Spawning and reproductive biology of blue grenadier in south-eastern Australia and the winter spawning aggregation off Western Tasmania

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Spawning and Reproductive Biology of Blue Grenadier in South-Eastern Australia and the Winter Spawning Aggregation off Western Tasmania

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2000/102 Spawning and reproductive biology of blue grenadier in south-eastern Australia and the winter spawning aggregation off Western Tasmania

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Objectives:

1. Estimate the annual proportion of non-spawning adults in the blue grenadier stock off south-eastern Australia
2. Describe macroscopic and histological maturation stages and gonad cycles
3. Accurately determine the size at maturity and the proportion of each age class developing to spawn
4. Evaluate levels of spawning of blue grenadier in areas outside the main spawning aggregation.

Non Technical Summary

Blue grenadier is an important species in the Southern and Eastern Scalefish and Shark Fishery (SESSF). Between 2001/02 and 2003/04, the catch of blue grenadier was the largest of all of the quota species in the SESSF and the most valuable in 2001/02 and 2003/04. The species is taken almost exclusively by trawl. In 1999, total catches approached the 10,000 t TAC for the first time due to the continuing development of the spawning fishery following the entry of 'factory trawlers'. In 2003, the agreed TAC was reduced to 9000 t, from 10,000 t (which it had been since 1994) due to concerns regarding poor recruitment to the fishery.

The assessment of blue grenadier considers fishing during the spawning season and that at other times/places separately: a ‘spawning’ sub-fishery that operates in winter (June, July, and August) off western Tasmania on the spawning stock, and a ‘non-spawning’ sub-fishery that includes all other catches in the trawl fishery. It uses catch (including discards), standardised catch rates and catch-at-age data (retained and discards) as well as estimates of absolute abundance based on the annual egg production method. However, results of the assessment are extremely sensitive to the biomass estimates from the annual egg production method.

Obtaining better information on the spawning behaviour and reproductive biology of blue grenadier to reduce uncertainty about biomass estimates was accorded a high priority for several years. Information needed includes fecundity estimates, maturity ogives and the proportion of non-spawners. A key area of uncertainty concerned the proportion of mature fish that spawn each year. New Zealand assessments are based on the assumption that 77%

of the potential spawners spawn each year. The same assumption is used in the Australian assessment; there are no data to support it.

Since the project commenced acoustic estimates of biomass have been derived. For these 'snapshot' estimates to be used in the assessment as absolute rather than relative spawning biomass an estimation of the turn-over rate (or residency time) became a crucial research priority.

Blue grenadier were sampled on board commercial fishing vessels off western Tasmania between June 1999 and August 2002 during the spawning season (June to August). Blue grenadier were also sampled during the non-spawning period and also throughout the year in three other fishing zones within the SESSF boundaries: east coast of Tasmania, eastern Victoria and western Bass Strait. The latter sampling was conducted with support of the Integrated Scientific Monitoring Program (ISMP).

The body weight and length of each fish was recorded. Fish were sexed, the gonads macroscopically staged and otoliths collected for ageing. A sub-sample of gonads was taken for histological examination. SETF logbook data (SEF1) were examined for the period 1986 to 2003.

By 1997, following the introduction of 'factory' trawlers, landings from the spawning fishery exceeded that of the non-spawning fishery. Catches by these vessels quickly contributed over 90% of total catches with average monthly catches peaking in July at over 2,500 t. Catches from all other areas remained low during the spawning season. During the study period the fishery, both spawning and non-spawning, was dominated by the 1994 and 1995 year classes passing through the fishery.

This study confirmed that the major spawning area was off the west coast of Tasmania. This was supported by fisheries data. However, a few reproductively active male and female blue grenadier were sampled off the east coast of Tasmania and in western Bass Strait during the primary spawning period. These individuals may have been captured during their migration to and from this area or possibly reflect intermittent very low level spawning outside the west coast.

The length and age at 50% maturity based on macroscopic examination of gonads was 63.7 cm SL and 5 years for females and 56.8 cm SL and 4 years for males. These lengths are somewhat lower than previous estimates but most likely reflect the influence of the slower growth of the strong 1994 and 1995 year classes. Blue grenadier are batch spawners with determinate annual fecundity. Estimates of fecundity ranged from 0.3 million eggs to 4.6 million eggs for fish ranging from 68 cm SL to 112 cm SL.

Based on histological examination exclusively, 35% of fish were classified as 'non-spawners' in non-spawning areas, 30% were found in the primary spawning area and 32% were found to be 'non-spawners' overall. However, it is also difficult to distinguish between immature fish and non-spawning adults. The blue grenadier fishery during the study period was dominated by small fish and there were few large fish (>80 cm SL) sampled outside the spawning area. Consequently, to remove uncertainty about these estimates, the 75% maturity (80.9 cm SL) ogive was applied to the data. 21% of fish were classified as 'immature' and of the fish classified as 'adult non-spawners' 5% were found in non-spawning areas and 18% were found in the primary spawning area. These estimates were weighted to the overall population given different abundances in each zone, particularly during the spawning season.

There is considerable uncertainty around our results. Few studies have been conducted to determine the degree of adult non-spawning in fish populations. However, all of these studies were based on the assumption that all fish sampled were fully mature (i.e. approaching 100% maturity). Consequently, we recommend the weighted proportion of adult non-spawners derived from the 75% maturity ogive (as this removes some of the uncertainty due to small fish) of 16% be used in future blue grenadier assessments.

Turn-over rates were assessed through an examination of sex ratios, gonad development, and size/age composition during the spawning period. Large, older fish enter the spawning area are first followed by a steady decline in the mean length of female and then male blue grenadier as the spawning period progresses, indicating that the spawning population is constantly altering. The best estimate of turn-over rate is 2x and this has been endorsed by SlopeRAG for use in the base case blue grenadier assessment.

The results of this study have refined our understanding of the reproductive biology of blue grenadier and provided estimates of the key areas of uncertainty; the proportion of non-spawning adults and the turn-over rate during the spawning season. Most of the results of this study have already been adopted by SlopeRAG for the assessment of blue grenadier in Australian waters.

OUTCOMES ACHIEVED

The main outcome of this project is the refinement in reproductive parameters for blue grenadier and estimates of the proportion of non-spawners and the turn-over rate during the spawning season. Importantly, the latter enables acoustic 'snapshots' to be used as absolute biomass estimates in the assessment. These results will provide greater certainty to the blue grenadier assessment and are already being used by the resource assessment group responsible for the assessment.

Keywords:

Macruronus novaezelandiae, reproductive biology, turn-over rates, adult non-spawners

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Background

Blue grenadier (*Macruronus novaezelandiae*) are found from mid New South Wales to southern Western Australia, including the coasts of Tasmania and across the Great Australian Bight. It is an important species in the South East Trawl Fishery (SETF) sector of the Southern and Eastern Scale Fish and Shark Fishery (SESSF). Note the SETF has recently been renamed the Commonwealth Trawl Sector (CTS).

Previous research supports the hypothesis of a single breeding population in Australian waters, which is genetically distinct from the New Zealand stocks. In Australian waters, the major spawning aggregation occurs off western Tasmania although there is some evidence of low level spawning in other areas (Gunn *et al.* 1989). The main spawning ground for blue grenadier in Australian waters was first located on the west coast of Tasmania (Wilson 1981). Further studies involving egg and larval distributions, combined with adult reproductive data, later confirmed the west coast of Tasmania off the continental shelf edge (near Cape Sorell) as the primary spawning area for blue grenadier (Wilson 1982; Blaber 1984; Thresher *et al*. 1988, 1989; Gunn *et al*. 1989). Wilson (1982) predicted blue grenadier spawning in Australia to occur from May to September. Egg and larval studies indicated that spawning generally begins in May-June, and peaks in July-August (Thresher *et al*. 1988; Gunn *et al*. 1989; Bulman *et al*. 1999). However, broad scale temporal differences at the start of spawning of up to one month have been observed, which is thought to relate to variation in the development of coastal current patterns around Tasmania (Thresher *et al*. 1988; Gunn *et al*. 1989).

Blue grenadier are dioecious, testes and ovaries are paired, development is synchronous, fertilization is external and they exhibit determinate fecundity (Gunn *et al*. 1989; Zeldis 1993; Zeldis *et al*. 1998; Schofield and Livingston 1998; Bulman *et al*. 1999). Histological studies show that female blue grenadier are total spawners, i.e. they shed all their eggs during the spawning period (Gunn *et al*. 1989; Zeldis 1993). However, they are capable of releasing all their eggs in two or three batches within the defined spawning period (Langley 1993; Zeldis 1993; Schofield and Livingston 1998).

Small pelagic juveniles (15-29 cm standard length [SL]) have been caught in very large numbers along the shelf break off eastern Tasmania, approximately seven months after spawning (May and Blaber 1989), and also in coastal bays along south-eastern Tasmania. These regions may be important nursery areas for blue grenadier (Wilson 1981; Thresher *et al.* 1992). However, it is likely that most of the population recruits offshore, with fish collected inshore representing marginal populations (Smith 1994; Smith 2000).

