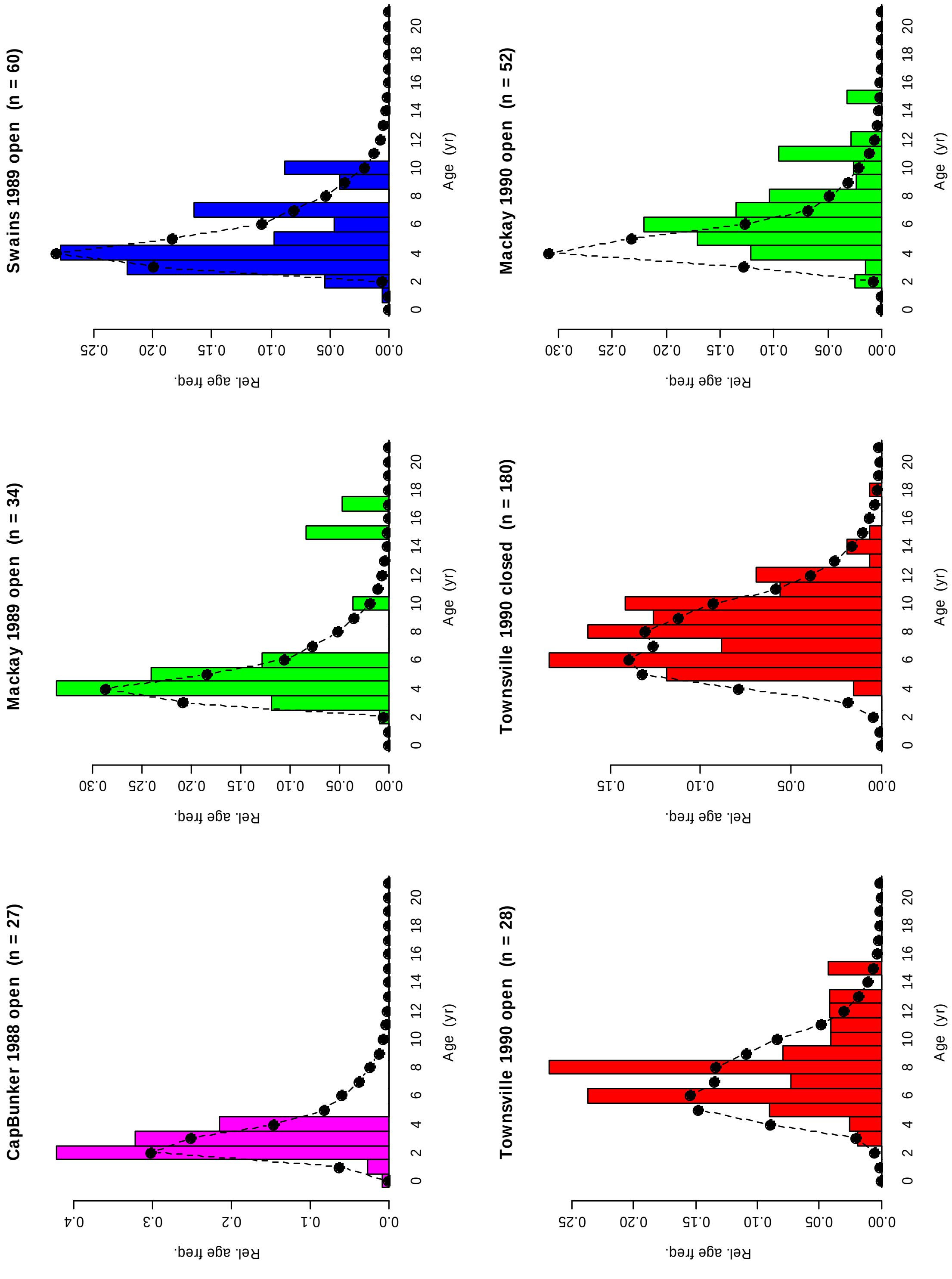

Figure 32: Histograms of observed age-frequencies by fish weight for predominantly open and predominantly closed reefs.
Age frequencies are shown as coloured bars, fits from the age-structured model are shown as black dots and dotted lines. Sample sizes are listed in parentheses. (Continued next 7 pages)

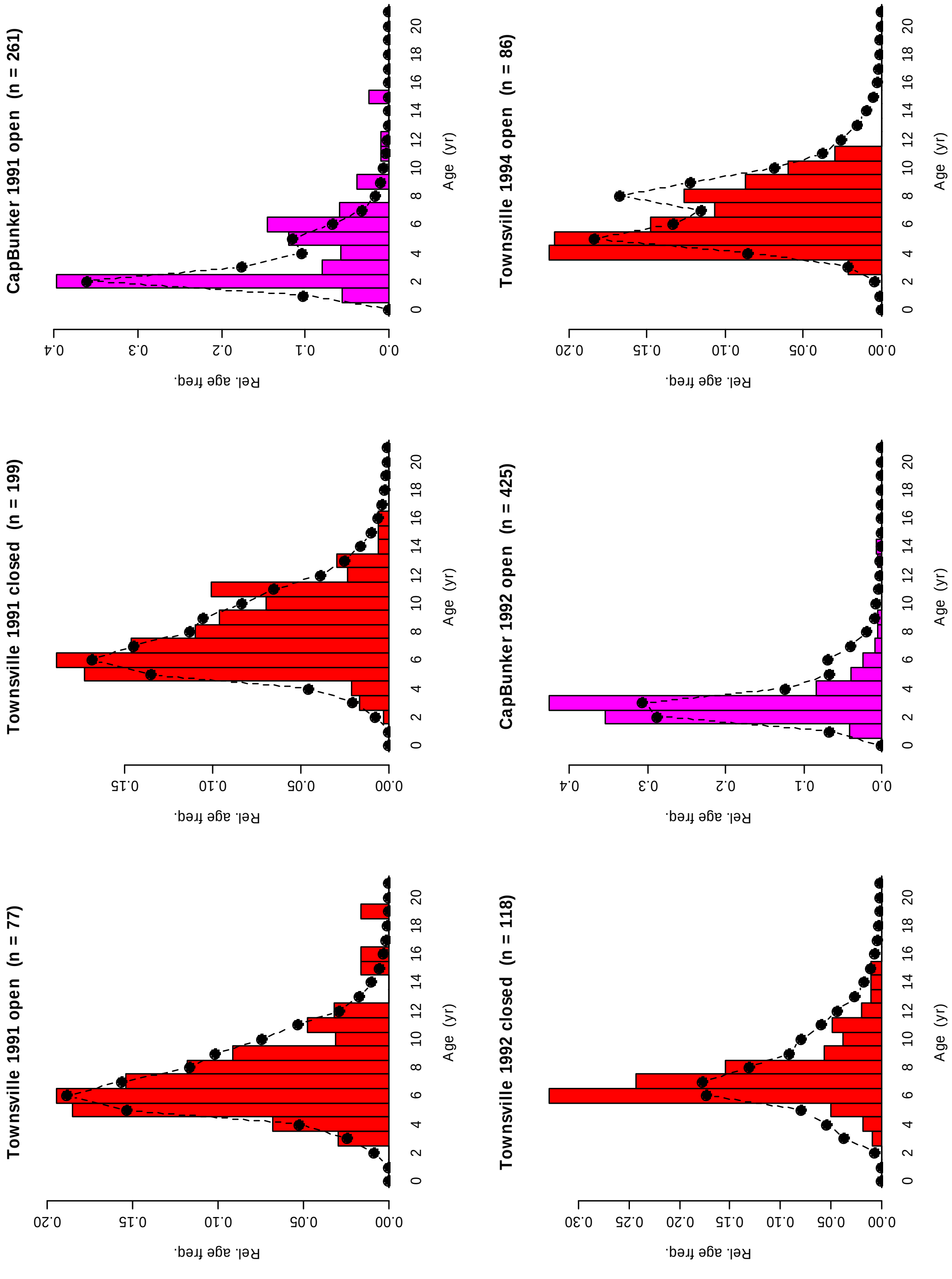

Figure 32: Histograms of age-frequencies (continued).

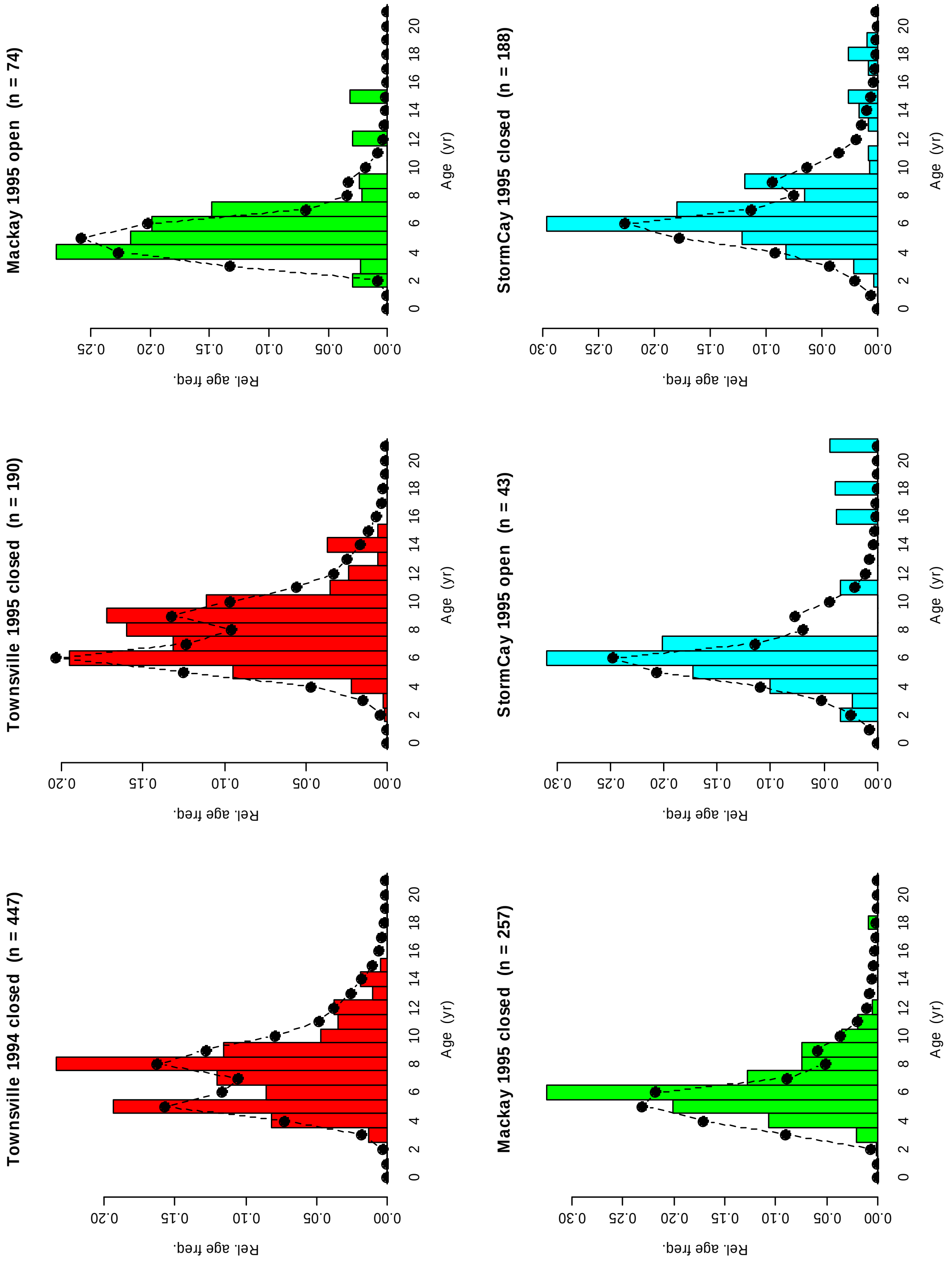

Figure 32: Histograms of age-frequencies (continued).

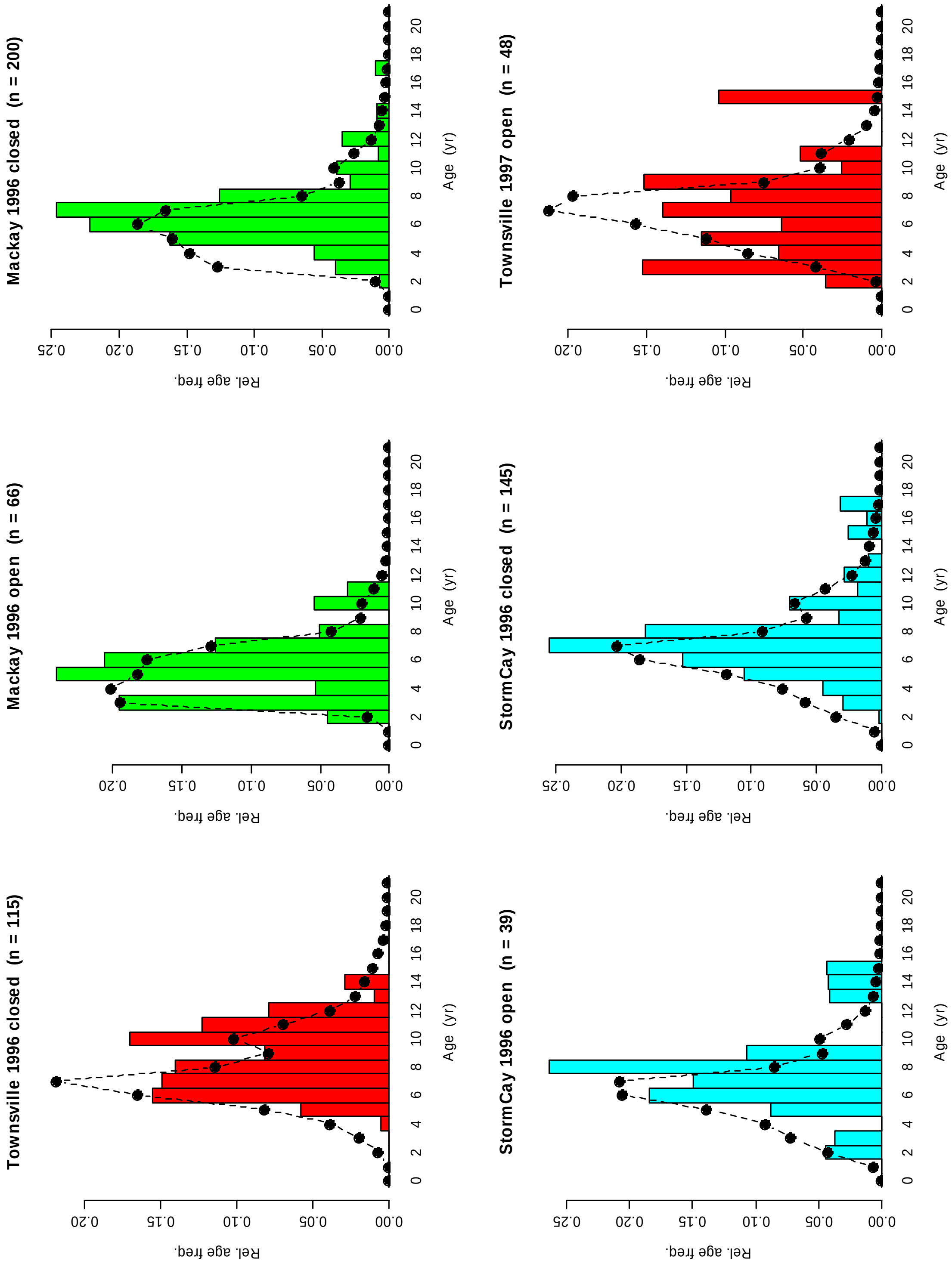

Figure 32: Histograms of age-frequencies (continued).

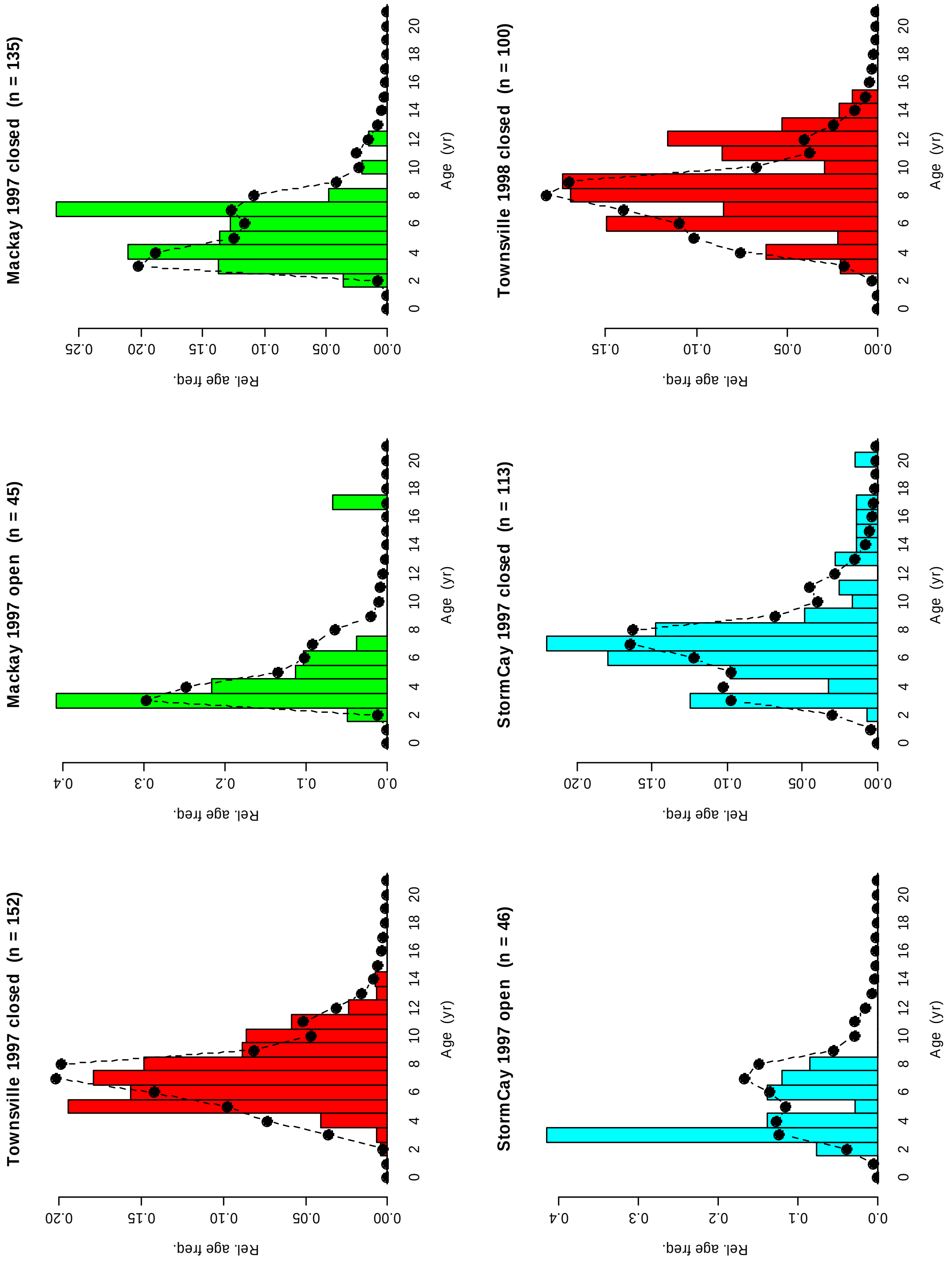

Figure 32: Histograms of age-frequencies (continued).

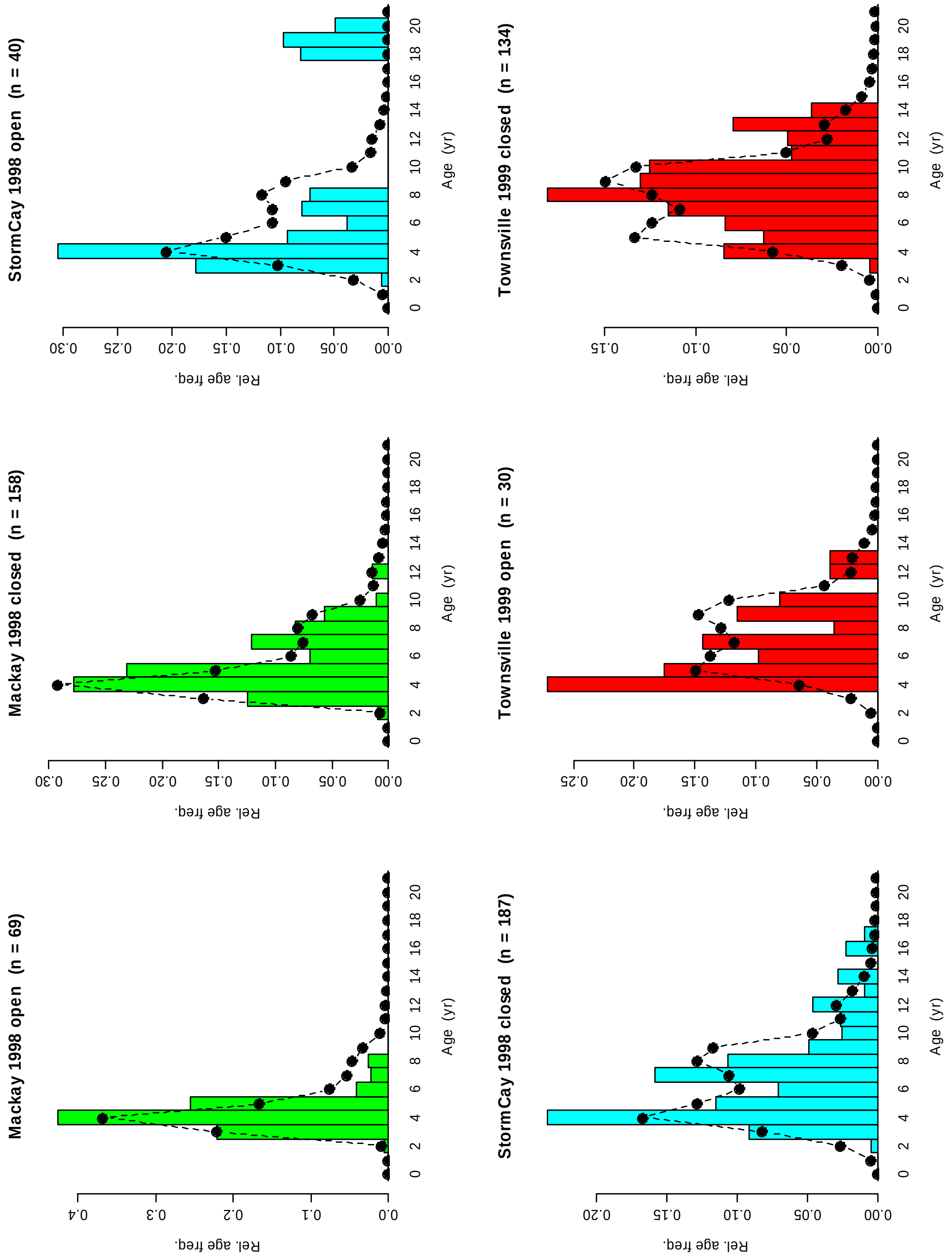

Figure 32: Histograms of age-frequencies (continued).