Adult blue grenadier in Australia are known to form dense schools on the seabed during the day, and disperse into the water column at dusk (Bulman and Blaber 1986). They annually migrate from their feeding grounds in autumn to the primary spawning area off western Tasmania, and disperse again during spring (Gunn *et al*. 1989; Smith 2000). There is currently no information available on the behaviour and/or movement of adults within the spawning grounds, or on the proportion of fish which undertake this annual migration to the spawning area (Smith 1994). Acoustic surveys conducted in 1992 suggested that adult blue grenadier aggregated at a number of points off western Tasmania during spawning (Koslow *et al*. 1994; Koslow 1995; Smith 2000).

Various estimates of reproductive maturity have been calculated for blue grenadier in Australasian waters. Initial estimates of maturity for females in Australia were 73 cm SL (Gunn *et al*. 1989), corresponding to 4-7 year old fish (Kenchington and Augustine 1987). However, it was generally agreed that males and females reach reproductive maturity at 65-70 and 60-70 cm SL respectively, corresponding to a respective age of 4 and 5 years old (Smith 2000; Punt *et al*. 2001a, b; Smith and Wayte 2004).

The blue grenadier fishery can be divided for statistical and assessment purposes into two sub-fisheries: a 'spawning' sub-fishery that operates in winter (June, July and August) off western Tasmania on the spawning stock, and a 'non-spawning' sub-fishery that includes all other catches in the trawl fishery (Smith 1998, Punt *et al.* 2001, Tuck *et al.* 2004). Catches by the 'non-spawning' sub-fishery primarily comprise sub-adult and small adult fish whereas the 'spawning' sub-fishery concentrates on mature fish, including large adults that are poorly represented in the catches by the 'non-spawning' sub-fishery.

Total landings of blue grenadier increased substantially following the introduction of 'factory trawlers' into the spawning fishery in the 1990s. The proportion of the total catch taken in the 'spawning' sub-fishery varied around a mean of 37% from 1986 to 1991 and then increased steadily to about 73% in 1997, to over 90% in recent years. By weight, the catch of blue grenadier was the largest of all of the quota species in the SESSF. Blue grenadier was the second most valuable species in the South East Fishery ($8.8 M during 1998).

In 1999, total catches approached the 10,000 t TAC for the first time. In 2003, the agreed TAC was 9000 t, down from 10,000 t which it had been since 1994. This reduction reflected evidence of a reducing biomass due to poor recruitment (see below).

The assessments of blue grenadier are based on the Integrated Analysis paradigm, in common with those for most species in the SESSF (e.g. Smith *et al*. 2001, Tuck and Smith 2004). The assessment uses catch (including discards), standardised catch rates and catch-at-age data (retained and discards) as well as estimates of absolute abundance based on the egg production method (see Bulman *et al.* 1999).

The Blue Grenadier Assessment Group (BGAG), formed in 1997, was originally responsible for the assessment but from 2004 it was undertaken by the Slope Fishery Assessment Group (SlopeFAG). Both groups comprised government and industry scientists, industry representatives and AFMA managers.

The results of the 1999 assessment were generally optimistic for the next five to ten years but were extremely sensitive to biomass estimates from the egg production method (Punt *et al*. 2001).

One key area of uncertainty concerned the proportion of mature fish that spawn each year. It was known from data in New Zealand that not all fish spawn annually (Livingston *et al*. 1997). However, there were no data on the proportion of non-spawners in Australia although there are anecdotal reports of adult fish (i.e. 'adult non-spawners') outside spawning areas during the main spawning season (Smith 1998).

The need to obtain better information on the spawning behaviour and reproductive biology of blue grenadier was a high research priority for several years and was identified as such by BGAG in 1998 and 1999. The information required included fecundity estimates, maturity ogives, and the proportion of non-spawners with the aim of reducing uncertainty in the assessment.

In 2003, SlopeRAG considered preliminary results from an acoustic survey of spawning blue grenadier (Kloser 2005). However, estimating the abundance of a dynamic population like blue grenadier from an acoustic 'snapshot 'is difficult (Harley *et al*. 2004). Estimating abundance from these acoustic 'snapshots' required information on the proportion of the stock on the spawning ground, the residency time and turn-over rates (Coombs and Cordue 1995, Bulman *et al*. 1999).

It is known that blue grenadier do not have a uniform arrival and departure on the spawning grounds but rather have a staggered arrival and departure for the duration of the spawning period. However, the rates of these movements are unknown for either sex (Smith 1994). Bulman *et al*. (1999) argued that the annual egg production method provided a better estimate of biomass than acoustic methods because of this uncertainty.

Consequently, this study was extended to include an estimate of turn-over rate for blue grenadier so that acoustic estimates of biomass could be used as absolute estimates of abundance rather than relative. Turn-over rate is defined as the proportion of fish that move into and out of the spawning ground from the broader population during the spawning period.

Need

Blue grenadier is an important species in the Southern and Eastern Scalefish and Shark Fishery (SESSF). Between 2001/02 and 2003/04 the catch of blue grenadier was the largest of all of the quota species in the SESSF and the most valuable in 2001/02 and 2003/04. In 1999, total catches approached the 10,000 t TAC for the first time due to the continuing development of the spawning fishery following the introduction of 'factory trawlers'. In 2003, the agreed TAC was reduced to 9000 t, from 10,000 t (which it had been since 1994) due to concerns regarding poor recruitment to the fishery.

The assessment of blue grenadier considers fishing during the spawning season off western Tasmania and that at other times/places separately. It uses catch (including discards), standardised catch rates and catch-at-age data (retained and discards) as well as estimates of absolute abundance based on the annual egg production method. However, results of the assessment are extremely sensitive to the biomass estimates from the annual egg production method (Bulman *et al*. 1999).

Obtaining better information on the spawning behaviour and reproductive biology of blue grenadier to reduce uncertainty about biomass estimates has been accorded a high priority for several years. Information needed includes fecundity estimates, maturity ogives and the proportion of non-spawners.

A key area of uncertainty concerns the proportion of mature fish that spawn each year. It is known from data in New Zealand that not all fish spawn annually. Assessments in New Zealand are based on the assumption that 77% (the average of the range of 68-85% reported by Livingston *et al*. 1997) of the potential spawners spawn each year. The same assumption is used in the assessment. However, there are no data on the proportion of non-spawners in Australia although there are anecdotal reports of adult fish (i.e. 'adult non-spawners') outside spawning areas during the main spawning season. It is important, therefore, that the actual proportion of non-spawning fish is established as this can have a significant impact on the mature biomass.

Since this project commenced acoustic estimates of biomass have been derived from an FRDC-funded project (Ryan and Kloser 2002). For these estimates to be used in the assessment as absolute rather than relative spawning biomass, an estimation of the turn-over rate has become a key research priority.

Objectives

1. Estimate the annual proportion of non-spawning adults in the blue grenadier stock off south-eastern Australia
2. Describe macroscopic and histological maturation stages and gonad cycles
3. Accurately determine the size at maturity and the proportion of each age class developing to spawn
4. Evaluate levels of spawning of blue grenadier in areas outside the main spawning aggregation.

Methods

Study area and sampling regime

Blue grenadier were sampled on board commercial fishing vessels off western Tasmania (WCT) between June 1999 and August 2002 during the spawning season (June to August). Fish were caught either by demersal or mid-water trawling at depths of 300-600 m. Mid-water trawling was a recent development in the SESSF at the start of this project, and is primarily used off the WCT which is the main spawning area for blue grenadier.

Each trawling operation consisted of three to five shots during a 24-hour cycle, with each shot lasting 1-4 hours. Towing speed averaged 4.5 knots and varied according to weather conditions and gear type. Whenever possible, the location, duration, fishing depth, sea temperature, and gear type deployed, were recorded for each shot. Between 50 and 200 fish were randomly selected from shots, and individually examined and processed immediately after capture. Additional samples were processed at port-based facilities and processing factories.

Adult blue grenadier exhibit diurnal migration, rising into the water column at night and staying close to the bottom, mainly in depths between 300 m and 600 m, during the day. Thus both bottom and mid-water trawls are used to catch blue grenadier commercially during the spawning period. The overall use of each gear type was similar across years; demersal trawls were more frequently used at the beginning and end of a spawning period. Mid-water trawls were more frequently fished in the water column during darkness, but were usually fished very close to the bottom during daylight hours. It is acknowledged that potential differences in gear type may bias certain results; however, an analysis of average fish size of blue grenadier by both demersal and midwater trawl revealed no significant differences in average size (Russell PhD thesis 2006).

Blue grenadier were also sampled during the non-spawning period in four main fishing zones (and code used in this report) within the trawl sector boundaries: western Tasmania (WCT), eastern Tasmania (ECT), eastern Victoria (EBS) and western Victoria (WBS) (Figure 1). The aim was to collect random samples of approximately 100 fish per region each month. Where possible every effort was made to maintain this sampling regime; however, due to limited commercial fishing in some areas, samples were not always available. The date, region and port of landing were recorded for each sample. As most blue grenadier caught during the non-spawning season are headed and gutted at-sea, arrangements were made for fish to be landed whole. Consequently, blue grenadier were mostly sampled at port-based facilities with the assistance of the Integrated Scientific Monitoring Program (ISMP) (Knuckey *et al*. 1999).