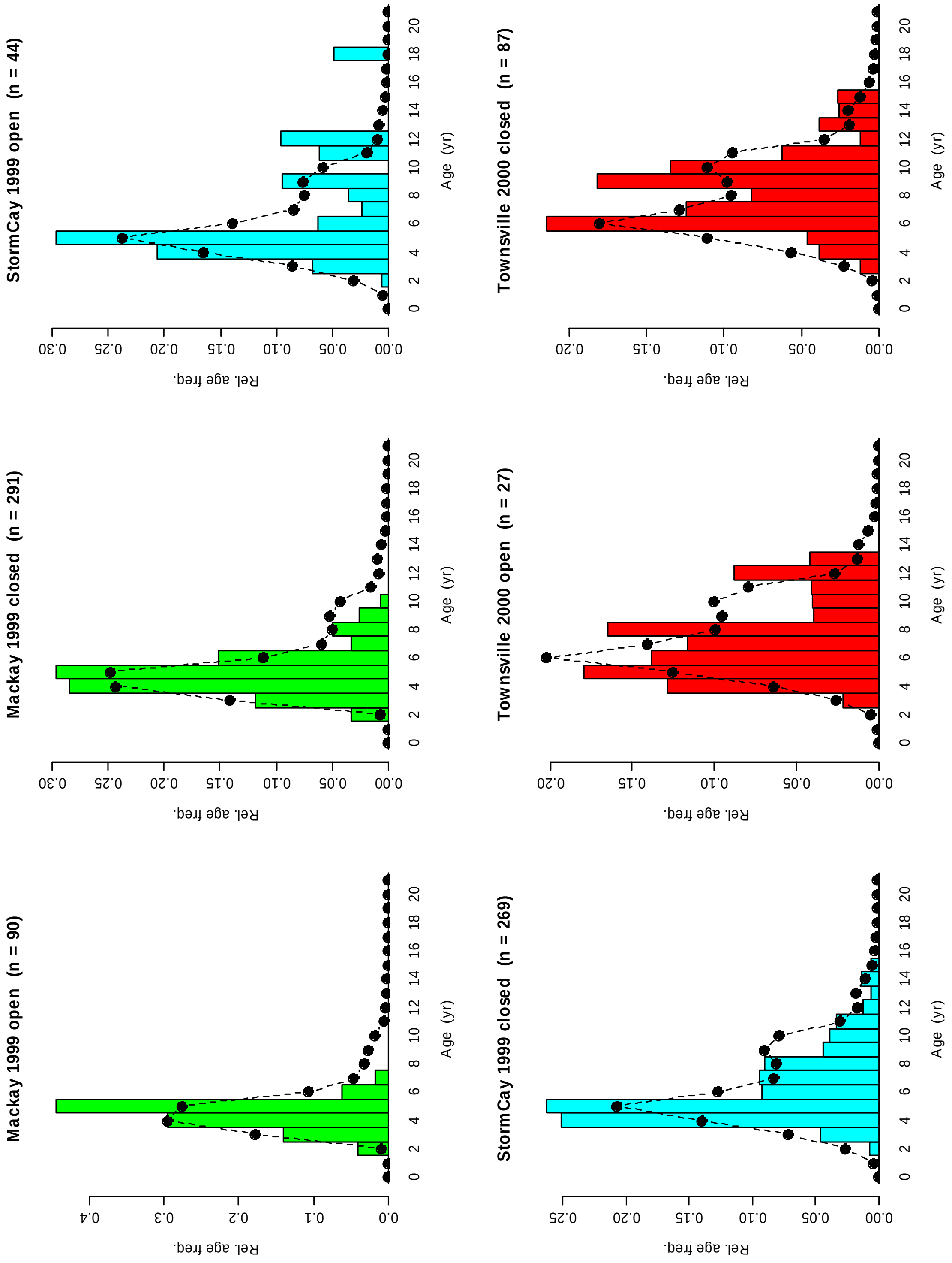

Figure 32: Histograms of age-frequencies (continued).

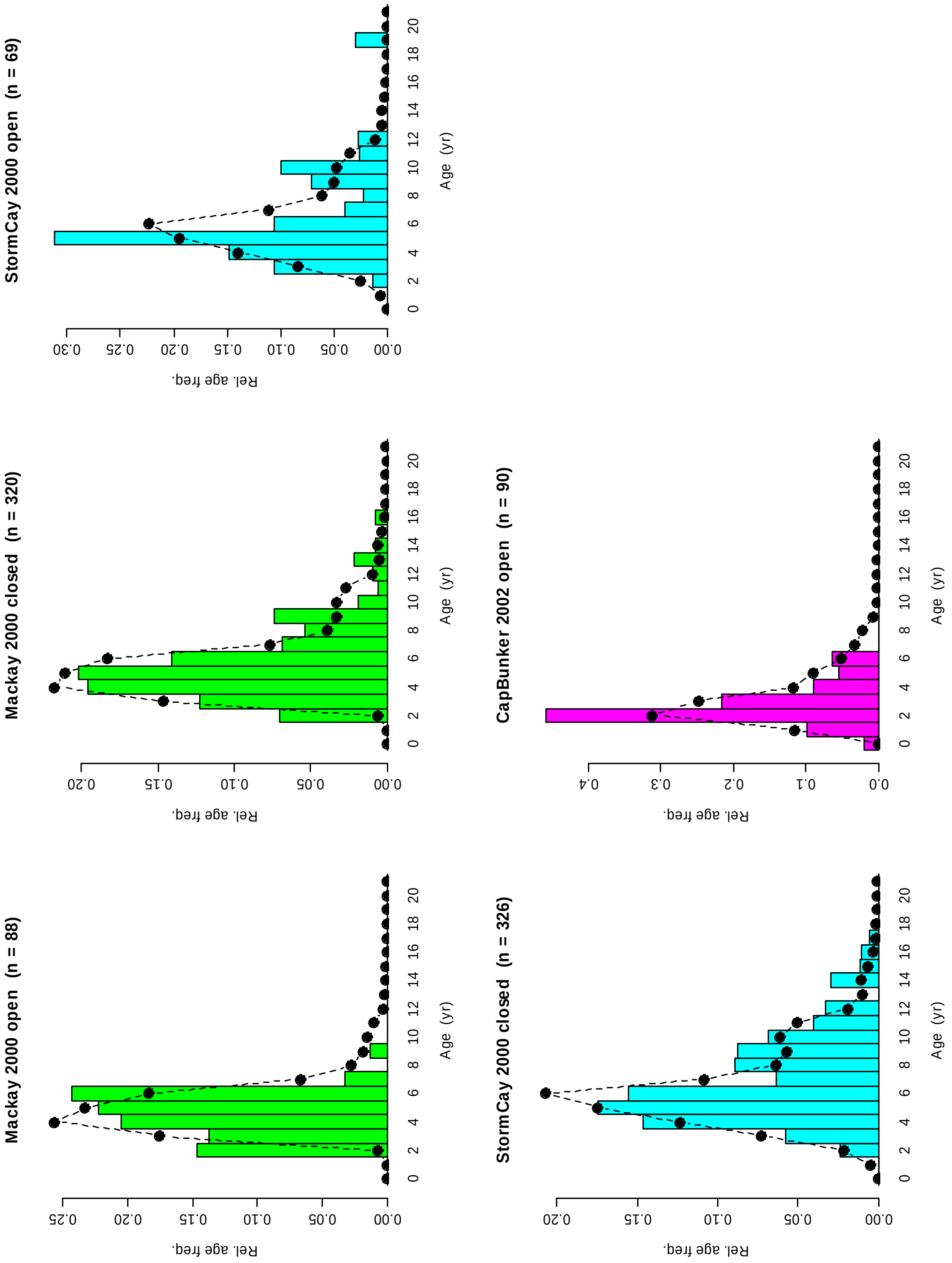

Figure 32: Histograms of age-frequencies (continued).

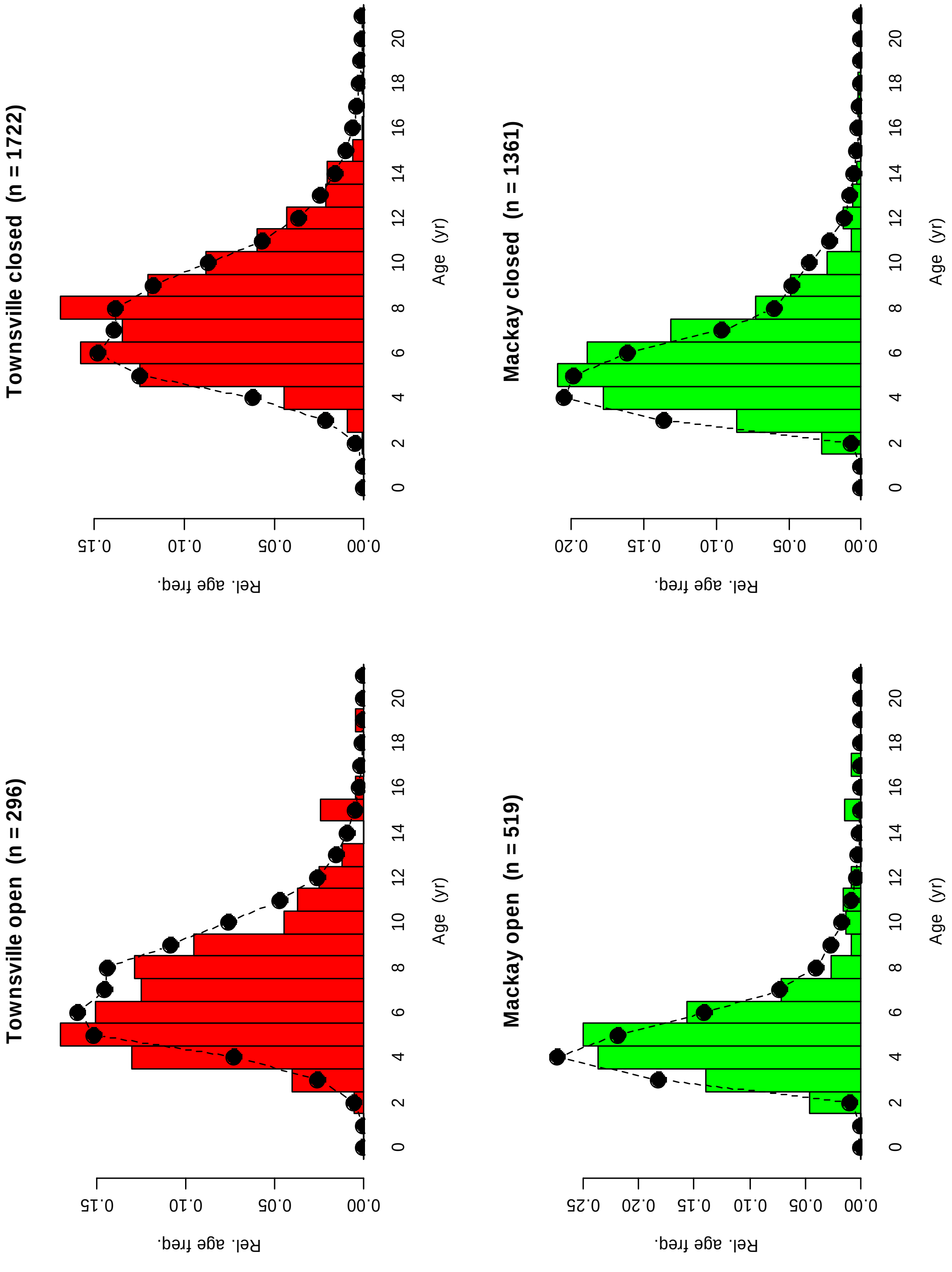

Figure 33: Histograms of observed age-frequencies by fish weight for predominantly open and predominantly closed reefs, by region for all years combined.
Age frequencies are shown as coloured bars, fits from the age-structured model are shown as black dots and dotted lines. Sample sizes are listed in parentheses. (Continued next page)

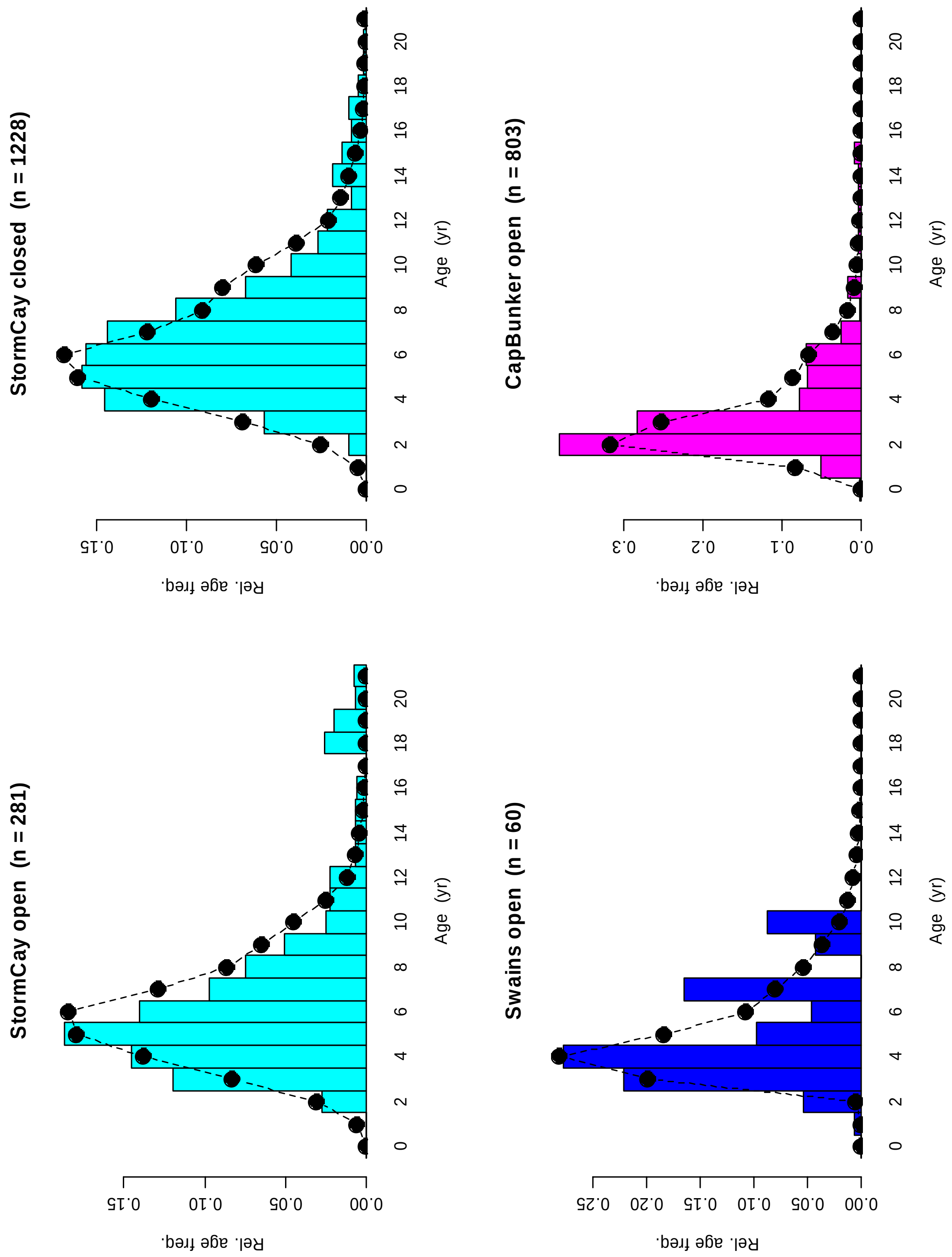

Figure 33: Histograms age-frequencies by region for all years combined (continued).

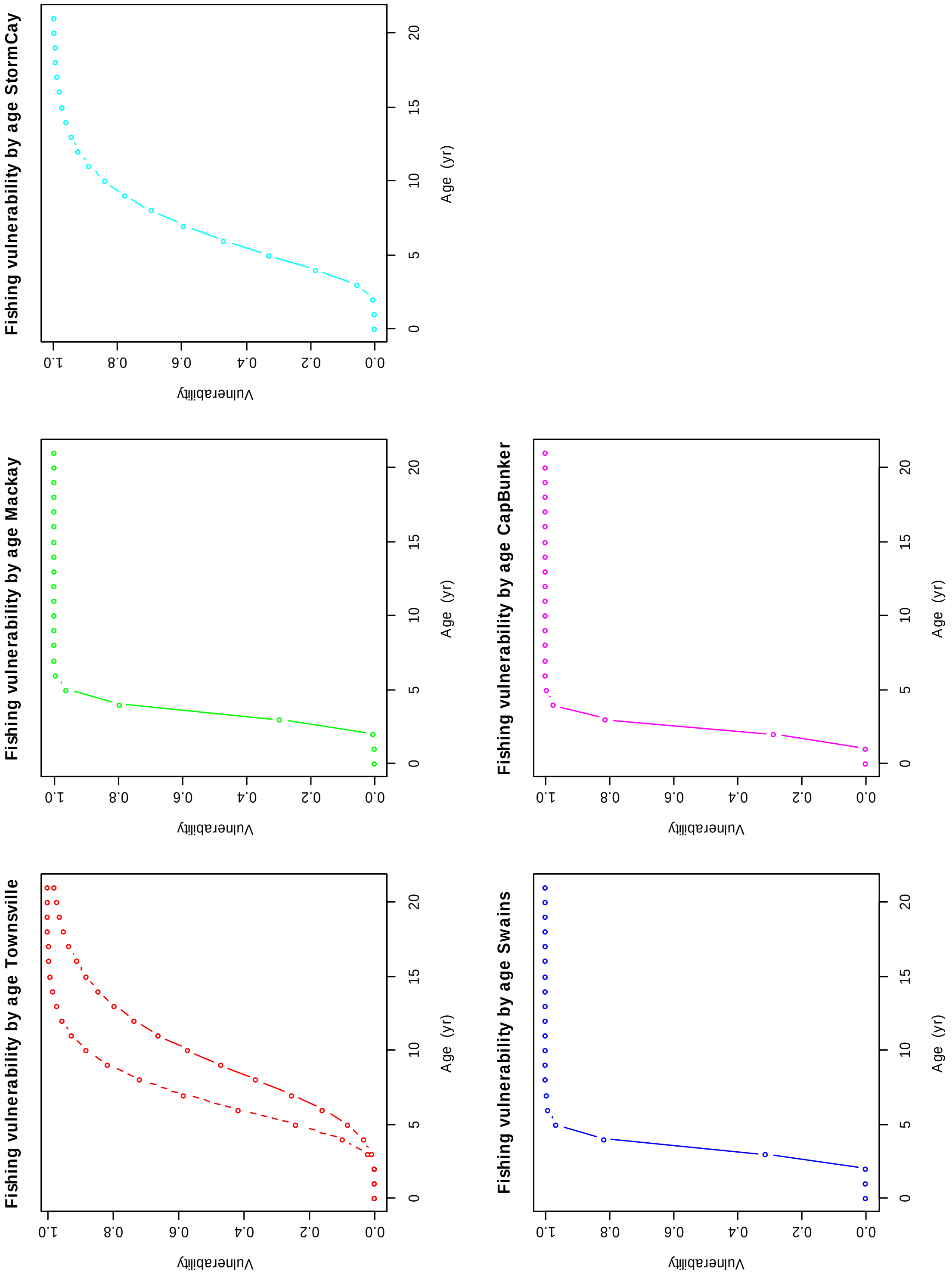

Figure 34: Estimated vulnerability of red throat emperor to fishing, by age and region. These estimates include the effect of the minimum legal size of 350 mm. The dotted line in the plot for the Townsville region is the curve in 1997, changed by Cyclone Justin.

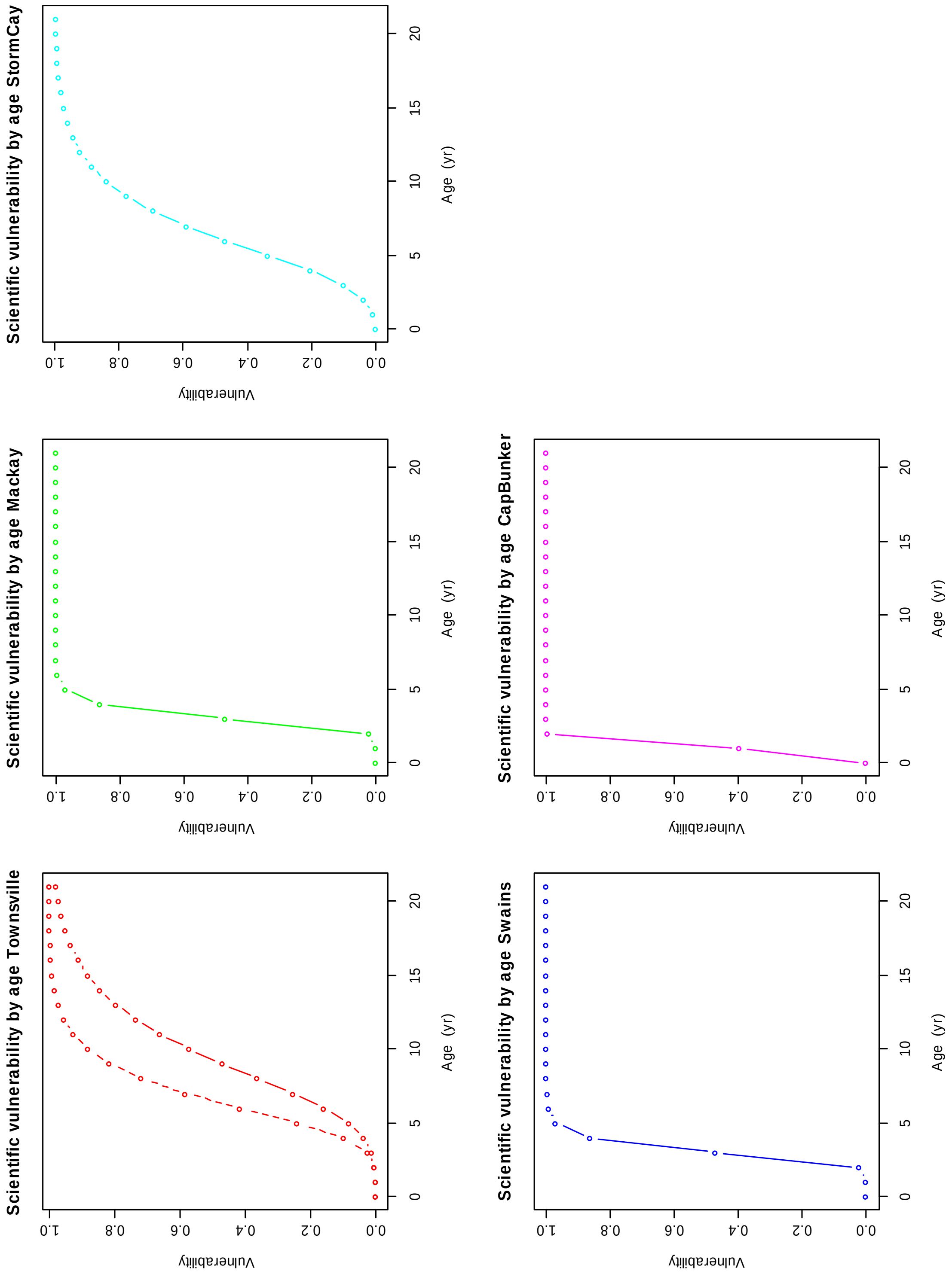

Figure 35: Estimated vulnerability of red throat emperor to scientific sampling, by age and region.
All fish caught are assumed to be retained, irrespective of their size. The dotted line in the plot for the Townsville region is the curve in 1997, changed by Cyclone Justin.

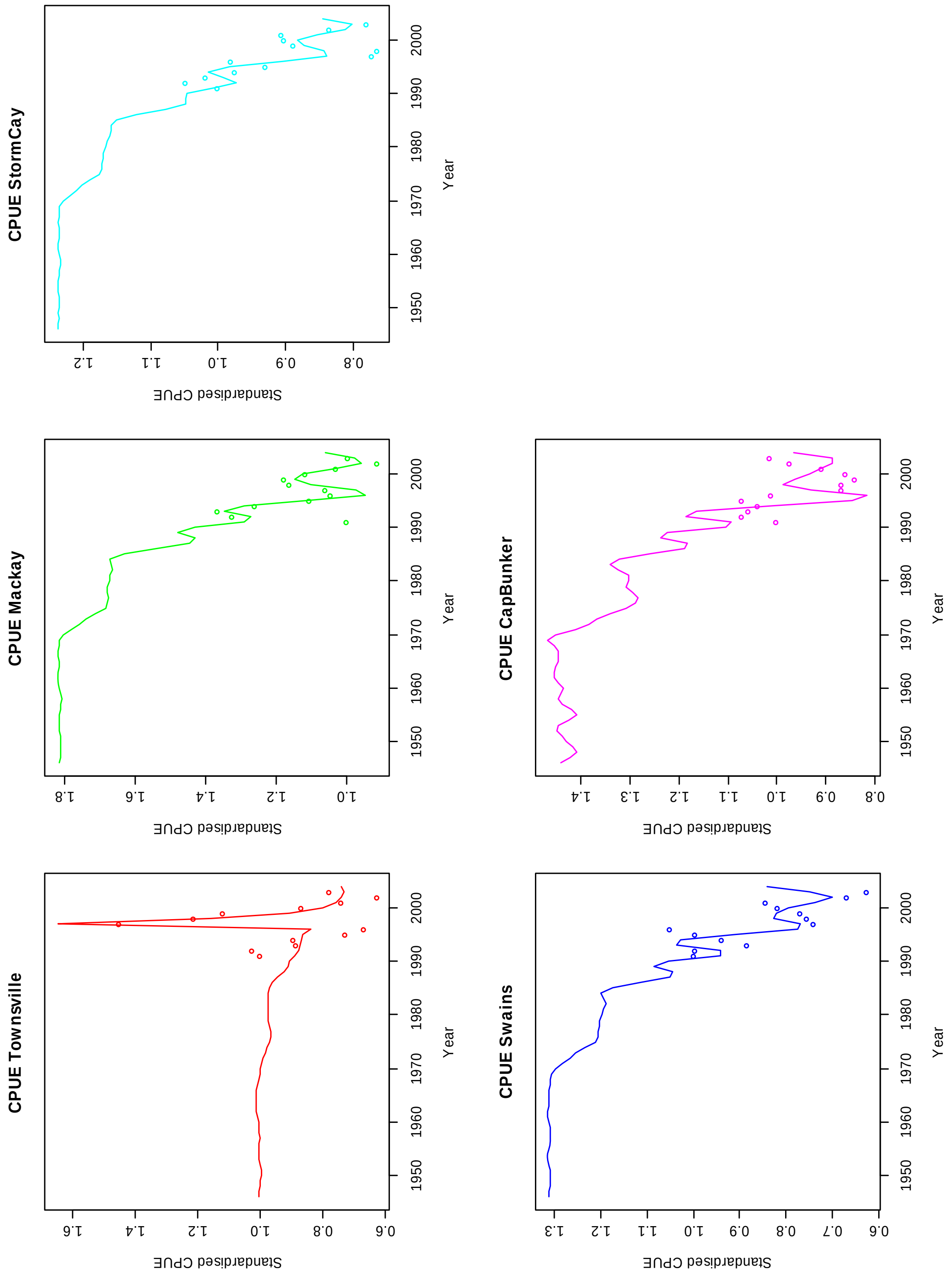

Figure 36: Observed (circles) and fitted (lines) standardised commercial catch per unit effort (CPUE, standardised to equal 1 in 1991) from the age-structured model.

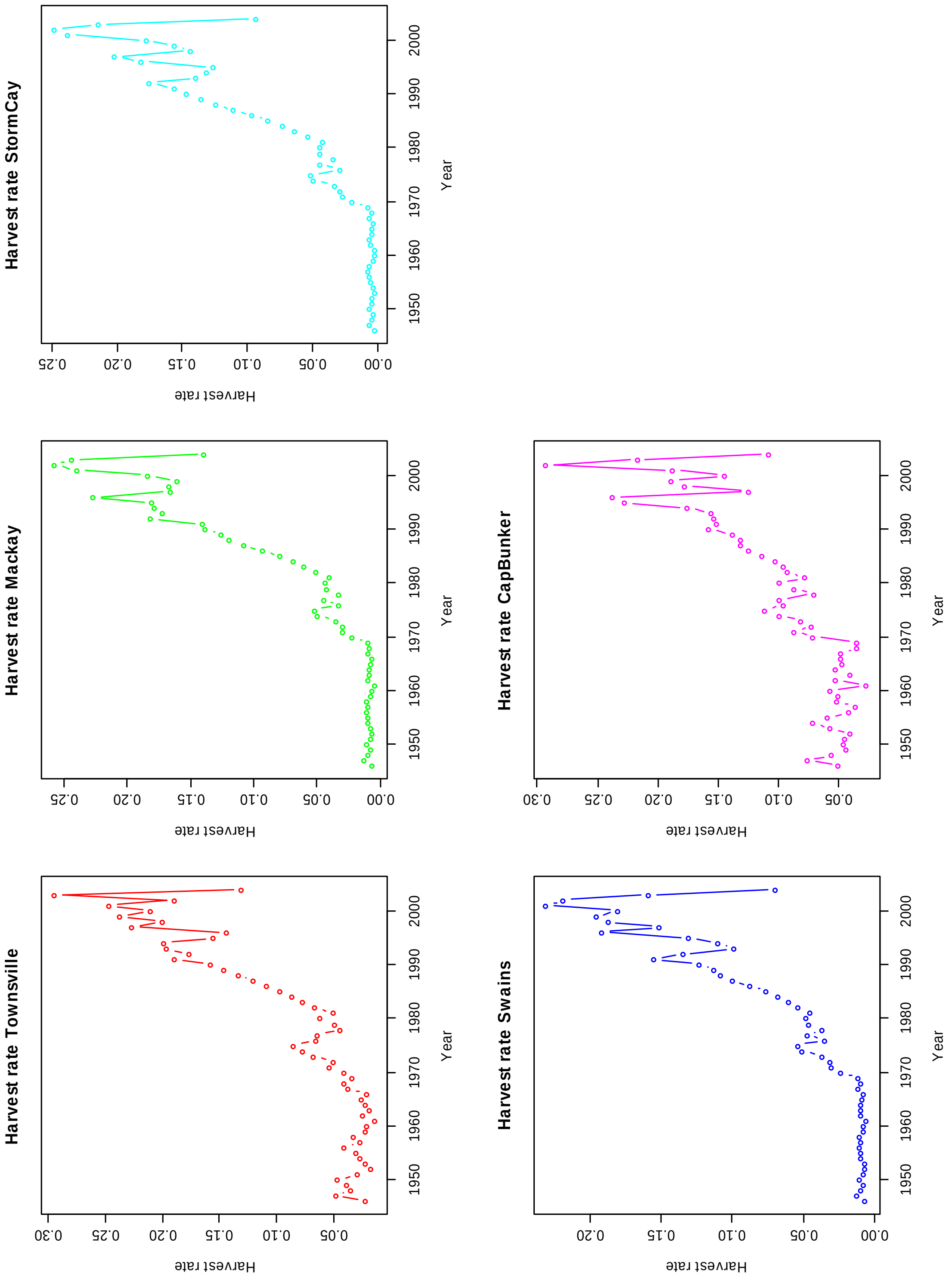

Figure 37: Estimated harvest rates (proportions of exploitable biomass that are harvested in each year) from the age-structured model.

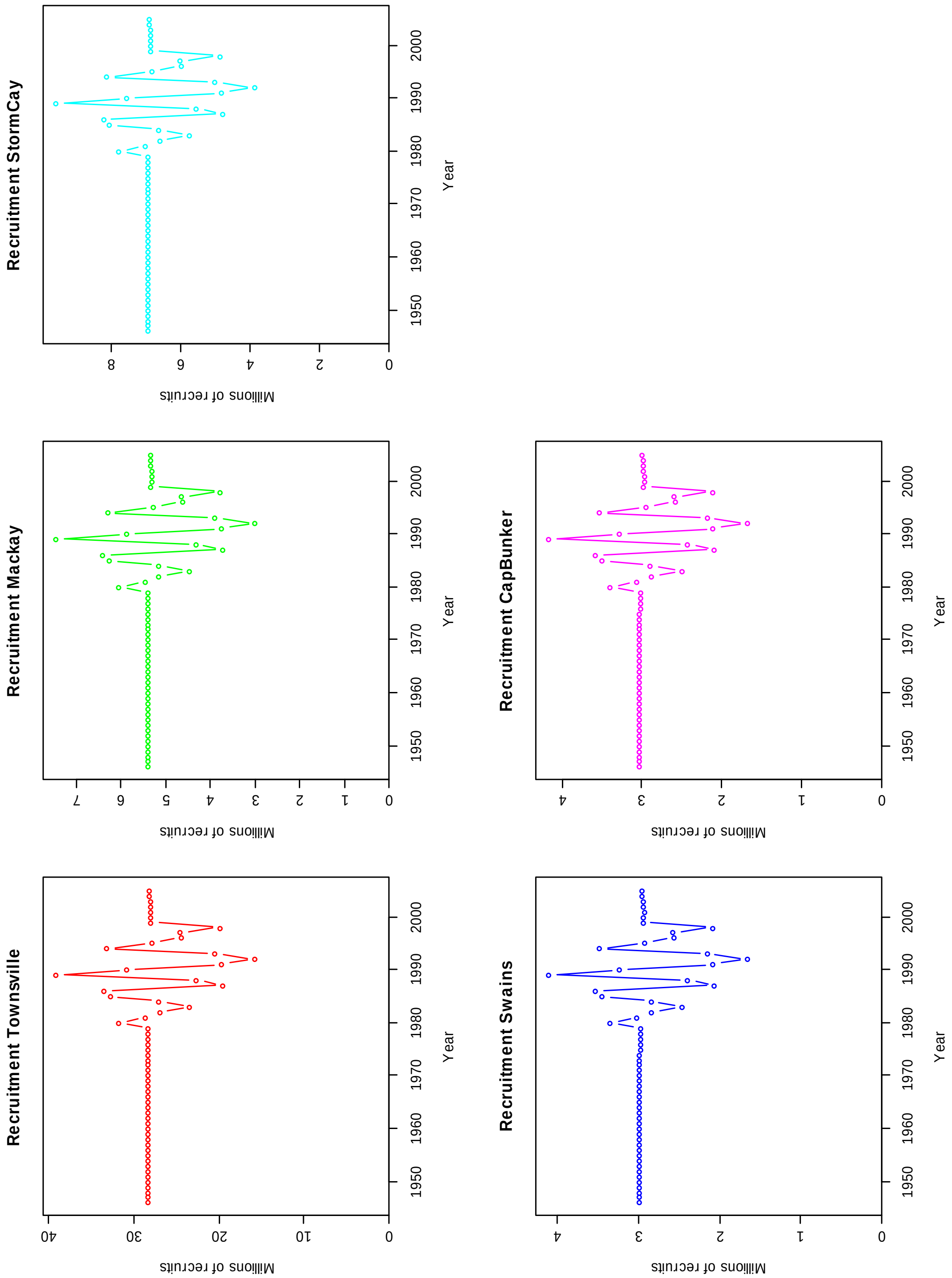

Figure 38: Estimated numbers of recruits in each year from the age-structured model.

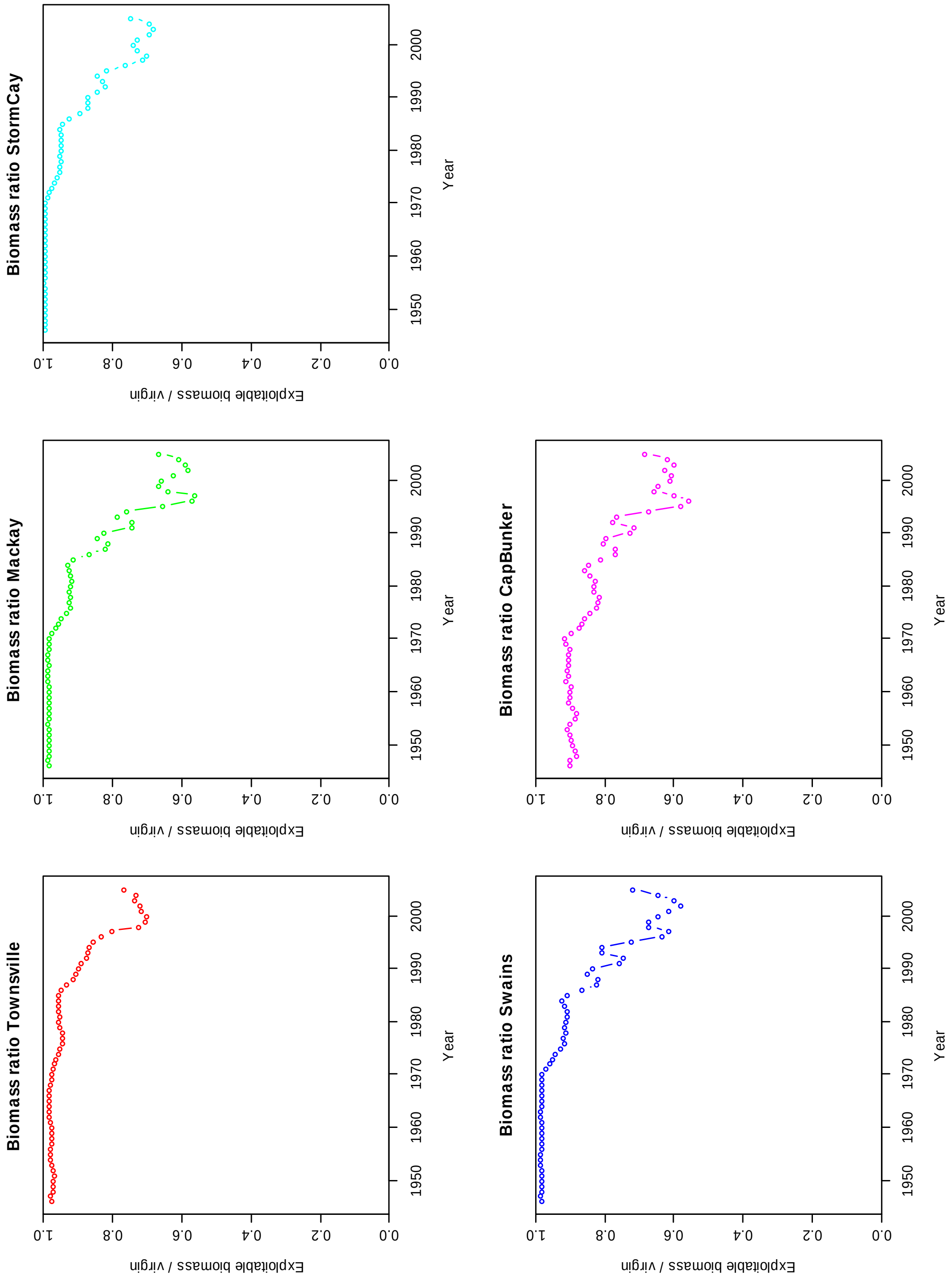

Figure 39: Estimated exploitable biomass in each year and region from the age-structured model.

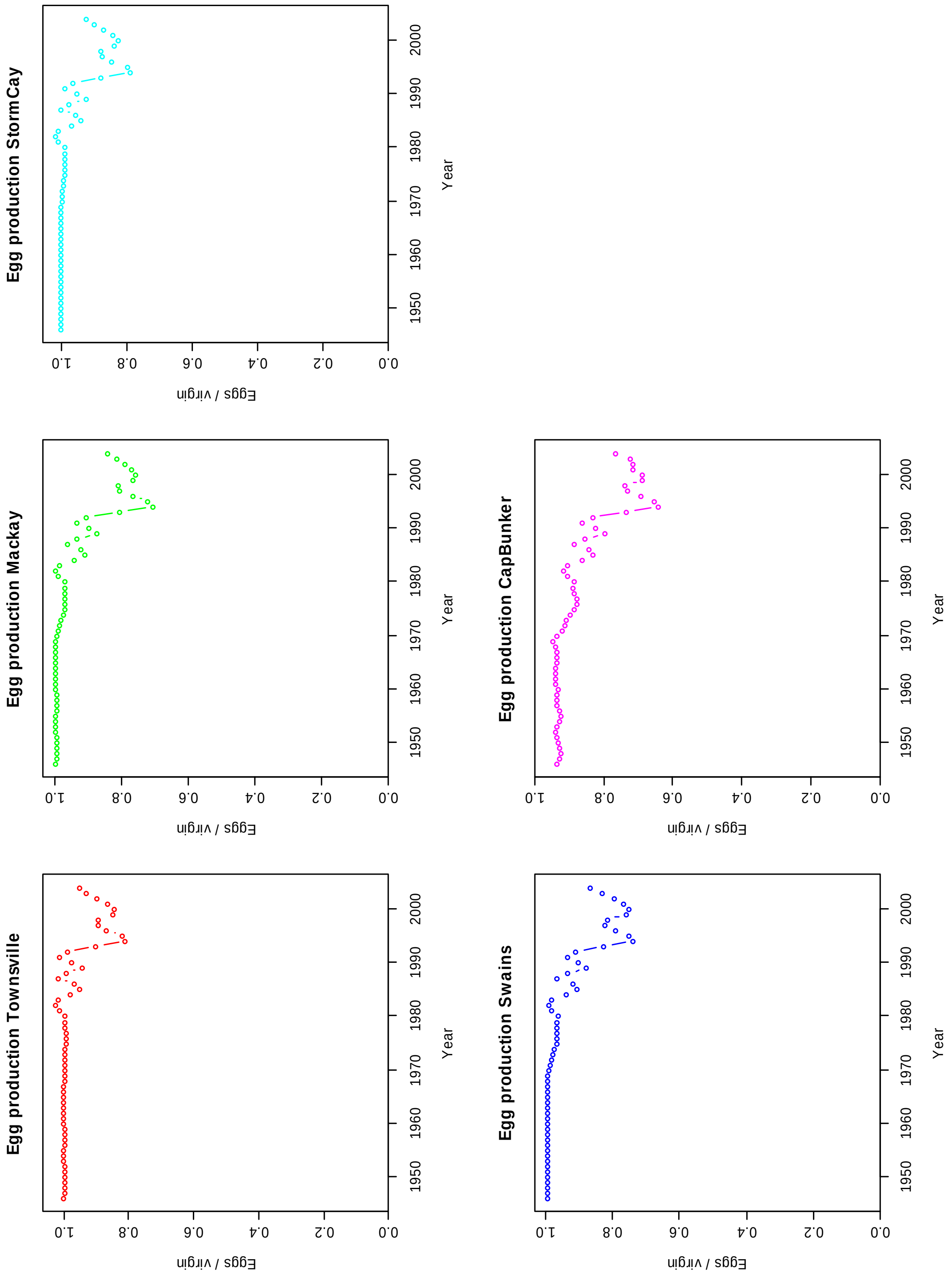

Figure 40: Estimated egg production, expressed as a fraction of virgin egg production, from the age-structured model.