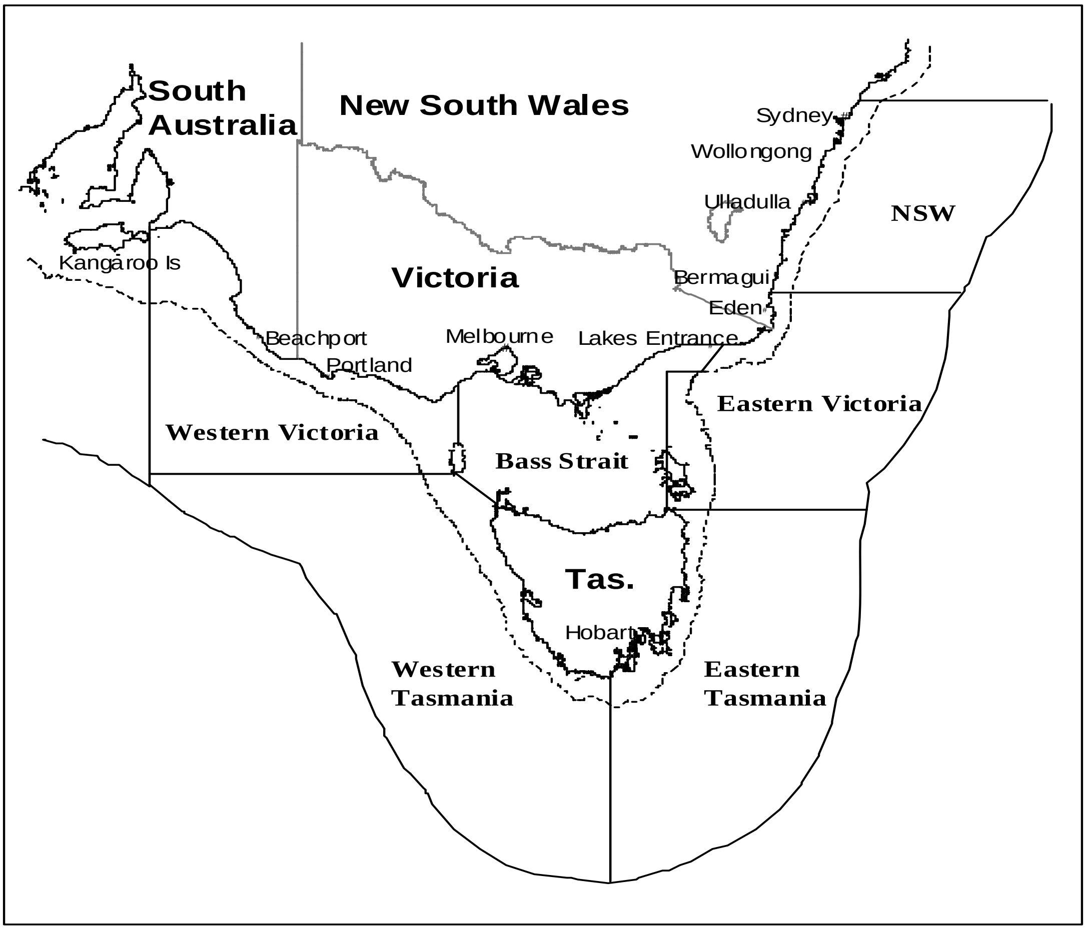


Figure 1. Map of southern Australia highlighting the various zones considered in this report.

Fishery data

SETF logbook data (SEF1) were examined for the period 1986 to 2003. As catches in logbook data are estimated, SEF2 records from the quota monitoring system were also used to enable SEF1 records to be scaled-up (see below).

Catches from the SEF1 logbook data were adjusted upwards to take account of fish reported as headed and gutted (multiple of 1.4 for the non-spawning fishery; 1.2 for the spawning fishery up to and including 1996; Smith *et al.* 1995)). These figures were then scaled up to the SEF2 data. As SEF2 data were only available from 1992, for the years 1986-1991 the average annual difference (about 9%) from 1993 to 1998 was used to scale the data. More recent conversion factors were obtained from on-board observer measurements using standard sampling techniques by the Integrated Scientific Monitoring Program (ISMP) (Knuckey *et al.* 1999).

These data were used to provide annual catch by zone and season and mean monthly catch by zone. These data, together with catch by depth were also used in the estimation of spawning in areas other than WCT and the proportion of adult non-spawners.

Biological sampling

Almost 32,000 blue grenadier were sampled between February 1999 and October 2001 (Table 1). A further 2,476 individuals were sampled during the 2002 spawning season, and while they were sexed they were not staged. An additional 13,245 individuals from various areas were measured only. During 1999 and 2002, samples were taken from the WCT region only. Male specimens were more abundant in the ECT, WBS and WCT regions, whereas they were poorly represented in EBS (Table 1).

The body weight of each fish was recorded to the nearest 10 g. Fish were measured (standard length [SL] and total length [TL]) and rounded down to the nearest 1 cm, sexed, and the gonads macroscopically staged using the maturity scale shown in Table 2 (adapted from Livingston 1990). Since it is assumed that development of male and female gonads is synchronous in most teleost species (West 1990), no further examination of male gonads was carried out.

Table 1. Sample numbers of blue grenadier examined for their reproductive status in all areas during spawning and non-spawning periods between 1999 and 2002.

Area	Period	Sex	1999	2000	2001	2002	Total
EBS	NS	F	-	188*^	114*^	-	302
		M	-	2*	73*	-	75
	SP	F	-	-	155*^	-	155
		M	-	-	106*	-	106
ECT	NS	F	-	300*^	417*^	-	717
		M	-	369*	1110*	-	1479
	SP	F	-	124*^	116*^	-	240
		M	-	476*	164*	-	640
WBS	NS	F	-	126*^	32*^	-	158
		M	-	184*	121*	-	305
	SP	F	-	125*^	39*^	-	164
		M	-	93*	115*	-	208
WCT	NS	F	318*	461*^	633*^	-	1412
		M	340*	397*	1177*	-	1914
	SP	F	4147*	2730*^	3691*^	1221	11789
		M	5929*	3199*	4289*	1255	14672
	Total		10734	8774	12352	2476	34336

* = staged macroscopically; ^ = gonad weight recorded

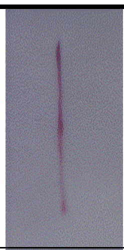
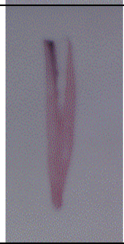
Abbreviations: EBS = Eastern Victoria; ECT = Eastern Tasmania; WBS = Western Victoria; WCT = Western Tasmania; NS = non-spawning; SP = spawning; F = female; M = male

The gonadosomatic index (GSI) was calculated using standard methods (eg. Knuckey and Sivakumaran 2001). Ovaries were weighed to the nearest 1 g, and the data used to calculate GSIs using the relationship:

$$GSI = \left(W_g / W_f\right) \times 100$$

where W_g is the weight of both ovaries (g); and W_f is the whole weight of female blue grenadier (g). Gonadal weight and corresponding gonadosomatic indices were recorded during the years 2000 and 2001 only. A total of 9,252 females were examined.

Table 2. Macroscopic description of blue grenadier gonads at various developmental stages (adapted from Livingston 1990).

Stage	Status	Plate	Ovaries	Testes
I	Immature		Slender, thread-like ovaries, transparent and sometimes pink in colour; no eggs visible; no blood vessels visible; ovaries occupy from 1-10% of body cavity	Slender thread-like testes sometimes slight lobing is visible; generally transparent but sometimes creamy/white in colour; no milt extrudable; no blood vessels; testes occupy from 1-10% of body cavity
II	Maturing /Resting		Swollen tube-like ovaries, creamy/white in colour; egg size is even with a granular appearance to the egg mass; blood vessels developing on outer sheath, ovaries are firm, occupying 20-50% of body cavity	Swollen multi-lobed testes; creamy/white in colour; no milt is extrudable; no blood vessels; testes occupy 20-70% of body cavity
III	Mature		Large swollen ovaries, creamy/white in colour (sometimes pink); two or more size classes of eggs present, some eggs may be translucent in appearance; distinct blood vessels present; ovaries often have a glossy appearance occupying 70-100% of body cavity	Large swollen multi-lobed testes; creamy white to pink in colour; some milt extrudable; distinct blood vessels; testes occupy 50-80% of body cavity
IV	Running ripe		Ovaries are large and swollen; generally pink to deep red in colour; clear eggs running free under slight pressure; distinct blood vessels present on the outer sheath; ovaries are fragile, occupying 90-100% of body cavity	Testes large and multi-lobed; pink and often bloodshot; milt flows freely under slight pressure; distinct blood vessels present; testes occupy 90-100% of body cavity
V	Spent		Ovaries are flaccid and tube-like; dark red to purple in colour; only a few eggs remaining attached to the ovary wall; blood vessels are not obvious; ovaries are tough and rubbery in appearance, occupying 20-50% of body cavity	Testes are thin and multi-lobed, dark pink in colour very bloodshot and often bruised; no milt present; blood vessels are not obvious; testes often have a rubbery appearance, occupying 20-50% of body cavity

Length frequency distributions

Length frequency data collected during this study were grouped into 1-cm length classes (to the nearest cm below). Where fish were sub-sampled from catches, length data for blue grenadier were weighted using the following relationship:

$$WF = A_f \times \frac{C_w}{S_w}$$

where WF is the weighted frequency; A_f is actual number of fish in the sample; C_w is the total weight of the catch (kg); and S_w is the sample weight (Smith *et al.* 1995). Weighted length frequencies were standardized by calculating the relative weighted proportional (RWP) length distribution for each sample.