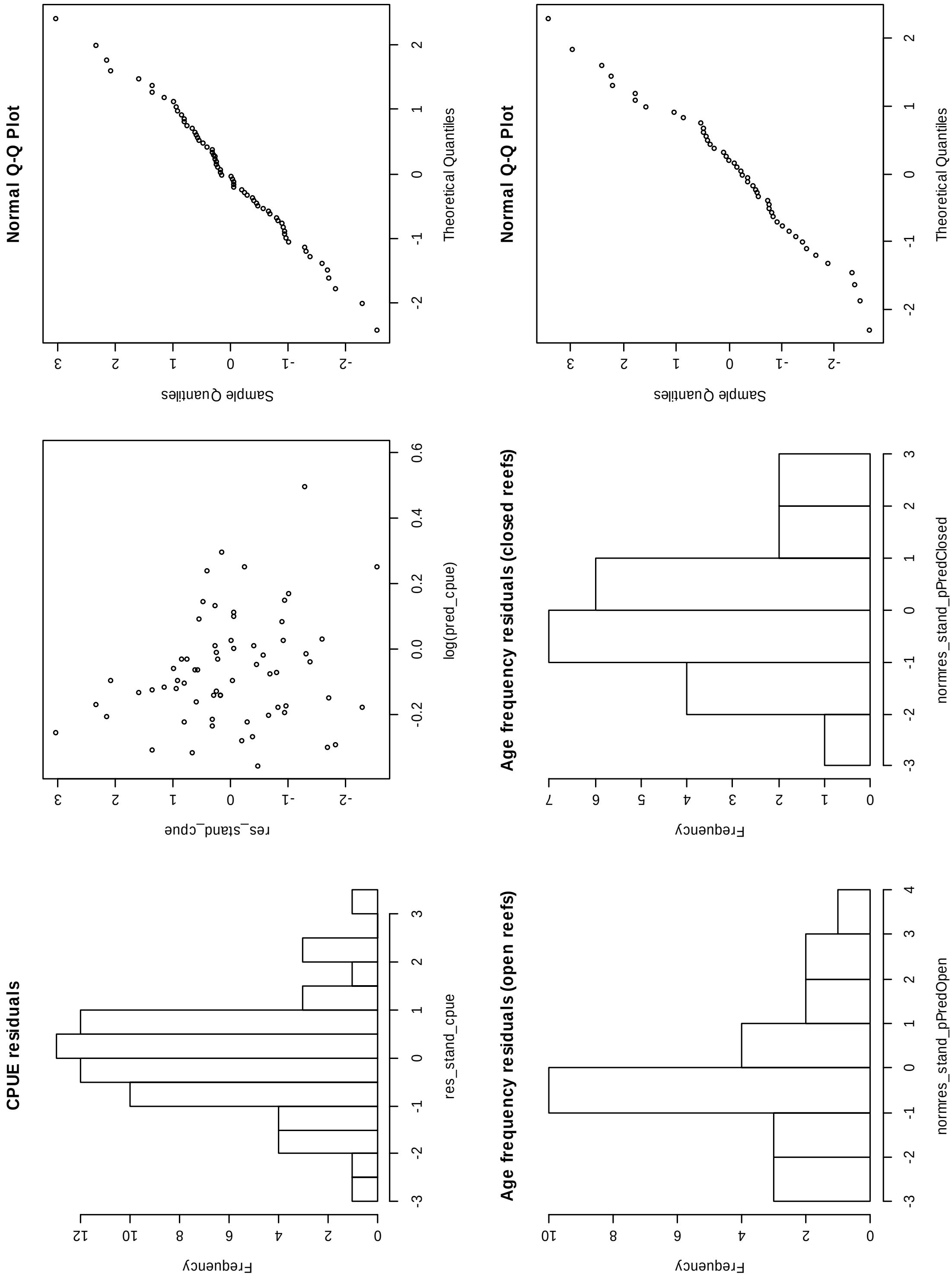

Figure 41: Plots of standardised residuals for fits to CPUE and age structure from the age-structured model.
CPUE (top row), age structure (bottom row), the top-middle chart is a plot of fitted values against residuals for CPUE. The right-hand charts are known as Q-Q plots and show quantiles of the residuals against quantiles of the standard normal distribution.

6.2.3 Future projections

For annual harvests of 1200 t in each year 2005–2024 (equivalent to a TACC of approximately the current level of 700 t), results are not much different to the current state. Small improvements in biomass and egg production may take place over the next 20 years (Figure 44 and Figure 45). These variables recover to about 80% and 90% respectively of their virgin levels. Harvest rates stay close to their peak levels in the Townsville, Mackay and Storm Cay regions, but are below peak levels in the Swains and Capricorn-Bunker regions (Figure 42).

Recruitment levels stay fairly constant on average, but are subject to substantial random variation (Figure 43). As stated above, the model did not find significant dependence of recruitment on stock size during the past history of the fishery; therefore the simulated future recruitment is much the same for all three levels of future annual harvest investigated. The forward projections do contain some dependence of recruitment on stock size through a non-infinite value of the parameter r_{max} (see Table 25), but projected population sizes do not fall to levels where this becomes important.

The 900 t annual harvest level (equivalent to about 400 t TACC) provides substantial improvements in biomass and egg production (Figure 47 and Figure 48). Egg production in particular recovers to about 100% of virgin. Harvest rates return to the levels that prevailed in the early 1990s (Figure 46).

At 1500 t annual harvest, the biomass declines to around 60–70% of virgin, but egg production remains at about 80% of virgin (Figure 50 and Figure 51). Harvest rates increase to historically high levels, especially in the Townsville and Mackay regions (Figure 49). Such high harvest rates would generally not be considered safe for a long-lived fish species. The model shows the fishery being sustainable at this harvest level, but sustainability could be put at risk by factors such as a series of poor recruitment years, or habitat degradation through coastal development pressure or global warming.

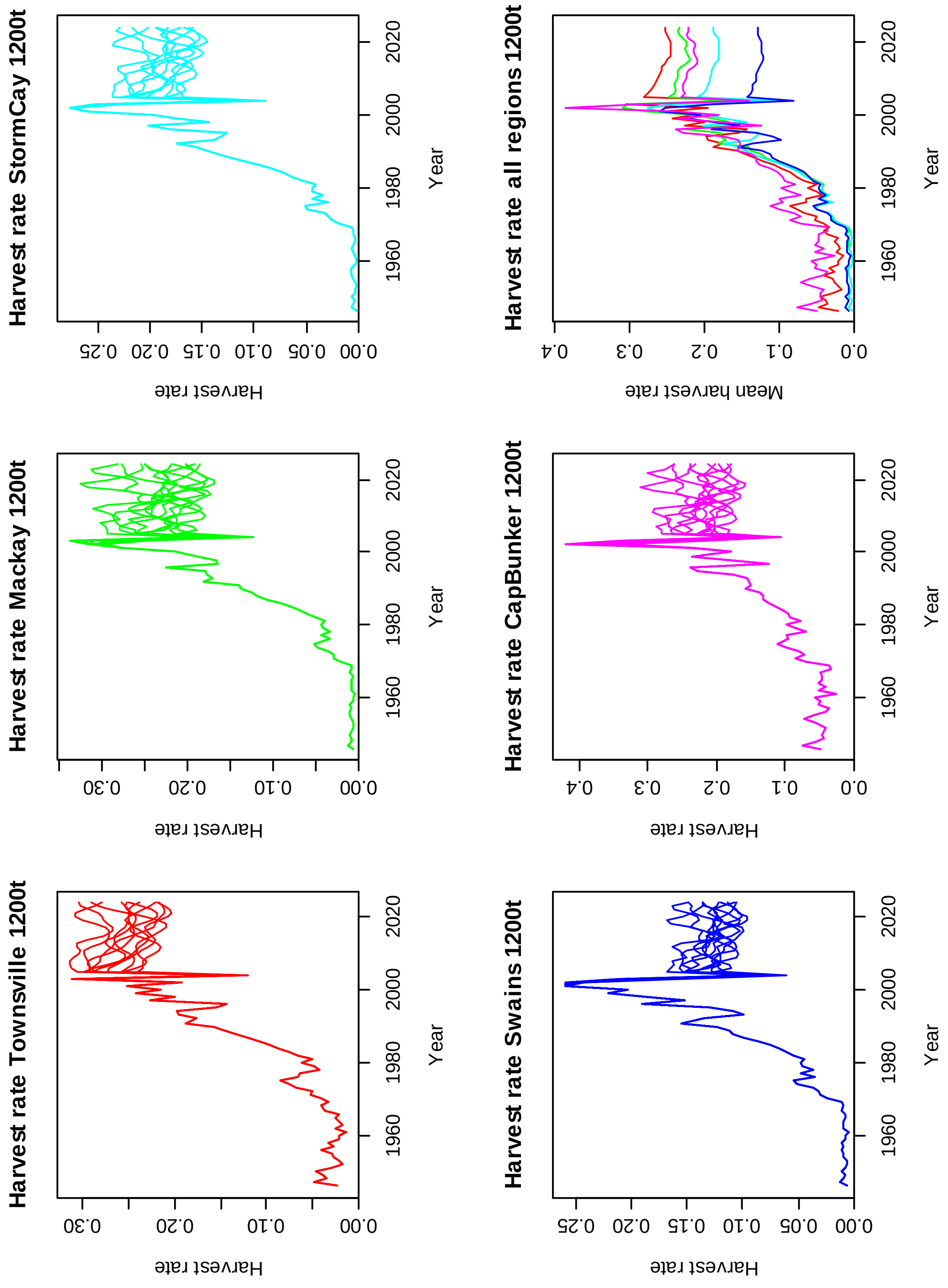

Figure 42: Trajectories of harvest rate 2005–2024 for annual harvests of 1200 t. Ten trajectories are simulated. The last graph is for the mean of the ten simulated trajectories, by region.

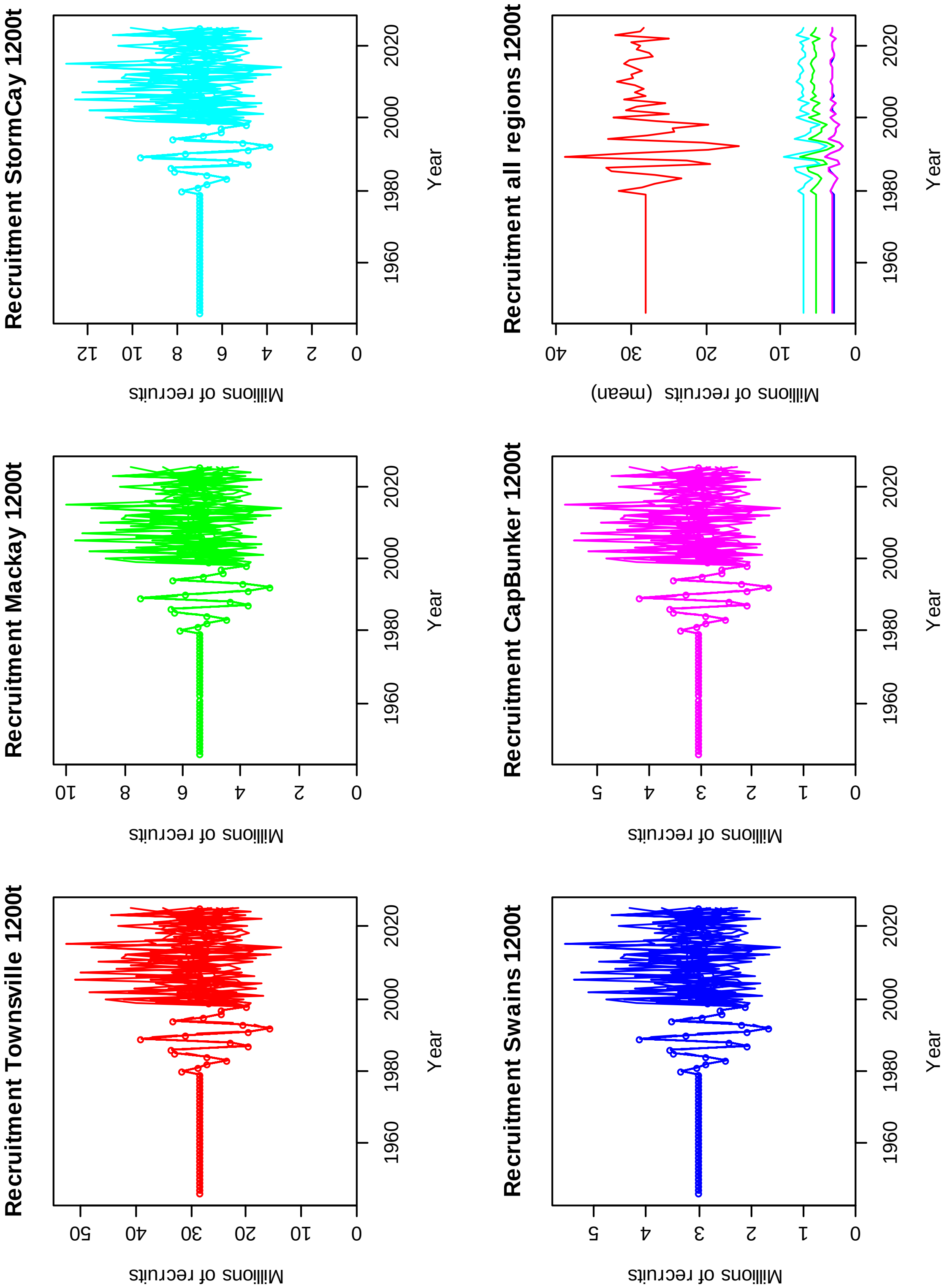

Figure 43: Trajectories of recruitment 2005–2024 for annual harvests of 1200 t.
Ten trajectories are simulated. The last graph is for the mean of the ten simulated trajectories, by region.

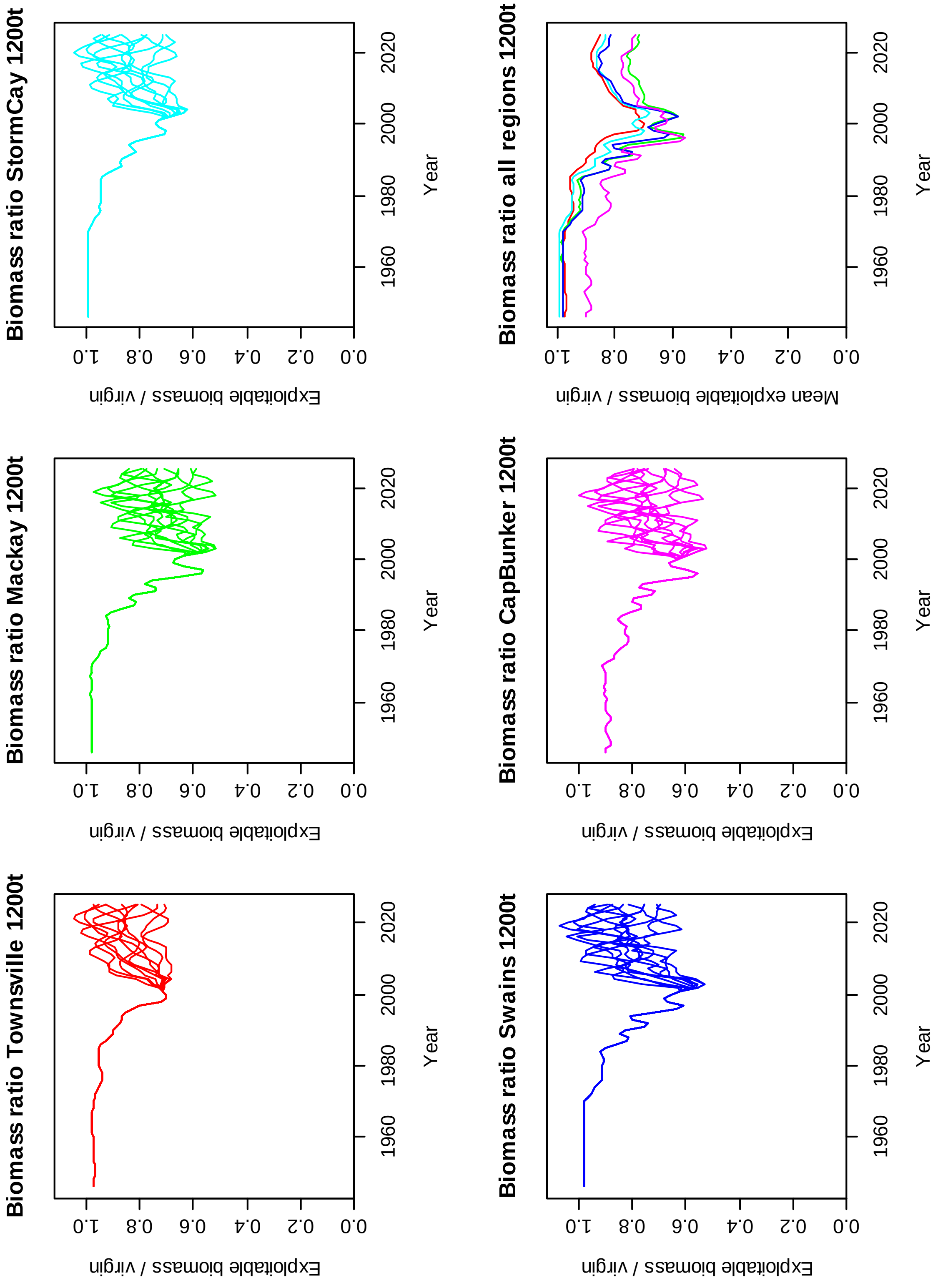

Figure 44: Trajectories of exploitable biomass 2005–2024 for annual harvests of 1200 t. Ten trajectories are simulated. The last graph is for the mean of the ten simulated trajectories, by region.

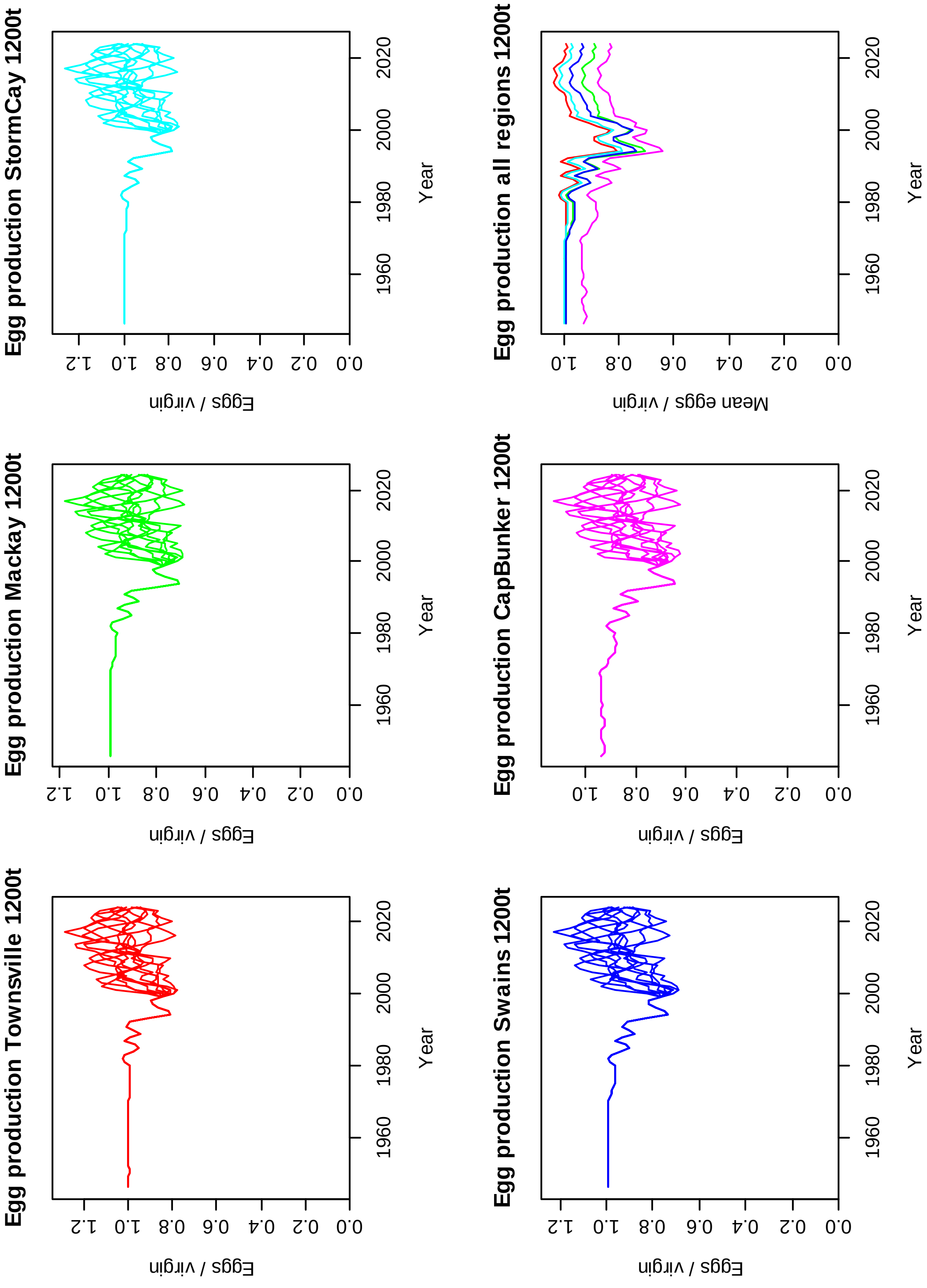

Figure 45: Trajectories of egg production 2005–2024 for annual harvests of 1200 t. Ten trajectories are simulated. The last graph is for the mean of the ten simulated trajectories, by region.

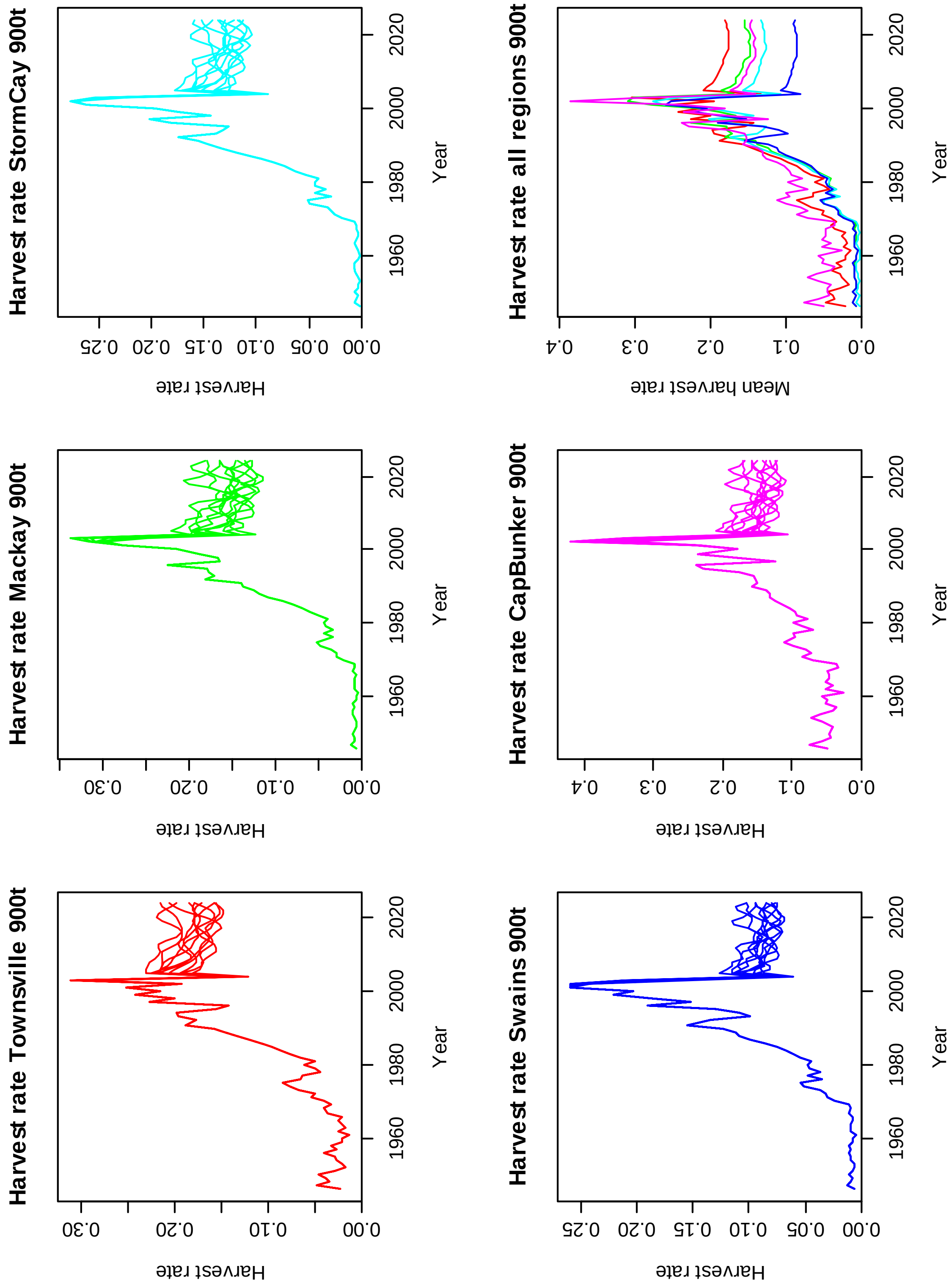

Figure 46: Trajectories of harvest rate 2005–2024 for annual harvests of 900 t. The last graph is for the mean of the ten simulated trajectories, by region.

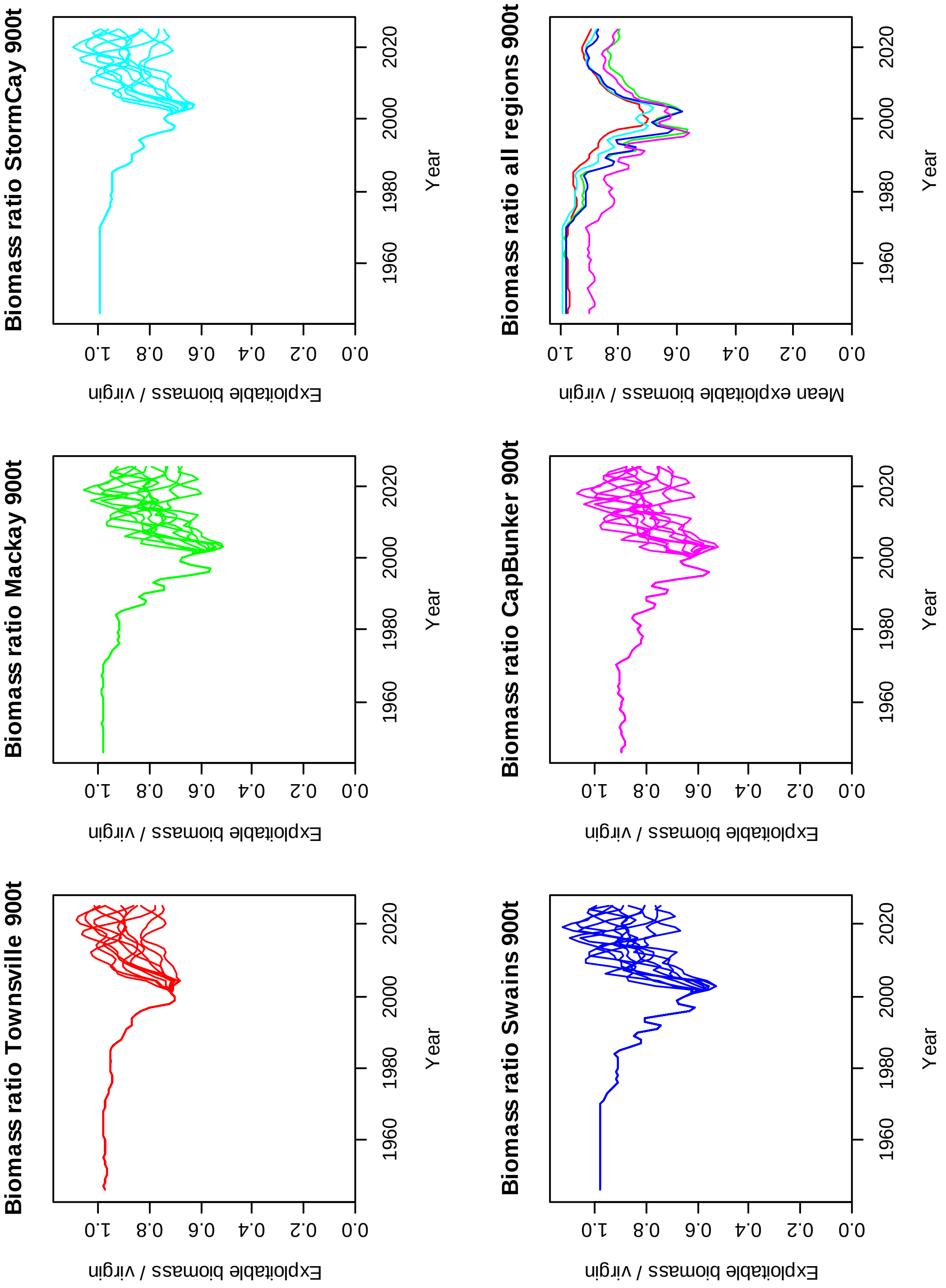

Figure 47: Trajectories of exploitable biomass 2005–2024 for annual harvests of 900 t. The last graph is for the mean of the ten simulated trajectories, by region.

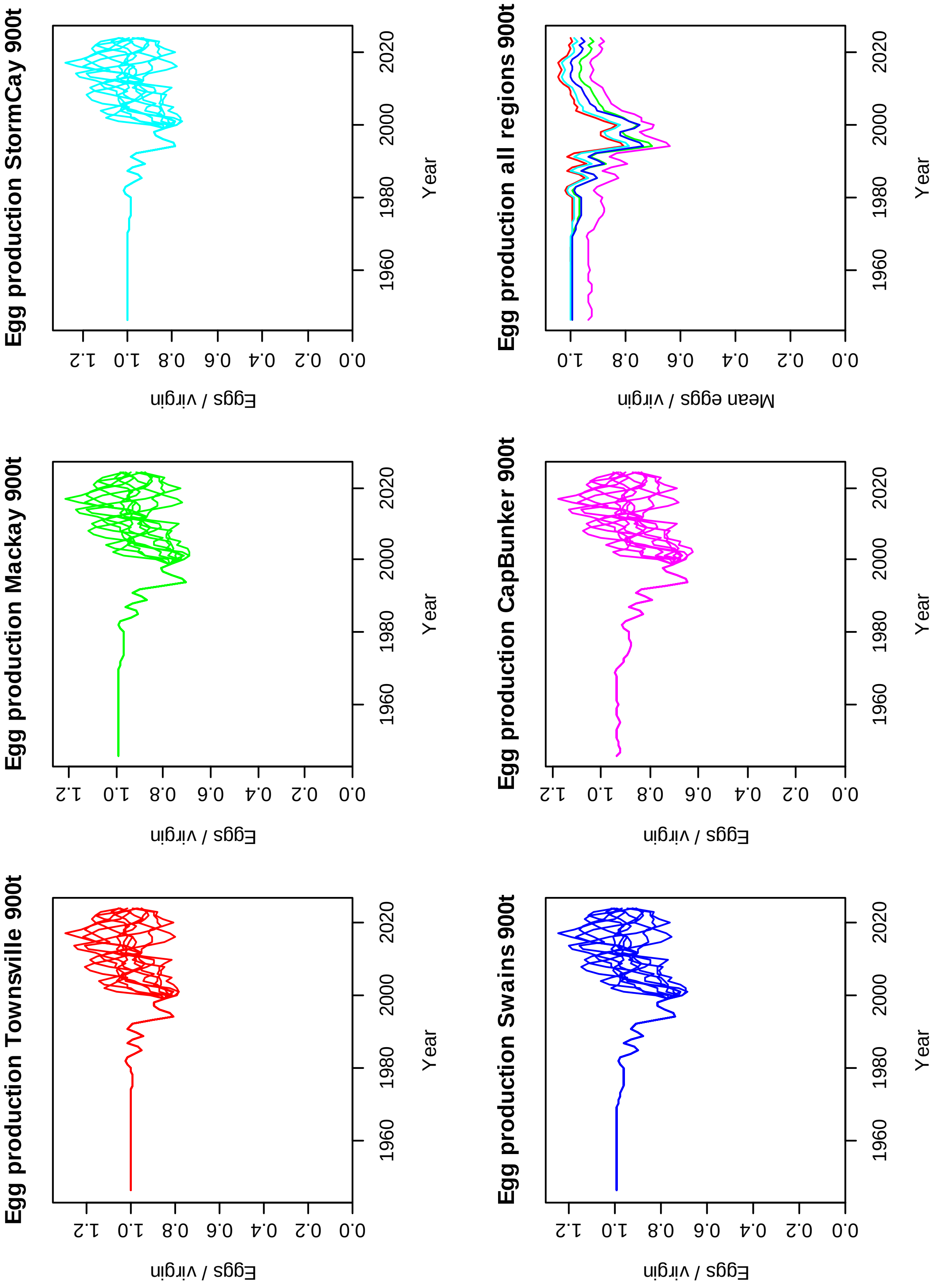

Figure 48: Trajectories of egg production 2005–2024 for annual harvests of 900 t. The last graph is for the mean of the ten simulated trajectories, by region.

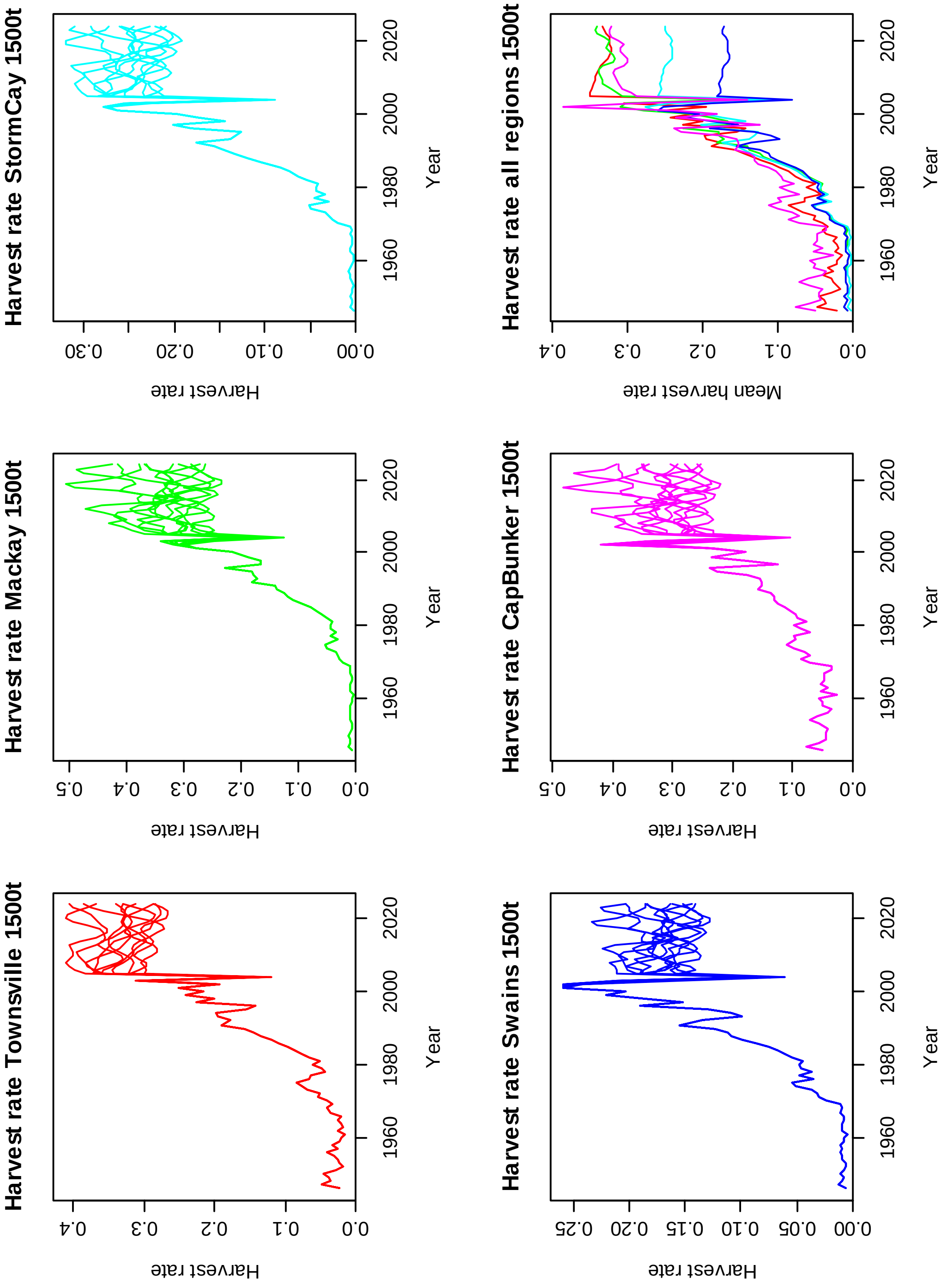

Figure 49: Trajectories of harvest rate 2005–2024 for annual harvests of 1500 t. The last graph is for the mean of the ten simulated trajectories, by region.

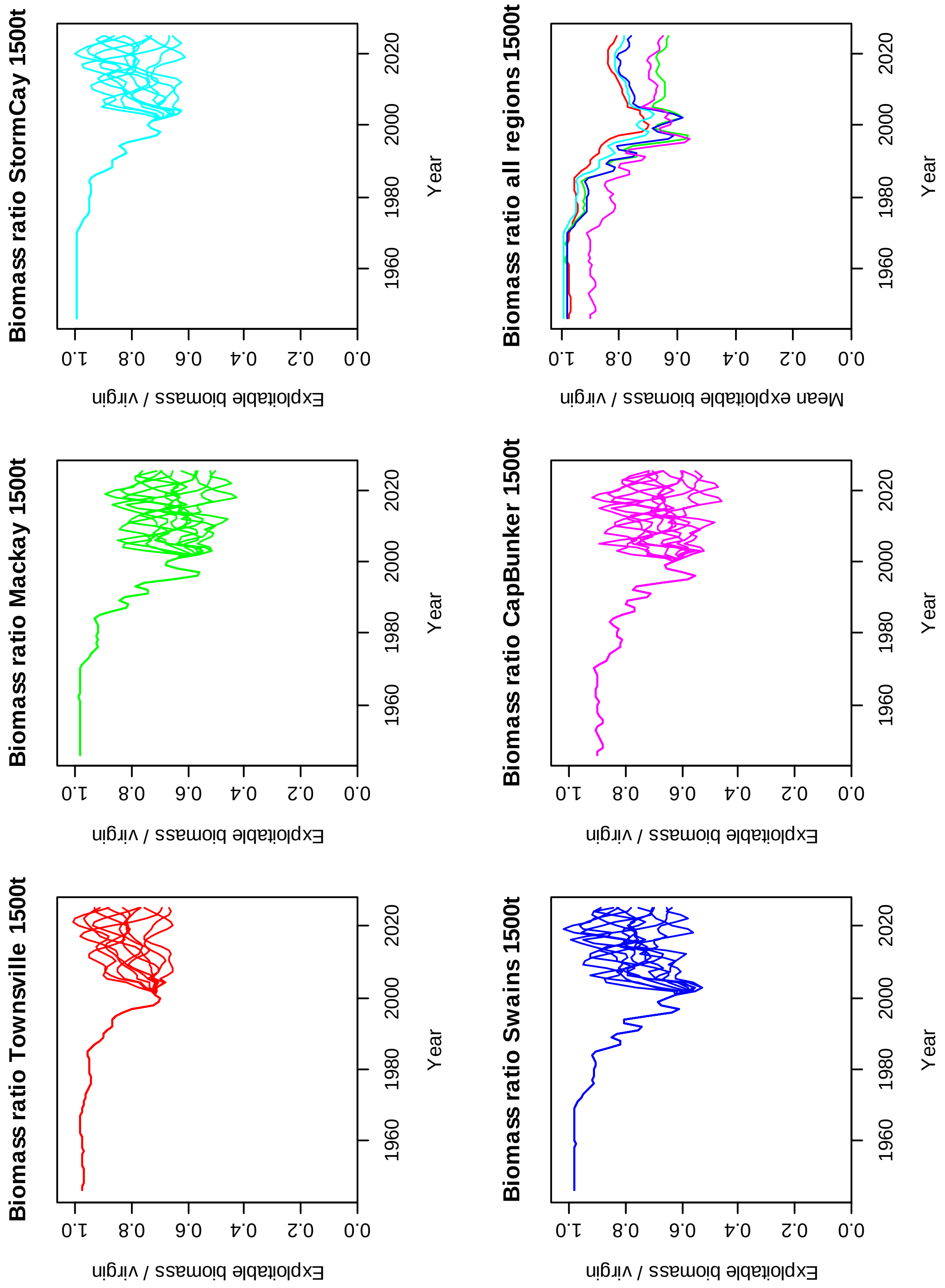

Figure 50: Trajectories of exploitable biomass 2005–2024 for annual harvests of 1500 t. The last graph is for the mean of the ten simulated trajectories, by region.