Age and growth

Sagittal otoliths were collected from 6,802 blue grenadier caught between February 1999 and August 2002. Ageing of blue grenadier was based on the counting of annuli in sectioned otoliths using standard techniques developed at the Central Ageing Facility (Morison *et al.* 1998). Validation of the ageing technique has been achieved using the bomb radiocarbon method (Kalish *et al.* 1997) and the progression of cohorts through the catches over a period of more than a decade (e.g. Punt *et al.* 2001, Tuck *et al.* 2004). The senior author (SR) undertook some ageing as a component of a PhD study but most of the age estimates reported here were from the CAF.

All increment counts were carried out using a stereomicroscope fitted with a polarising filter and a video camera to display the image on a computer monitor. Age estimates were made by counting the number of translucent zones visible along a line from the nucleus to the edge of the otolith using reflected light.

Blue grenadier otoliths contain many false checks and are often difficult to interpret (Kenchington and Augustine 1987). Thus primary otolith readings were conducted by one reader at the Central Ageing Facility (CAF), who has over ten years experience ageing blue grenadier otoliths. The CAF has developed procedures and protocols to ensure quality assurance in the process of production ageing. These include repeat ageing of a 25% sub-sample of otoliths collected and the estimation of age without reference to the size or sex of fish. A detailed description of these procedures and of the CAF ageing system is given in Morison *et al*. (1998).

Secondary readings by the primary reader of a sub-sample of 545 otoliths were used to estimate the index of average percent error (IAPE) using the equation:

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

where N is number of fish aged, R is number of times each fish is aged, X_{ij} is *i*th age determination of *j*th fish and X_j is average age calculated for the *j*th fish. The IAPE is considered a more informative estimate of age determination errors because it is not independent of the age of a species, unlike the traditional percent agreement method (Beamish and Fournier 1981). Estimates of IAPE were considered acceptable if they were below 5% as an IAPE below this level is indicative of consistent interpretation of ages (Morison *et al*. 1998).

Length and age data were applied to the von Bertalanffy growth equation using non-linear least squares. The data was examined for each sex separately and for the sexes combined including fish whose sex could not be determined or who were not sexed. The form of the von Bertalanffy growth equation used was:

$$L_t = L_\infty\left(1 - e^{[-K(t-t_0)]}\right)$$

where L_∞ is the theoretical maximum length; K is a growth coefficient; and t_0 is the theoretical age at zero length.

The relationship between length and weight of blue grenadier was examined using the standard equation:

$$W = aSL^{b}$$

where a is a constant; b is a parameter representing isometric growth; and SL is the standard length (cm). A preliminary analysis of covariance (ANCOVA) showed that the overall slopes of the regression of natural log-transformed weight against natural log-transformed length for males and females were significantly different during both non-spawning and spawning periods (p<<0.01). Hence, the length-weight relationships of both males and females were used separately in further analysis.

Length/age at maturity

The 50% length/age at maturity $(L_{50\% mature}, t_{50\% mature})$ was defined as the length/age at which 50% of the population sampled during the spawning season was sexually mature. This corresponds to stages III-V for both female and male blue grenadier. The length/age at maturity for blue grenadier was calculated using macroscopically staged gonads obtained from a sample of individuals collected over the spawning season in the four sampling regions.

Maturity relationships were established by plotting maturity ogives against both length and age. Length classes of 1 cm (SL) and age classes of 1 year were used. For each sex, a logistic curve was applied using the non-linear least squares procedure. The form of the logistic function used was:

$$\% mature = 100 / \left(1 + e^{a(b-c)}\right)$$

where a is a parameter representing the rate of increase in maturity; b is a parameter representing 50% maturity; and c is the 1 cm SL class or 1 year age class (Knuckey and Sivakumaran 2001).

Histological classification of ovaries

A total of 774 ovaries were examined histologically to verify macroscopic staging, to quantify the incidence of atretic oocytes, to observe the presence of postovulatory follicles (POFs) and to track seasonal changes in blue grenadier ovarian development (Table 3).

The transverse medial portions of the two ovaries at various stages of maturity were fixed in 7-10% buffered formalin and seawater to obtain measurements of whole oocytes. Whole mature, ripe and spent ovaries (stages III-V) were also fixed to obtain fecundity estimates. Ovaries were transferred to 70% ethanol for preservation after being kept for at least one month in the fixative.

Ovary samples were collected from May to September in 2000 (n = 261) and 2001 (n = 513). Data were pooled due to limited sample numbers collected in areas outside the WCT (Table 3).

Table 3. Numbers of blue grenadier ovaries staged histologically in all areas between 2000 and 2001 (data pooled by year).

Stage	Status	Area				Total
		EBS	ECT	WBS	WCT	
A	Chromatin nucleolar	-	-	-	-	-
B	Early perinucleloar	41	10	23	21	95
C	Late perinucleloar	64	9	14	6	93
D	Early cortical alveoli	46	4	6	1	57
E	Late cortical alveoli	16	1	10	4	31
F	Yolk	-	3	1	220	224
G	Nuclear migration	-	-	-	133	133
H	Hydration	-	-	-	96	96
I	Post ovulatory follicles	-	-	10	35	45
	Total	**167**	**27**	**64**	**516**	**774**

Abbreviations: EBS = Eastern Bass Strait; ECT = East coast of Tasmania; WBS = Western Bass Strait;

WCT = West coast of Tasmania

Ovary sections were blocked in paraffin wax and cut into 4 μm sections, mounted and subsequently stained in Harris's heamotoxylin and eosin (Luna 1968). Ovaries were staged on the basis of the most advanced type of oocyte present, regardless of their abundance (West 1990). The maximum and minimum diameters (mm) of five randomly selected oocytes, which had been sectioned through the nucleus, were measured (Foucher and Beamish 1980). Stages in oocyte development, postovulatory follicles and atretic oocytes were described according to several studies (Table 4).

Table 4. Microscopic description of histological sections and whole oocytes for female blue grenadier at various developmental stages (adapted from Hunter and Macewicz 1985 a, b, West 1990, Livingston et al. 1997).

Stage	Status	Histological oocyte	Whole oocyte
A	Chromatin nucleolar (CN)	Very small oocytes, large nucleus surrounded by a thin layer of dark-blue-stained cytoplasm	
B-C	Perinucleolar (PN)	Oocyte size increases slightly, as dark blue-stained cytoplasm thickens, nucleoli appear at the edge of the nucleus, cortical alveoli sometimes present in cytoplasm	Cytoplasm homogenous, brown and transparent, comparatively large dark brown nucleus
D-E	Cortical alveoli (CA)	Appearance of cortical alveoli in pale blue cytoplasm, pink-stained zona radiata distinguishable, oil globules appearing	Oocytes approximately spherical, cytoplasm thickened, darker, granular, but still translucent, nucleus still visible
F	Yolk (YO)	Marked increase in oocyte size, cytoplasm filled with pink-stained yolked granules, cortical alveoli and oil vesicles increase in size and number; degenerating; postovulatory follicles visible if spawning has started	Oocytes dark, completely opaque, size increasing with development, nucleus occluded; degenerating postovulatory follicles visible if spawning has started
G	Nuclear migration (NM)	Migration of nucleus to edge of oocyte, fusion of yolk granules into yolk plates; fusion of oil vesicles into the oil droplet; degenerating postovulatory follicles visible if spawning has started	Occurrence of partly translucent oocytes (hydrating), yolk plates visible, degenerating postovulatory follicles visible is spawning has started
H	Hydration (HY)	Further increase in size of oocytes, all pink-stained yolk granules fused into a few large plates	Occurrence of very large almost totally translucent oocytes, oil droplets visible
I	Postovularoty follicle (POF)	Postovulatory follicles type 1: zona radiata has numerous folds and an open cavity, granulosa cells aligned within the zona radiata Postovulatory follicles type 2: zona radiata has fewer folds, follicular cavity reduced, zona radiata thickened, granulosa cells are jumbled Postovulatory follicles are clearly visible, no yolked oocytes left except for a few undergoing atresia Oocytes at stages 1 & 2 predominate, no trace of postovulatory follicles left, advanced atresia of remaining yolked oocytes, hydrated oocytes sometimes still present in lumen	Postovulatory follicles visible, remaining yolked oocytes at early stage of atresia; Very small oocytes predominate, advanced atresia of remaining yolked oocytes

Fecundity estimates

Batch and annual fecundities were determined using the gravimetric subsampling method (Hunter *et al*. 1985). The annual fecundity of blue grenadier was estimated from the standing stock of yolked (YO) oocytes obtained from 140 females caught during the 2000 and 2001 spawning seasons. Only ovaries that exhibited no major atresia and no postovulatory follicles, and in which the oocytes were fully yolked, were used to estimate annual fecundity. Bulman *et al*. (1999) demonstrated that oocytes within blue grenadier ovaries were uniformly distributed. An analysis of variance conducted on data obtained from 10 fish showed no differences between subsamples across ovaries, or between subsamples along ovaries. However, Bulman *et al*. (1999) found a significant interaction between fish × ovary lobe, which suggested that while the effect is not consistent between left or right lobes, there was a significant difference between ovary lobes within the same fish. To overcome this, one 1 g tissue sample was randomly selected from within left and right ovaries, and the fecundity per fish then estimated as the average number of oocytes per lobe (Bulman *et al.* 1999). This recommendation was followed in the present study.