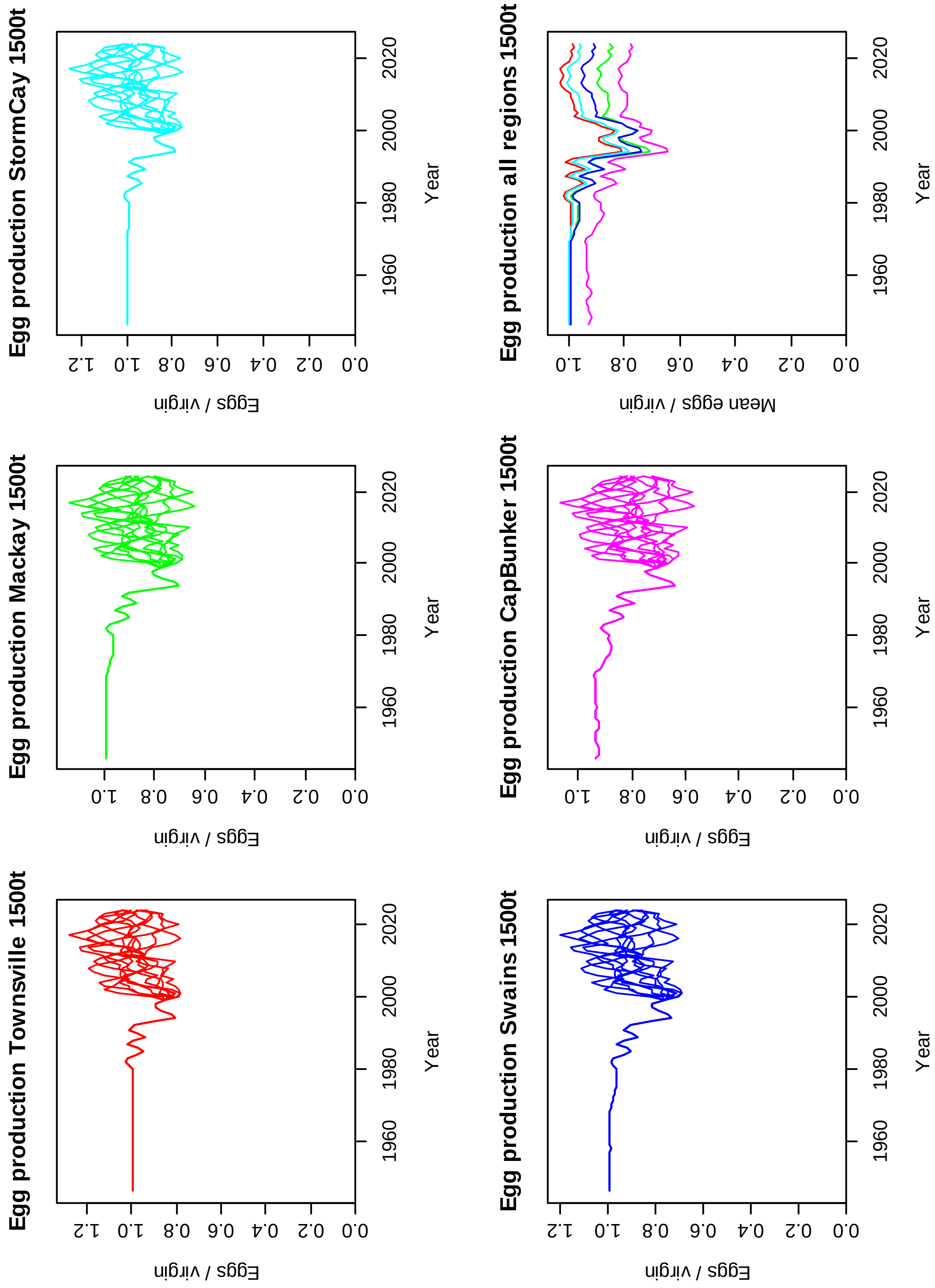

Figure 51: Trajectories of egg production 2005–2024 for annual harvests of 1500 t. The last graph is for the mean of the ten simulated trajectories, by region.

6.2.4 Sensitivity analysis for natural mortality and vulnerability

Parameter estimates for the case in which the instantaneous natural mortality rate M is fixed to 0.4 yr^{-1} are listed in Table 27. In contrast to the case of unconstrained M, the Richards parameter γ for the vulnerability curve did not approach infinity during convergence, and was included in the model, although its estimate is subject to high uncertainty.

Fixing M has had the effect of shifting the vulnerability curve (given by the a parameters) towards younger fish, thereby removing some of the security provided by having much of the population protected from fishing. The change can be seen clearly in Figure 52, where the new curves for the Townsville and Storm Cay regions asymptote to 1 more quickly than in Figure 35. There is little change in the Mackay, Swains and Capricorn-Bunker regions where vulnerability already asymptotes to 1 quite quickly in Figure 35. The estimates of virgin recruitment levels (N_0 parameters in Table 27) are lower in all regions than the values listed in Table 26, which is to be expected if the proportion of fish that are unavailable to fishing is less. Harvest rates (Figure 53) are higher than those in Figure 37 in the Swains and Capricorn-Bunker regions, which is to be expected from the smaller population sizes. Harvest rates are lower in the Townsville, Mackay and Storm Cay regions because harvest rate is defined in terms of *exploitable* biomass and more young fish have become available to fishing in these regions.

Results for the case with $M = 0.4\ \text{yr}^{-1}$ are generally less optimistic than those given for freely-varying M in Section 6.2.2. The biomass in the Mackay, Swains and Capricorn-Bunker regions now falls to around 45% of virgin in recent years, compared to about 60% (Figure 54 versus Figure 39). The difference is barely noticeable in the Townsville and Storm Cay regions because, in the face of lower M, the model has preserved the age structure in these regions by changing the vulnerability curve instead of the fishing mortality rate. Egg production shows less change, falling to about 75% of virgin in the Mackay and Swains regions (compared to 80%), and about 60% in Capricorn-Bunker (compared to 75%) (Figure 55 versus Figure 40).

Future projections show a slightly lesser recovery in biomass for the 1200 t and 900 t annual harvests than for freely-varying M (Figure 56 and Figure 57 versus Figure 44 and Figure 47). Results for 1500 t harvest show a continued decline in biomass in the Mackay and Capricorn-Bunker regions, compared to a possible slight recovery for the base case (Figure 58 versus Figure 50).

This case provides a much worse fit to the data than the case of estimating M by maximum likelihood, implying that, all other things being equal, the maximum-likelihood results should be preferred. The value of the minimised negative-log-likelihood was 481.37 compared to 511.84 for the results described in Section 6.2.2, a difference of 20.47 with an identical number of model parameters (33) in each case. As a comparison, when one model is a subset of another and contains less parameters, asymptotic likelihood theory states that twice the difference in negative-log-likelihood approximates a χ_ν^2 distribution where ν is the difference in the number of parameters: a difference of 20.47 could be expected if the test case contained about 41 fewer parameters than the base case, but in fact the number of parameters is the same.

Table 27: Parameter estimates for the age-structured model with instantaneous natural mortality rate M *fixed to 0.40* yr^{-1}*.*

Standard errors from the log-likelihood Hessian matrix are given. The parameter γ *was subject to high uncertainty and no standard error is available for it.*

Parameter	**Units**	**Value**	**S.e.**
$a_{05\ \mathrm{diff}\ 1}$	yr	3.7040	0.4328
$a_{05\ \mathrm{diff}\ 2}$	yr	1.2259	0.3987
$a_{05\ \mathrm{diff}\ 3}$	yr	2.0907	0.5532
$a_{05\ \mathrm{diff}\ 5}$	yr	0.3065	0.2500
$a_{50\ 1}$	yr	7.1191	0.1636
$a_{50\ 3}$	yr	3.9450	0.3117
$a_{05\ \mathrm{diff}\ 1\ 1997}$	yr	1.5059	0.7085
$a_{50\ 1\ 1997}$	yr	4.5554	0.3987
γ	–	11.3174	–
$N_{0\ 1}$	10^7 fish	0.8723	0.2269
$N_{0\ 2}$	10^7 fish	0.2224	0.0210
$N_{0\ 3}$	10^7 fish	0.2551	0.0823
$N_{0\ 4}$	10^7 fish	0.1209	0.0164
$N_{0\ 5}$	10^7 fish	0.1420	0.0120
log recres_{1980}	–	–0.1873	0.3481
log recres_{1981}	–	–0.2007	0.3346
log recres_{1982}	–	–0.1873	0.3149
log recres_{1983}	–	–0.2657	0.3029
log recres_{1984}	–	–0.0969	0.2735
log recres_{1985}	–	0.1250	0.2326
log recres_{1986}	–	0.1660	0.2113
log recres_{1987}	–	–0.3667	0.2646
log recres_{1988}	–	–0.2586	0.2293
log recres_{1989}	–	0.3445	0.1453
log recres_{1990}	–	0.1227	0.1594
log recres_{1991}	–	–0.2962	0.2048
log recres_{1992}	–	–0.4785	0.2224
log recres_{1993}	–	–0.2805	0.2022
log recres_{1994}	–	0.2037	0.1588
log recres_{1995}	–	0.0809	0.1877
log recres_{1996}	–	–0.0511	0.2183
log recres_{1997}	–	–0.1126	0.2458
log recres_{1998}	–	–0.1301	0.2480

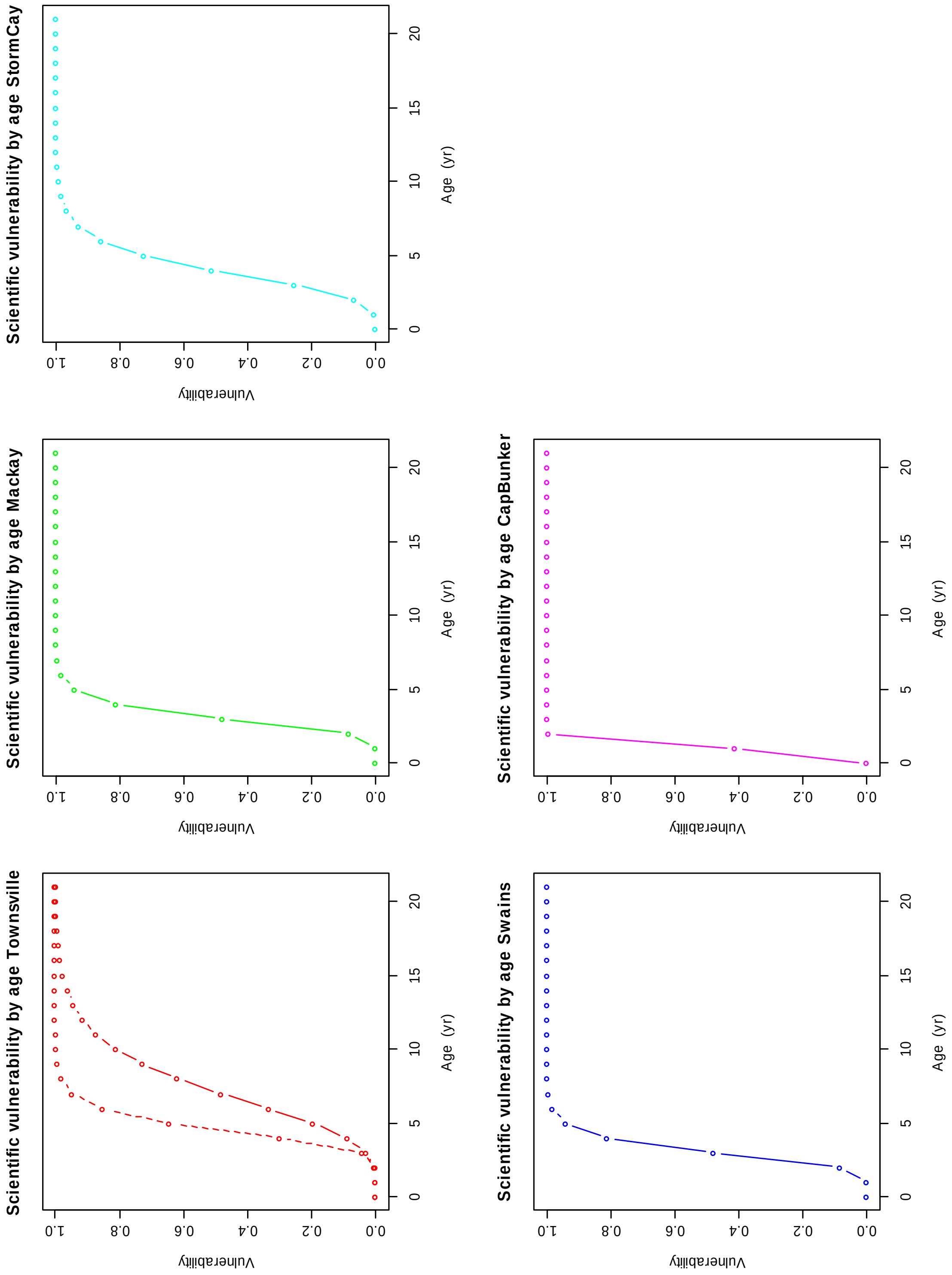

Figure 52: Estimated vulnerability of red throat emperor to scientific sampling, by age and region, with natural mortality rate M *fixed to 0.4* yr^{-1}.
The dotted line in the plot for the Townsville region is the curve in 1997, changed by Cyclone Justin. (Cf. Figure 35.)

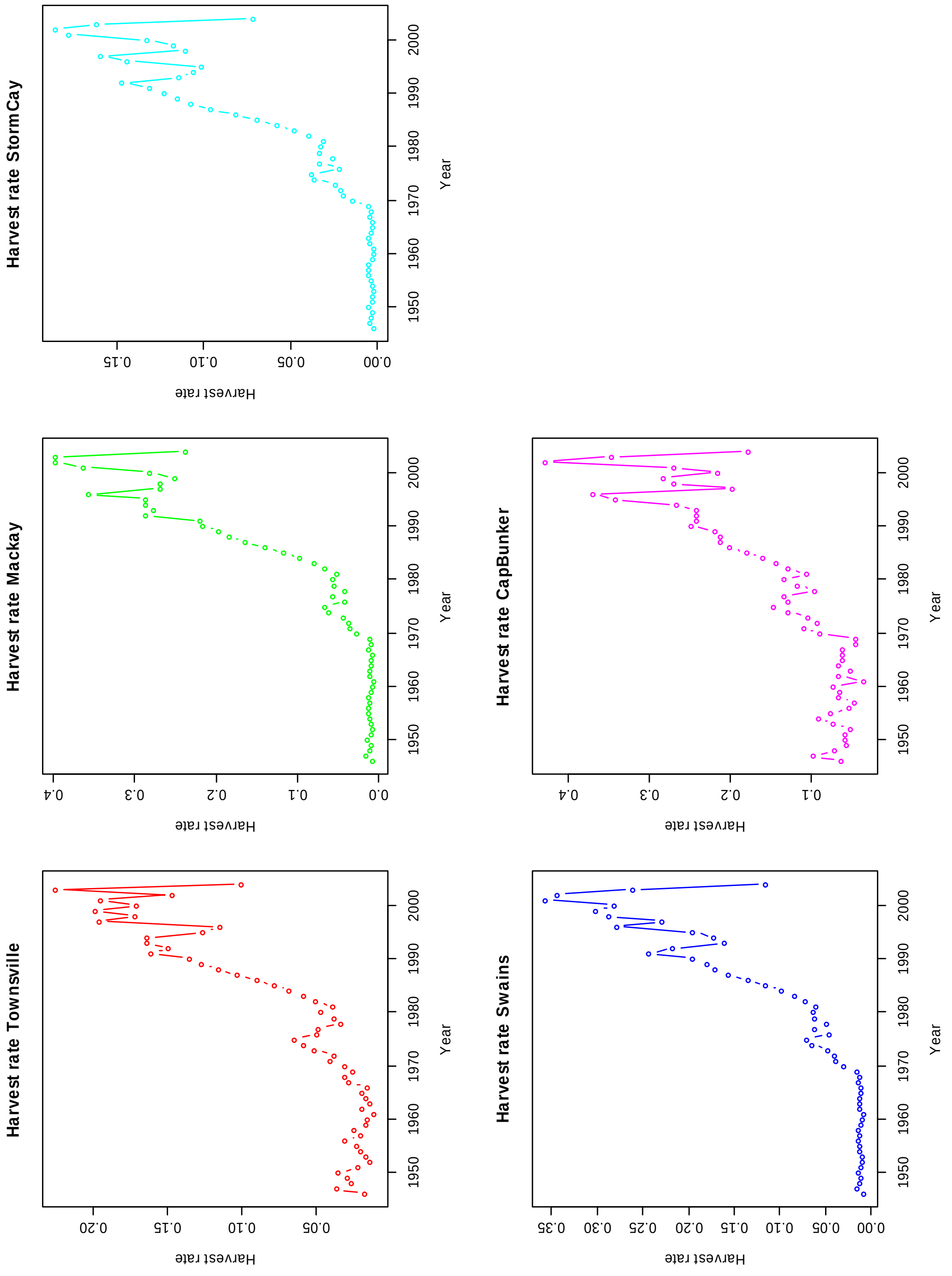

Figure 53: Estimated harvest rates from the age-structured model with natural mortality rate M *fixed to 0.4* yr^{-1}.
(Cf. Figure 37)

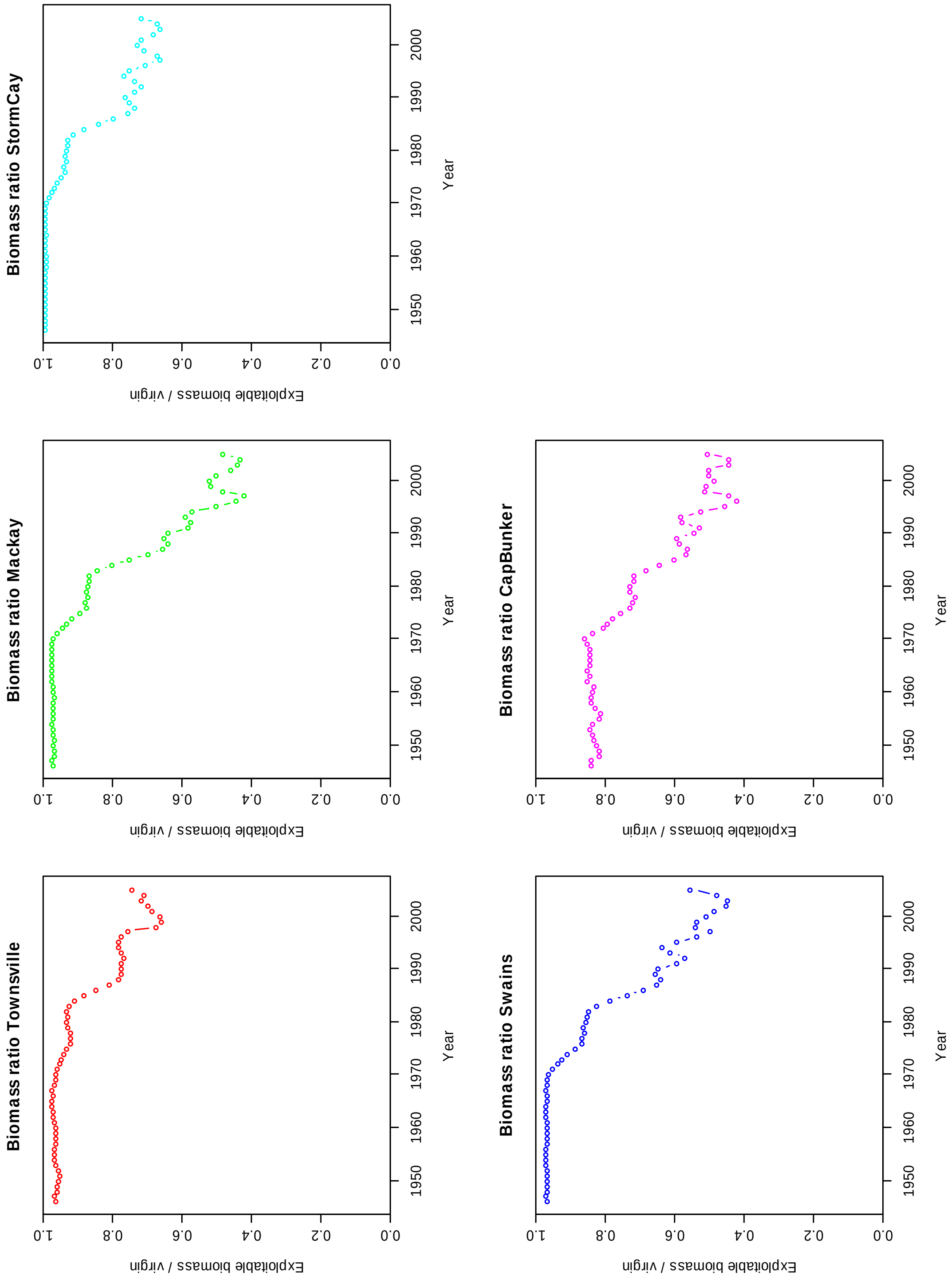

Figure 54: Estimated exploitable biomass in each year and region from the age-structured model with natural mortality rate M *fixed to 0.4 yr*$^{-1}$.
(Cf. Figure 39)