Oocytes were routinely dissociated from tissue samples and counted. These data were analysed and the following length fecundity equation applied:

$$fecundity = aSL^b$$

where a is a constant determined empirically; b is a parameter representing isometric growth; and SL is the standard length (cm) (Zar 1984).

Batch fecundity was estimated by counting the number of hydrated (HY) oocytes in the ovaries from 35 running ripe (stage IV) females. All samples were screened histologically, and only ovaries that showed no postovulatory follicles and no sign of major atresia were used to estimate batch fecundity. In addition, only ovaries in which hydrated oocytes formed a well defined mode were used. These data were analysed following the linear equation:

$$batch\_fecundity = a + bSL$$

where a is the point at which the line cuts the x-axis; b is the slope of the line and SL is the standard length (cm) (Zar 1984).

If a fish spawns more than once during a spawning period, yolked oocytes can be identified from unyolked oocytes at the beginning of the spawning period. Under these circumstances, annual fecundity is deemed determinate (Yamamoto 1956, Hunter and Macewicz 1985 *a*, 1985 *b*). To establish this for blue grenadier, sections from representative ovaries were selected and all individual oocytes were staged and then measured by taking the mean of the maximum and minimum diameters (mm) of randomly selected oocytes, which had been sectioned through the nucleus (Foucher and Beamish 1980). The size frequency of unyolked, yolked and hydrated oocytes were then plotted for each gonad stage.

Proportion of non-spawners

To determine female 'adult non-spawners' from 'adult spawners', ovaries were classified in two phases. Firstly, ovaries were staged histologically as 'non-spawners' or 'spawners' and secondly, 'non-spawners' were further classified as 'immature' or 'adult non-spawners' based on their length at 50, 75 and 95% maturity (Figure 2).

Phase I

Fish were classified as 'non-spawners' if the most advanced oocytes present were the chromatin nucleolar (CN), early perinucleloar (EPN), late perinucleloar (LPN) or the early cortical alveoli stage (ECA) corresponding to stages A-D. Fish were classified as 'spawners' if the most advanced oocytes present were at the late cortical alveoli (LCA), yolk (YO), nuclear migration (NM) or hydration (HY) stages, or if the sample contained POFs corresponding to stages E-I (Livingston *et al.* 1997) (Table 4).

Phase II

Following initial separation, 'non-spawners' were sorted into 'immature' or 'adult non-spawners' based on their respective lengths at 0, 50, 75 and 95% maturity (Figure 2). Due to the nature of commercial sampling during this study, limited numbers of large adult fish were caught outside the main spawning area (WCT). Therefore, to determine the proportion of 'immature' and 'adult non-spawners', a sensitivity analysis was conducted based on the histological maturity ogive established for female blue grenadier.

Histological maturity ogive

The 50% length at maturity was defined as the length at which 50% of the population sampled during the spawning season was sexually mature. This corresponds to histological stages E-I for female blue grenadier. The length at maturity was calculated using histologically staged gonads obtained from a sample of individuals collected over the spawning season in the four sampling regions. Maturity relationships were established by plotting maturity ogives against standard length. Length classes of 1-cm (SL) were used. Histological samples were not aged directly, thus non-spawning fish were sorted into 'immature' or 'adult non-spawner' based on length at maturity only.

Length frequency analyses

Length composition data were taken from a total of 9,251 fish in the four sampling regions (EBS, ECT, WBS and WCT) during the spawning period (June-August). Length data were grouped into 1-cm length (SL) classes, weighted length frequencies were standardised by calculating the relative weighted proportional (RWP) length distribution for each sample. The histological maturity ogive were overlaid over the length frequency histograms to examine any additional 'adult non-spawners' not examined histologically.

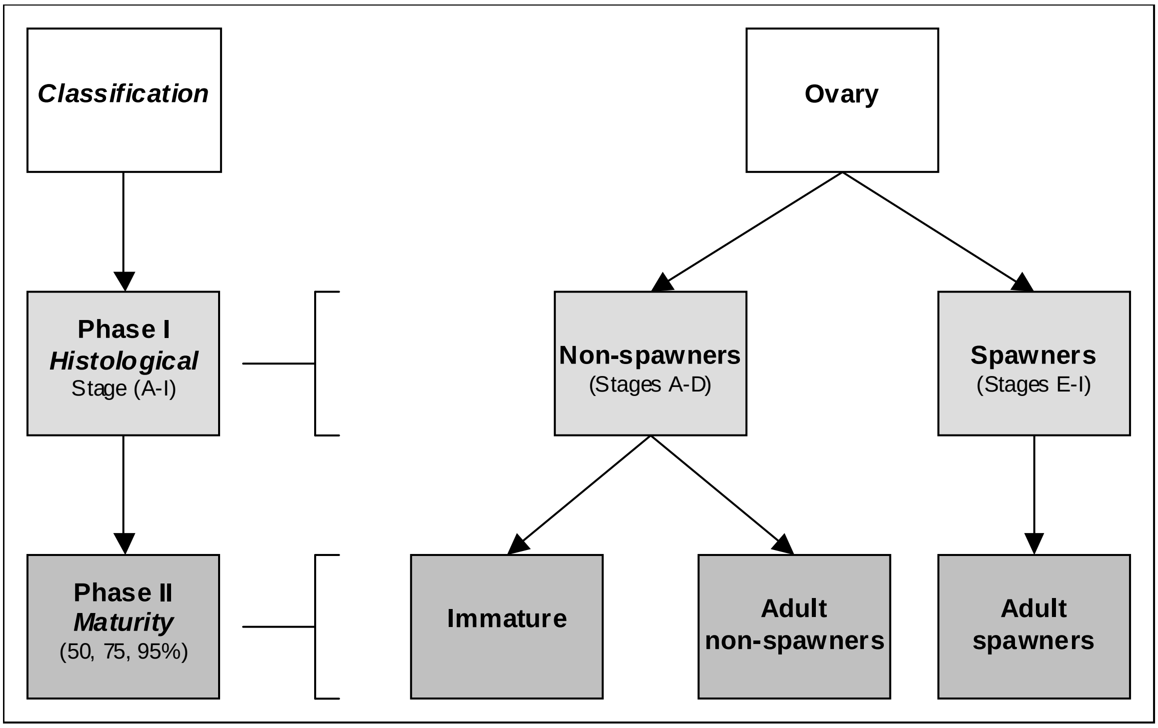


Figure 2. Classification of blue grenadier ovaries based on (i) histological status and (ii) length at maturity.

Turn-over rates

Length, age, sex ratio and gonadal stage data of blue grenadier collected during the spawning period from the WCT were summarised. These data were examined at a temporal scale of one month (June-August). Shifts in length, age, reproductive status and sex ratio were highlighted to determine the dynamics of blue grenadier during the spawning period. The primary objective of these analyses was to ascertain if there was clear evidence of a 'turn-over' of fish on the spawning grounds during the three-month spawning period and to provide some information on the likely amount. For the purpose of this study, 'turn-over' was defined as the movement of fish entering and leaving the grounds within the spawning period.

The average standard length and age of modes from frequency data were analysed by fitting normal distributions to the histograms of data using multinomial likelihoods (Haddon 2001). Age frequency data were obtained using age-length keys from otoliths collected during the spawning period, and the corresponding year when they were collected. Age/length-classes were weighted using the relationship used to weight length frequency distributions (see above). By following the changes in the modal groups (i.e. how age-classes change through the spawning system), the dynamics present are described. A conceptual model is presented and the likely extent of turn-over suggested.

Per recruit analyses

Standard age-based models were used in the per-recruit analyses. Both yield-per-recruit and eggs-per-recruit were modelled against age at one-year intervals, and models were used to calculate the recruit for a period of 25 years, the approximate maximum age recorded for blue grenadier (Kenchington and Augustine 1987, Smith 1998, Kalish *et al.* 1997).

Yield per recruit

Yield-per-recruit (YPR) analyses were carried out to examine the yield per recruit from the fishery that could be obtained from the stock, at different combinations of fishing mortality (F) and age at first capture (t_c).

Data required for the YPR analyses included the length-weight relationship and the von Bertalanffy growth function. Growth parameters were based on work conducted by the Central Ageing Facility (Morison 1996) at the Marine and Freshwater Resources Institute. The length-weight relationship was derived from the information collected in this study. The age-specific selection coefficient (s) was calculated as the proportion of each length class that is vulnerable to the fishing gear following Punt *et al.* (2001). Since Punt *et al.* (2001) determined that selectivity differs markedly during the non-spawning and spawning periods, two selection coefficients were used. The YPR was calculated using the following equation:

$$YPR = \sum_{t-t_c}^{t_\lambda} \frac{F_y^{ns} s_t^{ns} + F_y^{sp} s_t^{sp}}{F_y^{ns} s_t^{ns} + F_y^{sp} s_t^{sp} + M} N_t W_t \left(1 - e^{-\left(F_y^{ns} s_t^{ns} + F_y^{sp} s_t^{sp} + M\right)}\right)$$

where t_λ is the maximum age; t_c is the age at first capture; F_y^{ns} and F_y^{sp} are the fully selected, instantaneous rates of fishing mortality for the non-spawning and spawning periods in year y (in the yield-per recruit analyses these are assumed to be constant across years), respectively; s_t^{ns} and s_t^{sp} are the selectivity coefficients for each age-class t for the non-spawning and spawning periods respectively; M is the instantaneous natural mortality; W_t is the whole weight of blue grenadier at a given age t; and N_t is the number of blue grenadier surviving to time t. The parameter N_t was calculated using the following equation:

$$N_t = N_{t-1} e^{-\left(F_y^{ns} s_{t-1}^{ns} + F_y^{sp} s_{t-1}^{sp} + M\right)}$$

Egg per recruit

Egg-per-recruit (EPR) analyses were carried out to examine the maximum egg production from the fishery that could be obtained from the stock at different combinations of fishing mortality (F) and ages at first capture (t_c).

Data requirements for the EPR analyses are similar to those for YPR analyses. However, the growth parameters used strictly pertain to females, as does the length-weight relationship. In addition, the length-fecundity relationship and the logistic maturation curve are incorporated into these analyses.

As for YPR analyses, fishing mortality on a specific age class is modified by the proportion of that age class which is vulnerable to capture. This principle is also applied to fecundity (E_t), in terms of the proportion which is sexually mature (p_t), and age at first capture. Thus, total fecundity (T_t) is expressed in terms of:

$$T_t = \begin{cases} p_t E_t & t \geq t_c \\ 0 & t < t_c \end{cases}$$

Thus, EPR was then calculated as:

$$EPR = \sum_{t=t_c}^{t_\lambda} T_t N_t$$

Results and Discussion

Fishery data

As noted earlier, there has been a rapid increase in catches from the spawning fishery (Figure 3). Until 1996, annual catches from the non-spawning component of the fishery were consistently higher. This increase in catches was mostly due to a number of large vessels and factory trawlers operating in the spawning fishery. By 1997, these vessels accounted for over 90% of total landings and operated primarily during the spawning season. Consequently, to allow comparisons between fishing zones, mean monthly catch data were considered in two periods, 1986-1996 and 1997-2003 (Figure 4). NSW data are not shown because monthly catches were low compared to the other areas.

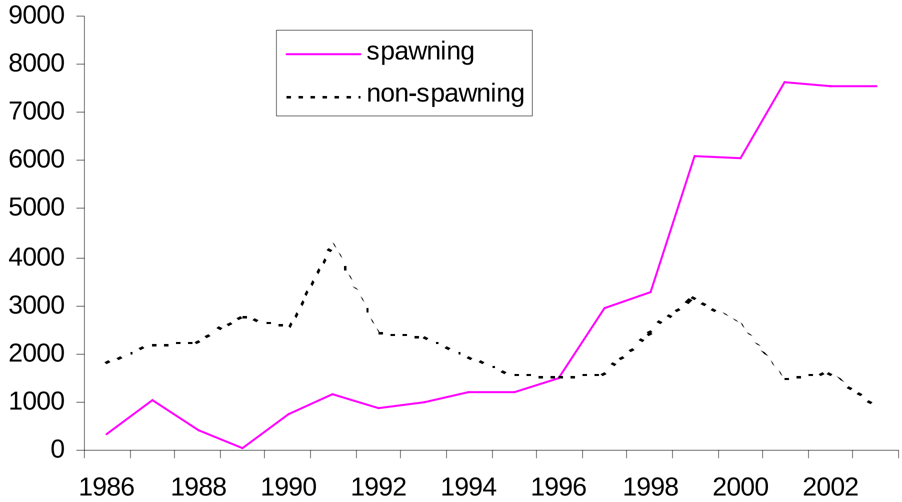


Figure 3. Annual landings of blue grenadier for the spawning and non-spawning fisheries

During 1986-1996 mean monthly catches were the highest off WCT during winter, peaking at over 230 t in July but were much lower during the other seasons. The pattern was similar during the second period (1997-2003) but mean monthly catches were considerably higher (July 2500 t). Monthly catches were considerably lower in the other zones (similar during both periods) with highest catches generally during late summer/autumn except off Eastern Victoria where catches although low (less than 50 t) showed a slight increase in June during both periods. In all areas, other than WCT, lowest catches were recorded in July and August.

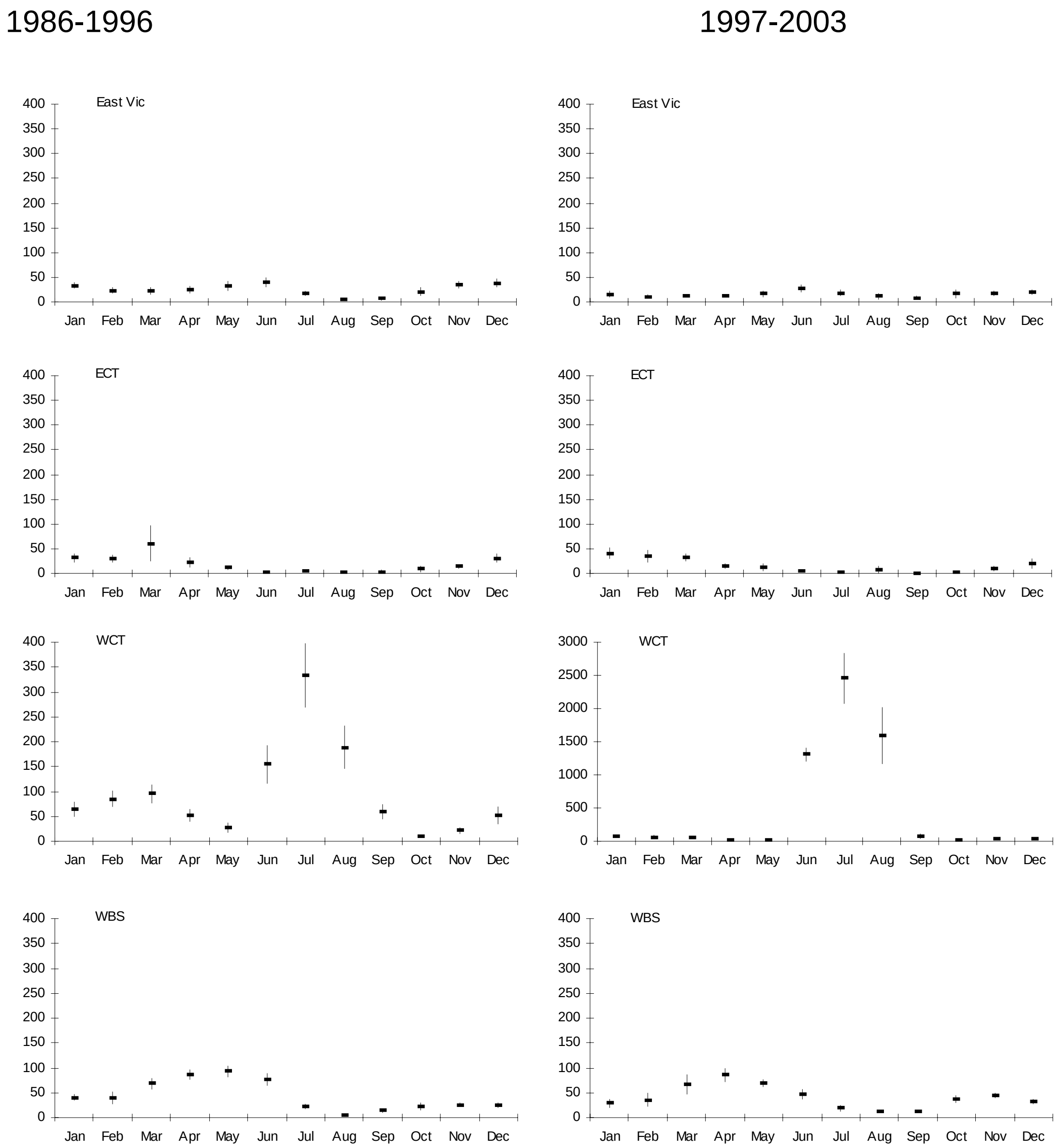


Figure 4. Mean monthly catch (tonnes) of blue grenadier by area for the periods 1986-1996 and 1997-2003. Note the different scale for WCT during the second period.