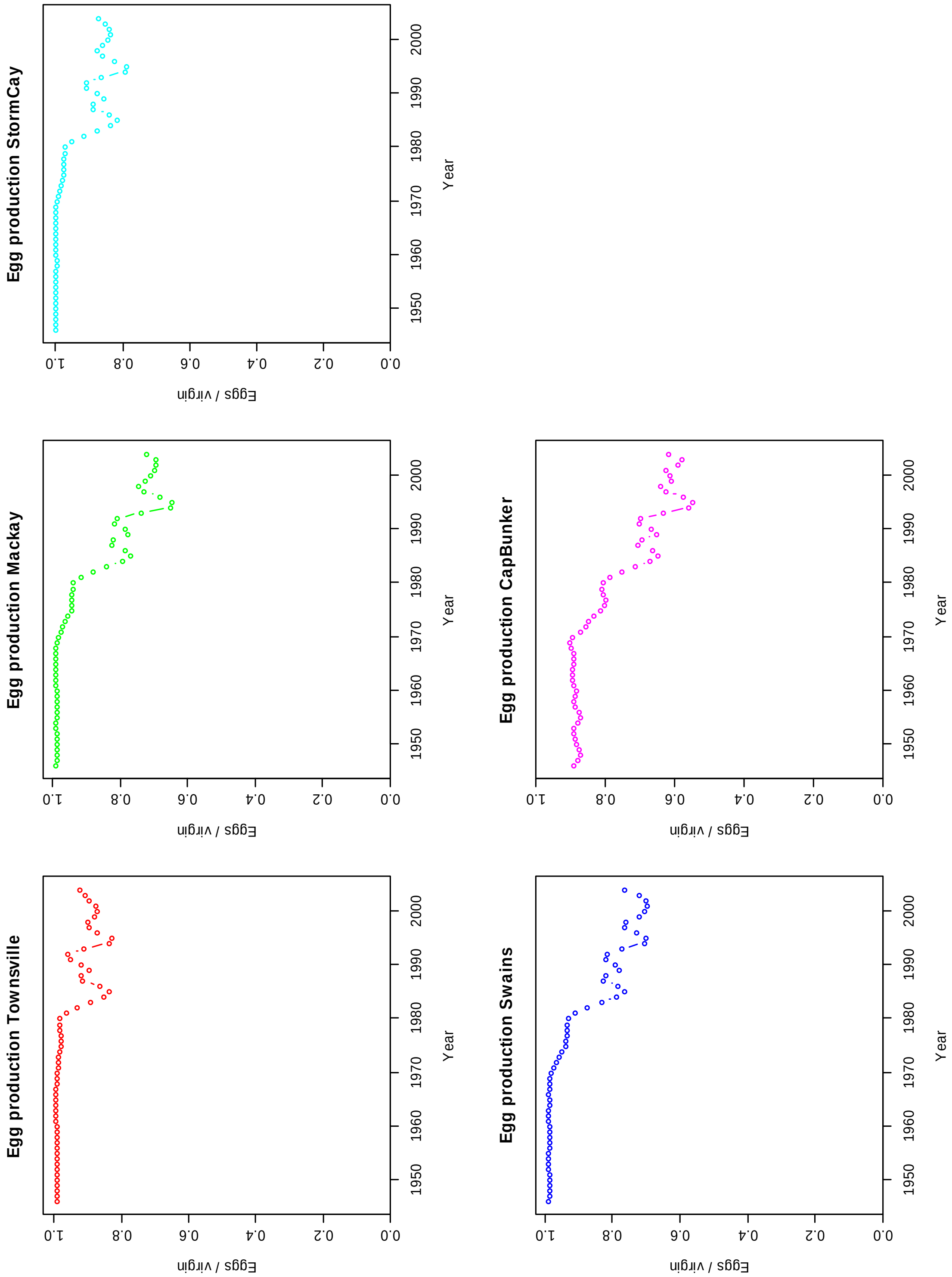

Figure 55: Estimated egg production, expressed as a fraction of virgin egg production, for the age-structured model with natural mortality rate M *fixed to 0.4 yr*$^{-1}$.
(Cf. Figure 40)

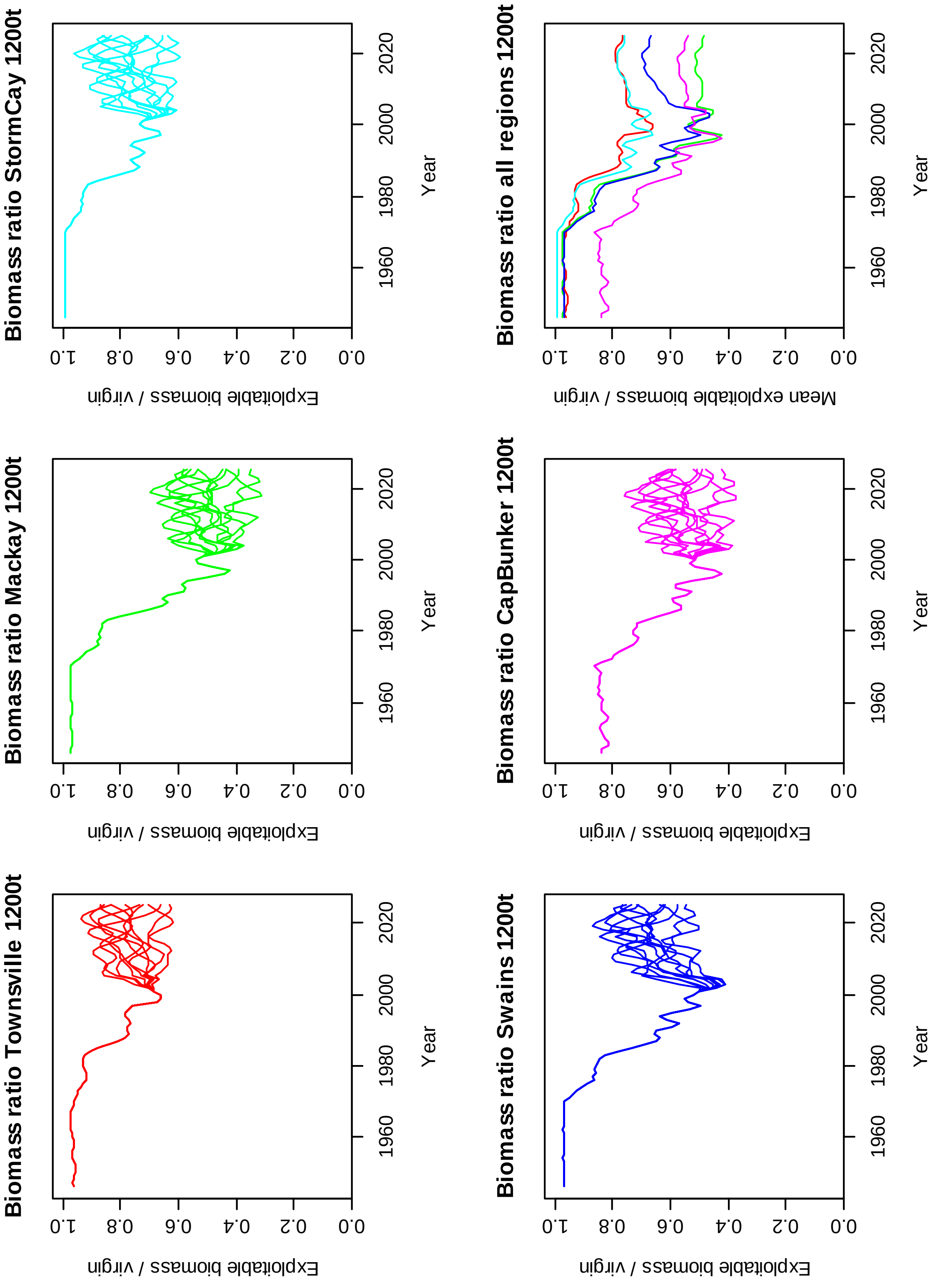

Figure 56: Trajectories of exploitable biomass 2005–2024 for annual harvests of 1200 t, natural mortality rate M *fixed to 0.4 yr*$^{-1}$.
(Cf. Figure 44)

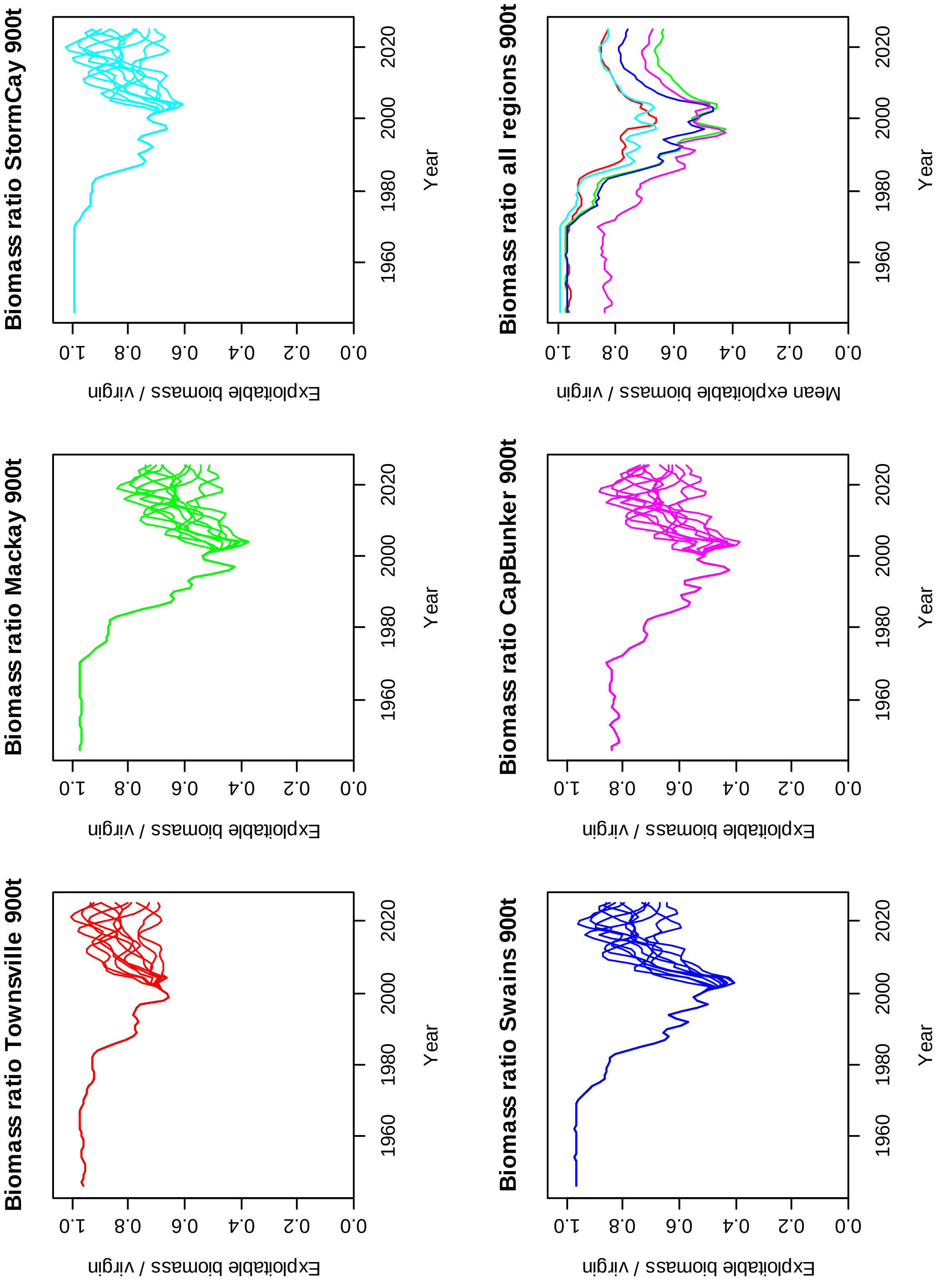

Figure 57: Trajectories of exploitable biomass 2005–2024 for annual harvests of 900 t, natural mortality rate M *fixed to 0.4 yr*$^{-1}$.
(Cf. Figure 47)

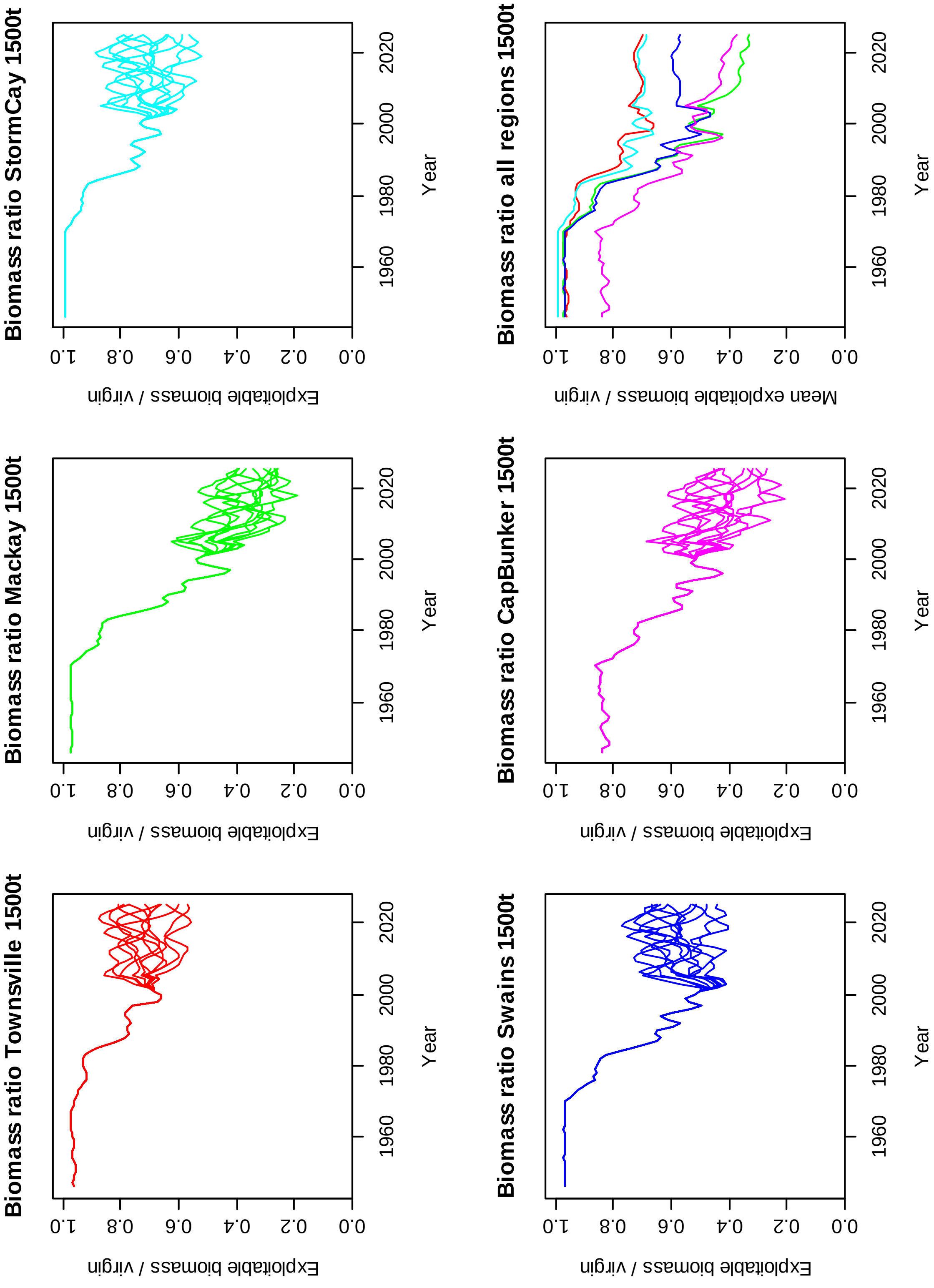

Figure 58: Trajectories of exploitable biomass 2005–2024 for annual harvests of 1500 t, natural mortality rate M *fixed to 0.4 yr*$^{-1}$.
(Cf. Figure 50.)

6.2.5 Sensitivity analysis for historical catch level and post-release mortality

The runs for different levels of historical catch produced results that were almost identical to those of the main analysis. Harvest rates were slightly lower in the case of the higher historical catches, but trends in biomass and recruitment were identical.

The results are therefore insensitive to the level of historical catch. We note that this conclusion also implies that the decision to classify the unspecified emperor as red throat emperor up to 1981 (Section 3.1.2 and Figure 10) has had little effect on the results of the analysis.

The reliability of the historical catch data varied somewhat between regions. As stated in Section 3.1.2, the Mackay, Storm Cay and Swains regions could not be distinguished in the Queensland Fish Board data (which ran up to 1981), because data were categorised only by port of landing. The allocation of catch among these three regions is therefore subject to considerable uncertainty. The sensitivity analysis shows, however, that the magnitude of catches up to 1981 is small enough that any reasonable changes would make little difference to the results of this assessment.

From 1991 onwards, we believe that the commercial catch data (from the CFISH database) are quite accurate, and that the reliability varies little among regions. For the period 1982–1991 there are no data, and we have interpolated them linearly from the averages of 1980–1981 and 1991–1992. Catch from all regions except Capricorn-Bunker increased greatly over this period. Therefore the catch from the Capricorn-Bunker region is probably insensitive to this missing data, but catches from all other regions may be sensitive to the trajectories by which the catch increased (whether it mainly happened early or late in the period).

For post-release mortality, the numbers given in Section 3.3 for release rates in the commercial sector imply that up until the end of 2003, out of every 100 kg of red throat emperor caught, 93 kg was retained; from 2004 onwards only 84 kg was retained. The ratio of these values is 93/84 = 1.107, meaning that an extra 10.7 kg of fish were caught for every 100 kg retained. Assuming a post-release mortality rate of 30% gives an extra 3.2 kg of fish that die for every 100 kg retained.

Therefore the effect of a 30% post-release mortality is to reduce the total harvest by a factor of 1 / 1.032 = 0.969 for the same effect on the population as fishing would have had under the old minimum legal size of 350 mm.

The result is that a TAC would have to be reduced by about 3%: instead of 1200 t, 900 t and 1500 t total harvest, the future projections of Section 6.2.3 would occur with harvests of 1163 t, 872 t and 1453 t respectively.

Post-release mortality therefore appears to have had only a small effect on the predictions, assuming that the change in commercial release rates is also representative of the recreational and charter sectors.

Post-release mortality will have a much bigger effect if the human population and the tourism sector in the region of the Great Barrier Reef grow strongly in the future. The recreational sector is currently managed by a minimum size limit and a bag limit. If these had to be tightened to maintain the size of the recreational harvest, we would expect the release rate of reef fish to increase substantially, and post-release mortality to become much more important. Such tightening is already happening in many recreational fisheries in other parts of the world.

There are few management options for limiting recreational fishing *effort* in fisheries (including the effort that goes into catching fish that are then released). Increases in effort must, in the long term, lead to increases in the release rate and consequently greater importance of post-release mortality.

6.2.6 Size-dependent vulnerability

The conversion of the vulnerability curves from age to length gave the parameter values listed in Table 28 and the fits plotted in Figure 59. For four of the five regions the logistic length-dependent vulnerability converged to a 'knife-edge' that has zero vulnerability below a certain length and 100% above it. Fits to the age-dependent vulnerability are good for the Mackay, Swains and Capricorn-Bunker regions, but show deficiencies for the Townsville and Storm Cay regions. The fit for Townsville is especially poor.

It therefore appears that, especially in the Townsville region, vulnerability cannot be modelled by a length-dependent function alone: recruitment of a red throat emperor to the fishery appears to depend on its age in addition to its length.

The length-dependent curves are still very different between regions (parameter estimates in Table 28), implying that regional differences in growth (Table 7) are unable to fully explain the regional differences in vulnerability as a function of age.

Table 28: Logistic function parameter values for vulnerability as a function of length.
Logistic function parameter values are defined in Section 6.1.7. Derived from growth curves (Table 7) and the age-structured model estimates of vulnerability as a function of age (Table 26). The standard deviation is that of the difference between fitted and observed age-dependent vulnerability, i.e. the difference between the curves in Figure 59.

Region	L_{05} **(mm)**	L_{50} **(mm)**	**Standard deviation**
Townsville	436.8	437.0	0.158
Mackay	356.9	357.1	0.021
Storm Cay	379.5	420.7	0.038
Swains	361.6	361.9	0.015
Capricorn-Bunker	340.9	341.2	0.007

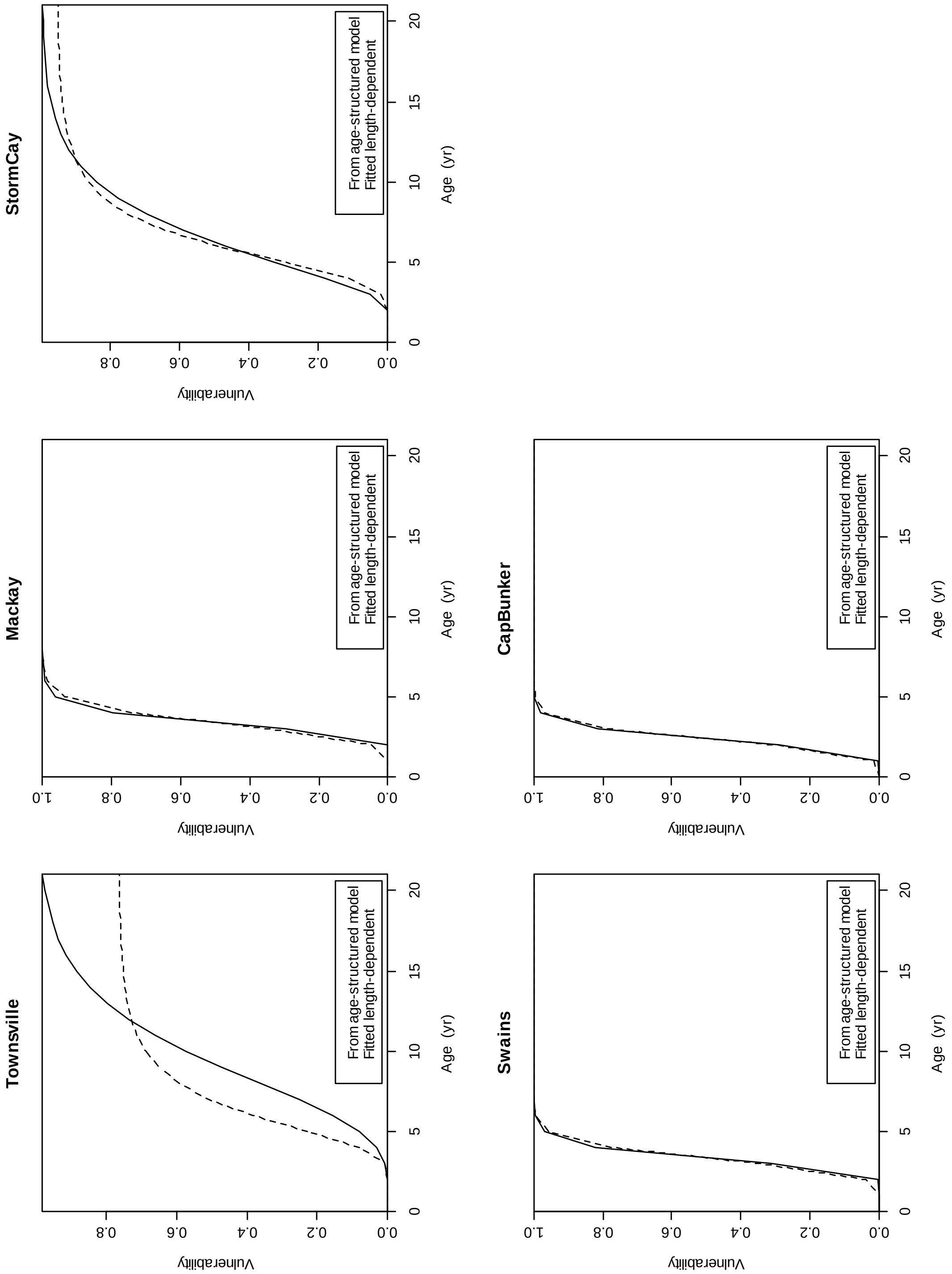

Figure 59: Fits of length-dependent vulnerability curves to the age-dependent vulnerability functions.
Curves are given by parameters in Table 28, functions are defined by parameters in Table 26.