Biological data

Length composition

As previously reported (e.g. Smith 1998, Punt *et al* 2001, Tuck *et al*. 2004), the length composition for the spawning and non-spawning fisheries differ markedly. Overall, between 1999 and 2002, blue grenadier sampled from the non-spawning fishery ranged in length from 35 to 121 cm SL but all annual size distributions were dominated by fish <75 cm SL (Figure 5). In contrast, while fish sampled from the spawning fishery covered similar length classes (42 to 121 cm SL), fish >75 cm made up a significant component of samples in each year (Figure 5). Reflecting this, the mean length of blue grenadier sampled from the non-spawning and spawning fisheries between 1999 and 2002 was 66.5 and 79.8 cm SL, respectively. However, both size distributions show modal progression, reflecting the strong 1994 and 1995 year classes passing through the fishery (see below).

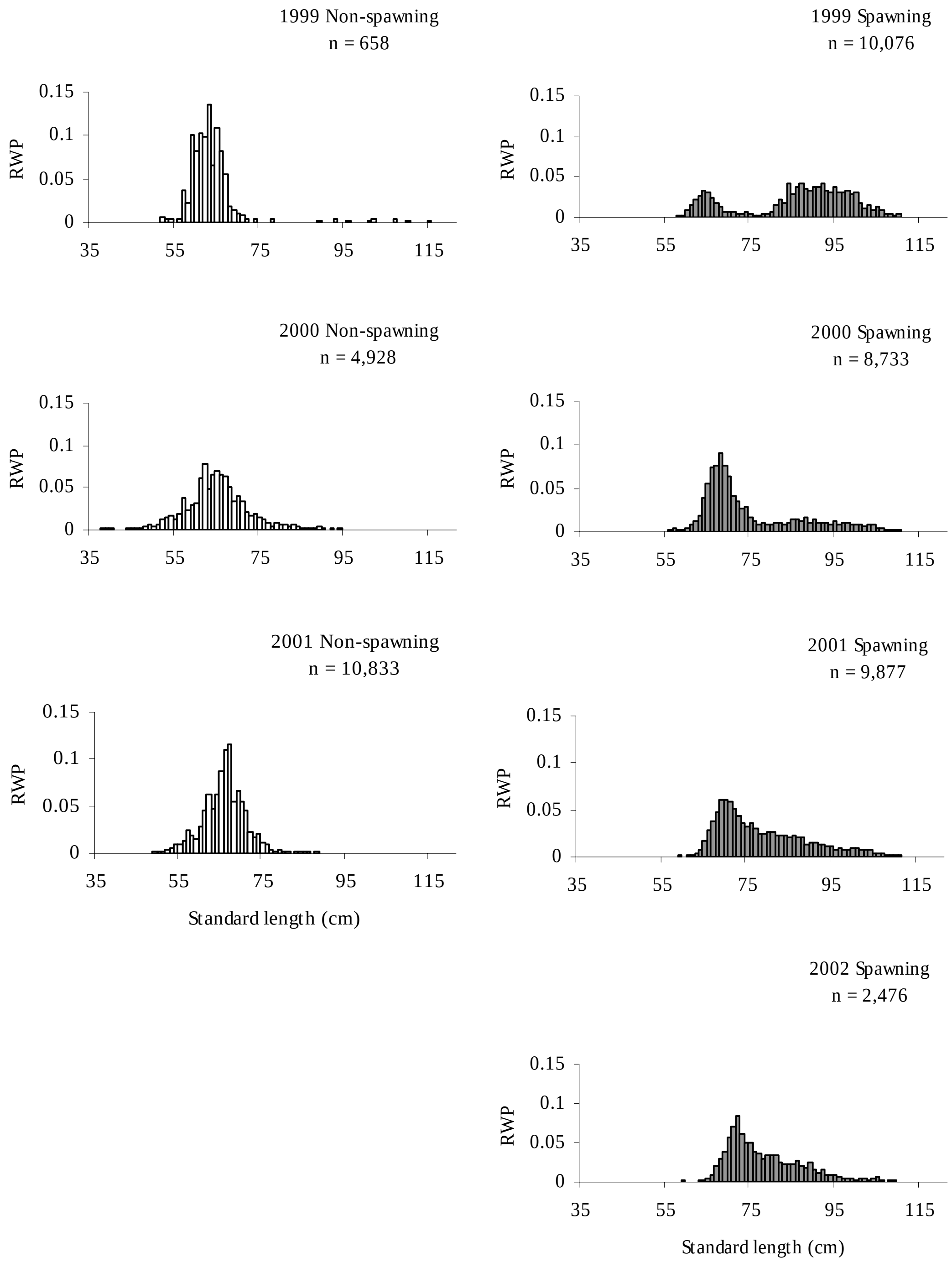


Figure 5. Length frequency distributions for blue grenadier taken by the non-spawning and spawning fisheries, 1999-2002.

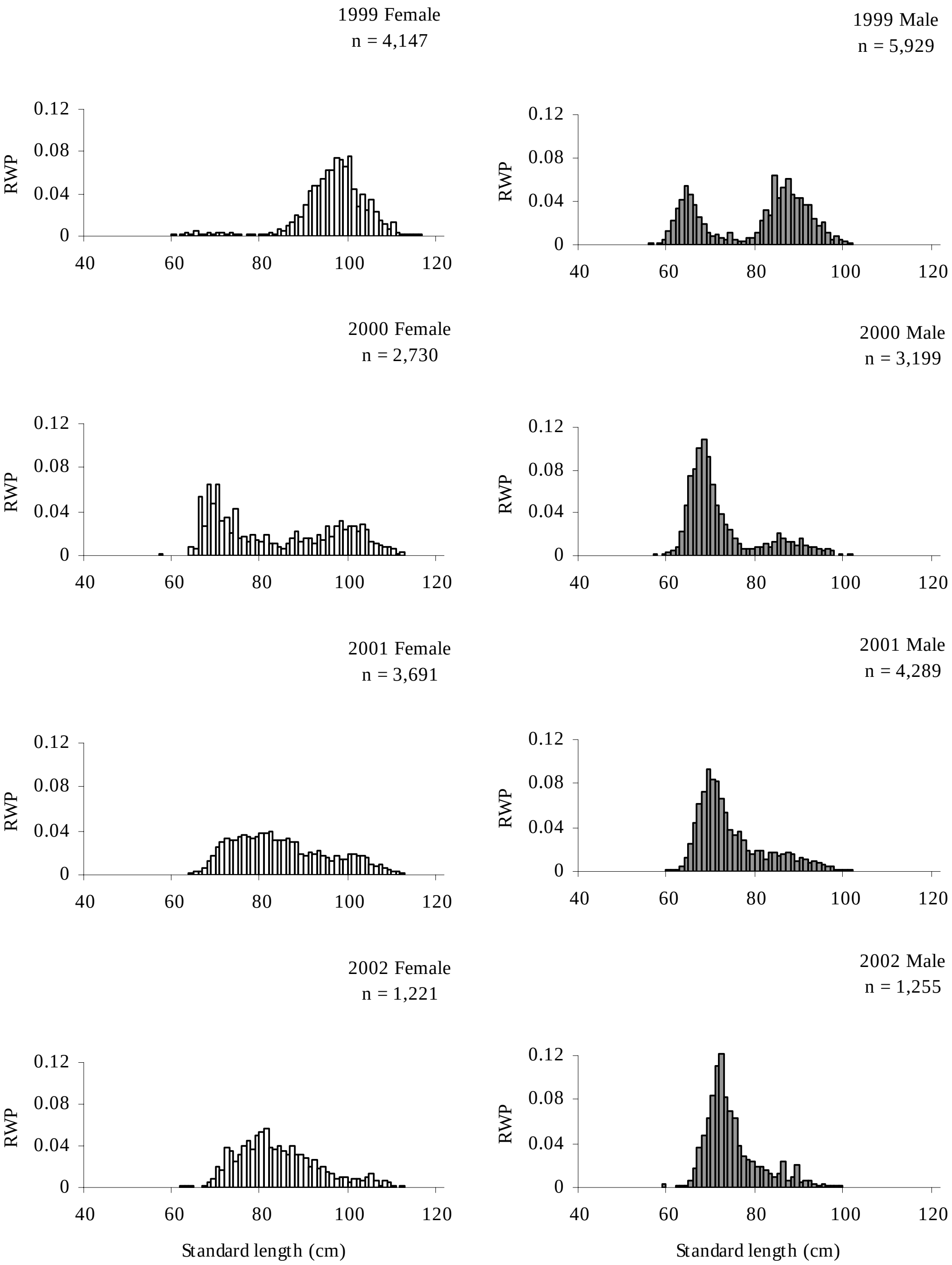


Figure 6. Length frequency distributions for female and male blue grenadier sampled from the spawning fishery, 1999 – 2002.

The length range of females and males was 56-121 and 42-108 cm SL, and the average length was 89.7 and 76.0 cm SL, respectively. The distribution of small males over time showed successive peaks at 63-65 cm SL in 1999, 67-69 cm SL in 2000, 69-71 cm SL in 2001 and 71-73 cm SL in 2002 (Figure 6). Similarly, small females exhibited this pattern with peaks at 67-69 cm SL in 2000, 81-83 cm SL in 2001 and 80-82 cm SL in 2002. However, the mode of small fish seen in the 1999 male distribution was not apparent for females. Excluding 1999, male and female blue grenadier <75 cm SL appear to dominate the distribution in all other years.