6.3 Model evaluation

The age-structured model is in general more optimistic than the surplus production model, mainly because it shows large numbers of red throat emperor that mature years before they become vulnerable to exploitation. We assume that these fish reproduce.

The sensitivity analysis with $M = 0.4\ \text{yr}^{-1}$ emphasises the need for caution and highlights that a substantial increase in total harvest is not advisable.

Handling of the Cyclone Justin phenomenon is more sophisticated in the age-structured model, and the model has highlighted a risk that the fishery could face if such an event were to happen again. Such a major disturbance can cause red throat emperor to become vulnerable to fishing years ahead of their normal time, and some year-classes could be fished heavily as a result.

Doubt about the quality of CPUE data (see Section 6.2.2 above) must also cast doubt on the results of the surplus production model, because catch and CPUE data are all that that model uses.

In addition to the presence of large numbers of non-vulnerable fish in the population, the age-structured model has also been more optimistic than the surplus production model in explaining declines in CPUE by a chance sequence of a few years of poor recruitment in the early 1990s, rather than by over-fishing. The age-structured model predicts a return to normal recruitment and a consequent recovery in the red throat emperor population.

The surplus production model attributes all declines in CPUE to population reductions caused by fishing because it is incapable of accounting for chance years of low recruitment.

The age-frequency data appear to be of better quality than the CPUE data; therefore we believe that the results of the age-structured model are to be preferred to those of the surplus production model. The age-structured model also uses the CPUE data but places more weight on the age-structure data.

The age structured model estimates a high number of red throat emperor in the Townsville region (Table 26, parameter $N_{0\,1}$). This happens because of the estimated vulnerability curve in this region, by which there are many fish in the Townsville population that are not available to fishing. In other regions recruitment is less gradual and this effect is less pronounced.

It is desirable to monitor the population closely to check whether the recovery in recruitment predicted by the age-structured model has actually occurred. Analysis of otoliths collected after 2000 is expected to shed light on this.

7. Discussion

This assessment has shown that, while there are causes for concern due to steep increases in harvest during the 1980s and 1990s, if 2003 harvest levels are not exceeded in future years the red throat emperor population is expected to recover to levels that are healthy by the standards of most of the world's fisheries. Red throat emperor appear to take many years to fully recruit to the fishery, and the population appears to contain large numbers of fish of reproductive age that are not available to fishing.

The age-structured model shows big differences between regions in the vulnerability of red throat emperor to capture (Figure 35). The following explanations for this can be advanced:

1. Vulnerability may, to a degree, be length-dependent, and therefore occur earlier in fish in regions in which they grow faster. Figure 5 especially contrasts the growth curve for the Capricorn Bunker region to those for the Townsville and Storm Cay regions; the former region has both faster growth and higher vulnerability-at-age. The analysis in Section 6.2.6 indicates that regional variation in vulnerability is greater than can be explained by this effect.
2. Vulnerability may have been shaped by fishing mortality. The Capricorn-Bunker region has been fished at significant levels for much longer than the other regions (Figure 20). This may have resulted in younger fish coming into the fishery to replace the older fish that were caught. There is little support for this hypothesis from the estimated harvest rates, which follow a similar pattern for all regions (Figure 37). Some evidence for the hypothesis comes from the age-frequency plots for all years combined (Figure 33), which show higher than expected numbers of young fish present on reefs open to fishing. This can be seen in the proportion of four-year-old fish in the Townsville region and three-year-old fish in the Storm Cay region, both of which lie above the fitted curve for open reefs but below it for closed reefs. Red throat emperor may recruit to the fishery at younger ages in areas of heavy fishing, replacing older fish that are no longer present.
3. Vulnerability may be determined by water temperature. Younger red throat emperor may prefer colder water. In the northern regions cold water is available only at depth, and in deep water the fish may not be available to the fishery. In the southern GBR, especially the Capricorn-Bunker region, shallow water is colder due to increasing latitude, and therefore may be inhabited by younger fish. It was noted in Section 1.4.4 that the juvenile habitat of red throat emperor is unknown but may be in deep water. The effect of Cyclone Justin in 1997 supports this hypothesis in that a sudden influx of new fish that were not previously vulnerable to fishing corresponded to a substantial drop in sea surface temperature at the time Cyclone Justin struck.
4. Migration between regions may contribute to apparent differences in vulnerability, as hypothesised by Williams (2003). It was noted in Section 6.1.4 that this effect appears unable to fully explain the magnitude of the variation in vulnerability between regions. Differences in age structure between open and closed reefs (Figure 33) also imply that migration is limited (see Section 6.2.2).

The evidence for point 2 is quite weak, but it should be borne in mind as a possibility that heavy fishing may reduce the fraction of the population that is protected from fishing. Hence the population as a whole may be less robust than the model results indicate. The age-structured model has not accounted for this effect.

Differences in age distributions between regions were much larger than differences between open and closed reefs within a region (Figure 33). This suggests that factors other than fishing mortality may be causing the large regional differences in the vulnerability and age structures. Any migration that takes place between open and closed reefs would, however, tend to mask differences in age structure between these classes of reef.

Whatever the explanation for regional variation in vulnerability, region-specific management may be desirable for the red throat emperor fishery. The fact that fish become vulnerable at a younger age in the Capricorn-Bunker region may mean that more protection is needed in the south than in the north of the GBR. There is an argument for a separate TACC and recreational bag limit for the Capricorn-Bunker region. However, we have found little evidence that the population in the Capricorn-Bunker region is currently in danger.

Region-specific management recommendations are complicated by the poor correlation between length and age for red throat emperor (Figure 5 in conjunction with the estimated standard deviation of 31.2 mm about each curve). It is difficult to fix a minimum legal size that allows the fishery to target certain age-classes. We note that, using the parameter estimates in Table 7, the current minimum legal size of 380 mm protects 94% of fish aged three (at the end of their two-year-old year) and 61% of fish aged four (at the end of their three-year-old year) in the Capricorn-Bunker region.

The Cyclone Justin event, according to the age-structured model, substantially stressed the red throat emperor population in the Townsville region. The model estimated that this event not only made fish vulnerable to fishing that ordinarily would not have been vulnerable, but also occurred at a time of poor recruitment. The lowest recruitment estimated was for the 1992 year-class which was five years old in 1997 and just becoming vulnerable to fishing in the Townsville region. The population appeared to withstand the 1997 stress relatively well, and so may be quite resilient to major one-off events. Further years of age-frequency data are desirable to confirm this interpretation.

Our conclusions are based on the age-structured model, which we have preferred over the surplus production model for several reasons. The surplus production model:

- Relies almost totally on CPUE data for its results, and the CPUE data show signs of hyperstability (see Section 6.2.2).
- Cannot model gradual recruitment of year-classes over a long time; it assumes that all fish in the population are mature and fully vulnerable to fishing.

Results from the age-structured model rely on the assumption that fish of reproductive age that are not available to the fishery do actually reproduce. It is impossible to directly test this assumption unless these fish can be caught by some scientific means and examined.

The weight factor to use for conversion from numbers to weights of recreationally and charter-caught fish is still uncertain. As mentioned in Section 2.2.2, the actual weights may be up to one-third higher than those reported in this assessment, due to fishers tending to retain larger fish and release smaller ones even though they are of legal size. We assumed for this assessment that the decision to retain or release a red throat emperor does not depend on the margin by which it exceeds legal size.

The effect of increasing recreational and charter catch weights would be fairly constant over time, and would therefore have little influence on our conclusions regarding the status of the red throat emperor population. It may, however, impact on the effectiveness of management measures. If retained fish were already well over minimum legal size, the change in size limit from 350 to 380 mm would have little effect on the recreational and charter fisheries. Also if the recreational sector is a proportionately larger part of the total fishery, the introduction of a total allowable catch for only the commercial fishery would have relatively less effect.

R code for both the age-structured and surplus production population dynamic models is publicly available from DPI&F, and will be placed on the DPI&F website.

The formal review of this assessment by Mike Allen (University of Florida) is reproduced as an Appendix to this report. Prof. Allen's comments have, as far as possible, been incorporated into the text. (The only point we have not responded to is his Point 5 (re: the influence of CPUE data on the results of the age-structured model) because it would have required a substantial amount of extra analysis.)

8. Management, research and monitoring recommendations

Red throat emperor appears to be resilient to fishing techniques that have been used to date, but may be especially vulnerable to changes in fishing technology or behaviour which may catch the species in deep water where it was previously not open to exploitation.

The deep-water interpretation is still somewhat speculative, but it would be wise to monitor the technology and habits of fishers to ensure that undue fishing pressure is not applied to deep-water populations. In addition, we recommend monitoring the Coral Sea trap fishery which may have an impact on red throat emperor populations.

The current TACC is believed not to put the population in imminent danger of overfishing, but we recommend that this assessment be revisited when several more years of ageing data are available. Current TACC levels do not appear to leave much margin of safety. The population will obviously be boosted by commercial fishers currently catching substantially less than the TACC, but this effect is not expected to last once fishers become familiar with the ITQ system.

We have found no evidence that spawning stock sizes have fallen to a level that can reduce recruitment of new zero-year-old fish to the population. On the other hand, recruitment is a variable process and the population would obviously be at risk if a sustained fall in recruitment were to occur by chance in the future. The population appears to have coped well with the combined stress of Cyclone Justin and a sequence of low-recruitment years in the 1990s, but may not be so fortunate if the same events happen again in the future and the population is already under stress from another source.

Region-specific management may be desirable at some stage in the future, because of large differences in population age structure between regions. This is not recommended as a high priority at present, but could be considered for the future. In particular, the population in the Capricorn-Bunker region may be potentially more at risk from fishing pressure than populations in other regions.

A major assumption in this assessment is that red throat emperor that are not vulnerable to fishing are able to reproduce. It is desirable to check this assumption to make sure that survival of the population does not depend wholly on fish that are vulnerable to fishing. However, sampling is difficult if the fish that need to be examined cannot be caught.

The whereabouts of juvenile red throat emperor less than 150 mm FL are also unknown. They are assumed to be in deep water, and may inhabit the same places as adult red throat emperor that have not yet recruited to the fishery. Research on juvenile habitat is desirable in order to know how to protect it.

Fecundity of red throat emperor is an additional unknown quantity, and a study on how fecundity varies with age would aid future assessments. We have assumed for this assessment that fecundity is proportional to a function of fish length. Prof. Mike Allen in his review of this assessment has pointed out that fecundity may depend strongly on age (presumably increasing with age, as is the case with most fish species) even though length does not for older fish. He gives the example of the red tropical snapper *Lutjanus campechanus* in the Gulf of Mexico where such a situation has been found. In the case of red throat emperor the residual proportion of female fish that do not change to male (Section 2.6, Table 10 and Figure 7) may turn out to be a very important source of egg production for the population.

We also recommend ongoing monitoring of the fishery to record the regional age structures each year, validation of commercial fishers' catches, and surveys to ascertain the size of the recreational catch. Much of this is already happening, and a transition is under way whereby DPI&F will assume responsibility for sampling previously undertaken by the ELF Project. Keeping records of age structure is particularly important given that length is a poor indicator of age for this species.

More work is also needed to evaluate effects of post-release mortality on management of this fishery, in view of expected future coastal population increases and growth in the tourism sector. Both modelling efforts and the ongoing field estimates of post-release mortality are needed, and will become increasingly important in the future.

Appendix: Review by Prof. Mike Allen, University of Florida

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March 28, 2006

Dr. Tony Courtney
Southern Fisheries Centre
Department of Primary Industries
Queensland, Australia

Dear Dr. Courtney;

I am writing to provide a review of the stock assessment entitled 'Stock Assessment of the Queensland East Coast Red Throat Emperor Fishery', by Leigh et al. (2006). I have reviewed the assessment in detail and have some comments that will hopefully improve the clarity and value of the assessment, and provide direction for data that will be needed for future management of the red throat emperor (RTE) fishery.

I found the assessment to be quite comprehensive and unique in that it utilized data from so many sources, including all sectors of the fishery and several past and ongoing scientific collection efforts. The result is a very comprehensive depiction of the current fishery status. I commend the authors' approach to openly describing the uncertainty and caveats associated with the analyses throughout the document. The assessment is very clear about the assumptions made, and sensitivity analyses were incorporated for key parameters.

Below I begin with some major points that I believe need revision and additional explanation, and then make some more minor comments.

Major Points

1. Perhaps the most interesting finding in the assessment was the high variability in the vulnerability schedules for RTE across regions. The estimated vulnerability schedule differences (Figure 34) appear to be real based on the differences in observed age frequencies between regions (Figures 32 and 33). However, the assessment didn't address three areas here where more elaboration is needed.

   First, potential mechanisms for why these vulnerability schedules vary so widely among regions was never discussed. One potential mechanism is the regional variation in fish growth rates. Based on Table 7, the L_∞ values for Townsville and Storm Cay regions are the two lowest among regions (e.g., below 500 mm FL), and these two regions have the most gradual vulnerability schedules (i.e., vulnerability increasing only slightly across a large number of ages). Conversely, the L_∞ values for the CapBunker, Mackay, and Swains region are higher (e.g., over 500 mm FL), and these regions of the fishery have more truncated age frequencies. The growth coefficient K varied inversely with L_∞ as expected across regions.

It is possible that differences in growth rates among regions contribute to the differences in vulnerability with age, because fish in ‘faster growth’ regions would be expected to become vulnerable to harvest at a younger age, resulting in truncated age frequency distributions. Conversely, fish from ‘slower growth’ regions likely become vulnerable to fishing over more ages resulting in age distributions comprised of older, but relatively smaller, individuals. What is not known in this supposition is whether the fishing mortality among regions has substantially modified the growth curves, which could also occur. The estimated exploitation rates among regions are not drastically different (Figure 37), which suggests to me that differences in growth rates could explain the differences in vulnerability. I believe the assessment could be improved by exploring these relationships in more detail. It would be interesting to contrast the size distributions of fish harvested among regions, and to further explore how size-at-age varied among regions. If adequate data exist, a table showing the size range of fish at each age for each region could identify whether growth was contributing to the vulnerabilities.

Secondly, it is noteworthy that the differences in age distributions among regions were much larger than differences between open and closed reefs within a region, but this was not mentioned. Data from closed reefs was not available for the Swains and CapBunker regions, but the differences across regions are striking compared to open and closed reefs within the three other regions. This could suggest that factors other than fishing mortality are causing the large regional differences in the vulnerability and age structures. Again, that could go back to growth rate differences or differences in fish accessibility to fishers among regions.

Thirdly, differences in vulnerability schedules have implications for management on a region-specific basis. Although the assessment concludes that the fishery is not in danger at the present time, it seems that more discussion is warranted regarding the potential to manage the RTE fishery on a region-specific basis. Regions with very sharp vulnerability curves would require more protection (e.g., size limits) than regions where fish become vulnerable to fishing over a wide range of ages.

In summary of this point, the assessment would benefit from more analysis and discussion of the potential mechanisms for regional variation in the vulnerability. The management implications of those differences should also be described.

2. The assessment assumes that fecundity is related to fish size (Section 2.7) because of a lack of available data for how fecundity varies with size and age. Given

hermaphrodism in RTE and the highly asymptotic relationship between age and length, I suspect that fecundity also varies with fish age even for fish of the same size. Older fish that did not change to males could have a very different fecundity compared to younger fish of similar sizes. Recent information for red snapper *Lutjanus campechanus* in the Gulf of Mexico suggests that fish age explains a significant component of fecundity over that explained by fish size. I don't recommend any changes to the document regarding this point, but future assessments would benefit from studies that elucidate the relationship between fish size, age, and fecundity for RTE.

3. The obvious impact of the Cyclone Justin on the CPUE across regions is very interesting, and certainly should be reported in the peer-reviewed literature following completion of this assessment. It also left some question on the influence of the storm on CPUE in other regions. As noted on p. 52, CPUE in the Storm Cay, Swains, and CapBunker regions declined along with the large increase in CPUE for Townsville. Without this decline in those three regions in 1997, it would be difficult to identify any declining trend in CPUE across the time series in Figure 21. The age-structured model attributed this to weak year-classes in the early 1990's in Section 6.2, which is also a plausible explanation for lower CPUE. However, neither of these explanations results from fishing mortality shifting in the population biomass, yet the surplus production model assumes that all changes in population biomass are a result of changes in catch. This should be discussed when comparing the surplus production model results to the age-structured model, as the surplus production model would not consider such factors (in addition to the factors mentioned such as the lack of age structure in the surplus production model, etc.). Given these limitations, I agree that the surplus production model was not realistic and overly pessimistic. Comment #5 below further addresses the potential CPUE influence on the age-structured model.

4. The age structured model is really unique, because it fits the model to CPUE and the age structure data simultaneously, and it accounts for differences among regions and among open and closed reefs within regions where they exist. I believe the model is a significant advance in stock assessment techniques, and it fit the age-structure data very well (Figures 32 and 33).

   However, not all parts of how it works were clear in the equations and text. Why was recruitment about an order of magnitude higher for the Townsville region (i.e., $N_{0\,1}$ in Table 26) than for all other regions (Figure 38)? Is it due primarily to the differences in vulnerabilities among regions? This appears to be the case, because the mortality parameters (e.g., exploitation, M) are similar among regions. Given that mortality components are similar and recruitment is much higher at the Townsville region, the model is predicting that adult population abundance and biomass is much higher in this region, correct? More description here would be helpful, as the paper never shows this result or discusses how predicted fish abundance varies across regions.

   I would also prefer some justification about the assumption that the relative magnitude of recruitment was the same for all regions. Because stock-recruit equation handled each region separately (p. 64), why was it necessary/desirable to make this assumption? More detail needed as to how the model is treating each region. It appears that the stock recruit relationship is the same for all regions, but the total recruits are allocated differently across regions based on the differences in adult fish abundance, which occur largely due to the vulnerability schedules. Is this correct?

5. I agree with the authors comments that hyperstability is a concern with the CPUE data, and fitting the model to both CPUE and the age structure data is a strong point of the assessment. Assuming that CPUE data are an adequate index of population abundance is usually risky particularly with reef fishes, where fishers move to new patches in order to keep CPUE high after depleting local reefs. Although the age structured model didn't fit the CPUE data well and also considered the age structures explicitly, would it have made any difference in the model predictions if CPUE data were not used? Given the likelihood of hyperstability, it would be informative to know if the CPUE data were strongly influencing the age-structured model predictions.

6. The potential effects of post-release mortality are not adequately described, particularly with the changes that are likely in the future of this fishery. It appears that commercial catch is likely to remain stable or decline due to limited access, the TAC, and fuel prices, whereas recreational catch could increase substantially due to increasing human population size and tourism in Queensland. Section 6.2.5 discounts post-release mortality as a significant factor that could influence the management of the fishery. However, because the recreational fishery has few management options for limiting fishing effort, the recreational component of total catch is likely to increase in the future. Post-release mortality could have strong impacts on the success of minimum size limits for this sector, and the assessment should acknowledge this and point out that more work is needed to evaluate effects of post-release mortality on management of the fishery. Both modeling efforts and the ongoing field estimates of post-release mortality are needed and will be increasingly important in the future.

Minor Points

- check the significant digits in the tables. Figure 6 has values out to five decimal places. Round off these values and the rsquare values.

- p. 31 above Figure 9, consider expanding on this later in the Discussion by noting that even if all unspecified emperor were RTE, it would be unlikely to influence the results based on the sensitivity analyses with variation in historical catch estimates.

- Table 13 does not have landings separated by regions, but the text suggests that it does. I'm not sure why this table is needed when Figure 11 contains this and more information. Suggest delete.

- The assessment included substantial work compiling the catch data across sectors of the fishery and the regions. Having these in one place will really help future assessments as well. The sensitivity analysis suggested that changes in the magnitude of landings didn't strongly influence the model predictions, but uncertainty in the landings trajectories also likely varied among regions (e.g., some regions have reliable data whereas other maybe less so). The authors should consider discussing the relative reliability of the landings data among regions and the potential impacts on their results. Although changes in the total landings didn't influence the model predictions, changes in landings on one or more regions could have influenced the results.

- The x axes for Figures 32 and 33 should be age instead of year. On the figures I recommend making the x and y labels a larger font, as it was difficult to read the labels on the axes.

In summary, I believe this assessment did a very thorough job of data analysis and estimating uncertainty in the model predictions. Most of my comments can be addressed with more explanation in the text, although more analysis on the potential mechanisms for differences in vulnerability among regions would be a great addition. The age-structured model is a significant advance and handles the multiple data sources very well. This is among the most comprehensive stock assessments that I have seen. I wish the authors good luck with revisions, and with management of the red throat emperor in Queensland.

Cordially,

Dr. Micheal S. Allen
Associate Professor
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Acknowledgements

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