Age composition

Out of 6,802 blue grenadier otoliths that were aged during this study, 3,228 were from females, 3,439 from males and the remainder were unsexed. The oldest age recorded for females and males were 23 and 22 years, respectively. The age composition of spawning and non-spawning blue grenadier differed distinctly. During non-spawning periods, the catch consisted of primarily fish <7 years old). The composition during spawning periods was initially distinctly bimodal, ranging from 2-23 years old, but this pattern became less marked as the strong 1994 and 1995 year classes dominated the fishery (Figure 7). The progression of these year classes is clear in samples from both fisheries. The overall average age of blue grenadier during non-spawning and spawning periods between 1999 and 2002 was 5.7 and 9.0 years, respectively. The age compositions of each sex in the spawning fishery were relatively similar except that young males entered the fishery one year earlier than females and, at least initially, females were more abundant in the older age groups.

The seasonal length and age distributional pattern is largely explained as a reflection of the geographical distribution of blue grenadier throughout the year. Blue grenadier are found widely along the continental slope and shelf edges from central NSW to southern WA, including the coast of Tasmania and across the Great Australian Bight (Kailola *et al.* 1993, Smith 1994). It is generally accepted that mature adults ready to spawn annually migrate from this extensive range to the primary spawning grounds on the WCT (Thresher *et al.* 1989, Gunn *et al*. 1989, Smith *et al.* 1995). Thus, during non-spawning periods, the fish are dispersed widely and small-young fish make up a greater proportion of catches. During the spawning period the entire size range of the mature population is recruited to the fishery and is aggregated on the WCT. Fishery data, particularly mean monthly catch by area as described above, are consistent with a major migration of adult fish to the WCT in winter.

In 1999, five year old males were the dominant age class but there were few five year old females. By 2000, six year olds dominated for both sexes. This suggests that at least in 1999, males reached maturity earlier and/or behave differently from females. This has also been noted in several other reports on the maturity of blue grenadier from New Zealand (Annala *et al*. 1999, 2003).

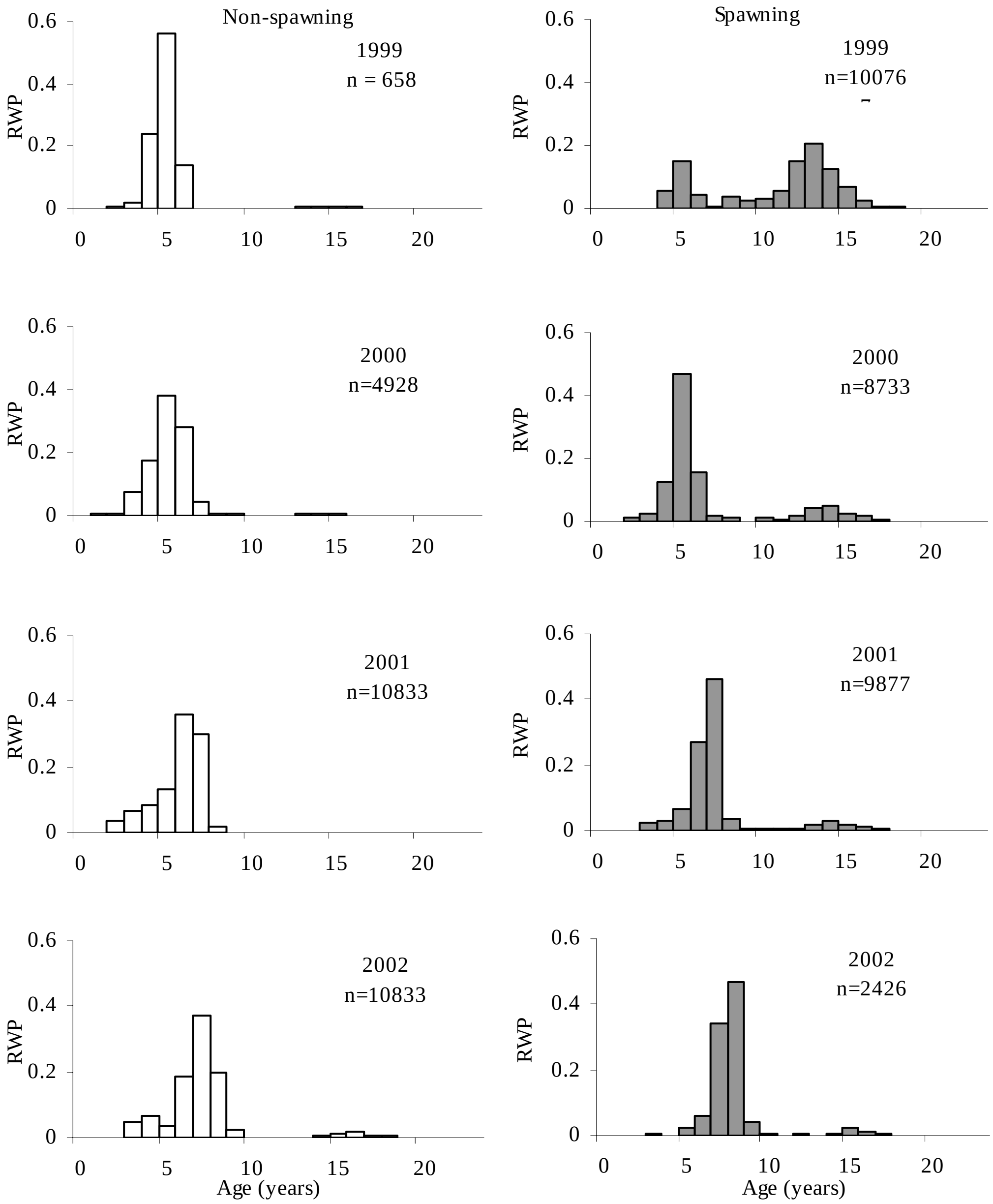
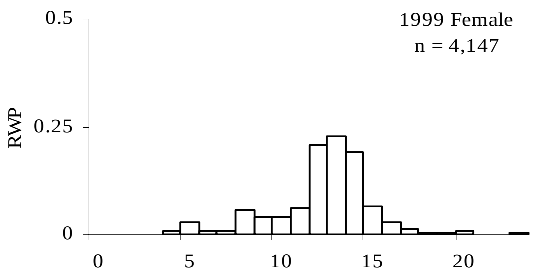
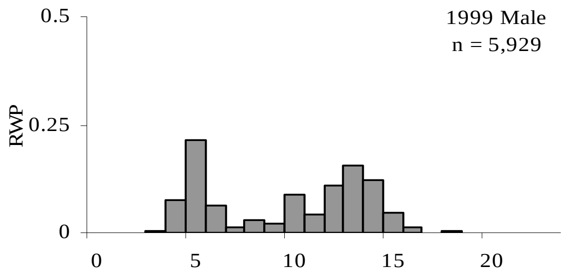
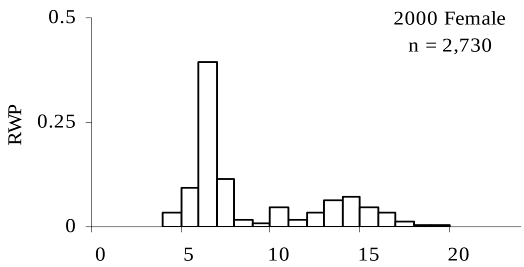
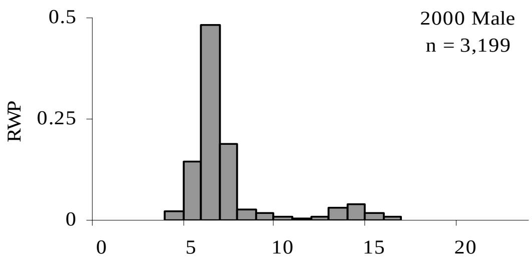


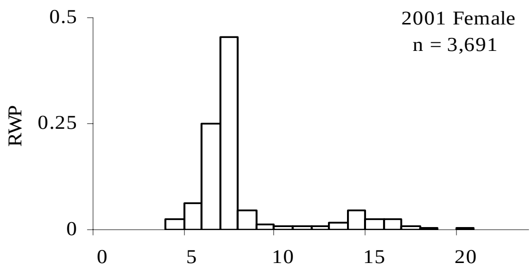
Figure 7. Age composition of blue grenadier, non-spawning and spawning fisheries, 1999-2002.

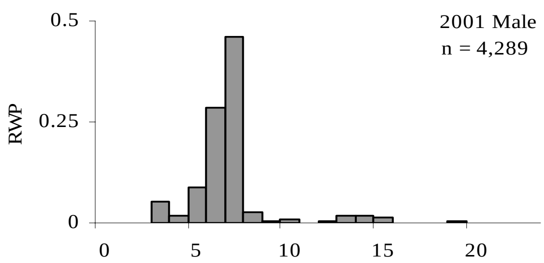

1999 Female
n = 4,147
RWP
0.5
0.25
0
0
5
10
15
20


1999 Male
n = 5,929
RWP
0.5
0.25
0
0
5
10
15
20


2000 Female
n = 2,730
RWP
0.5
0.25
0
0
5
10
15
20


2000 Male
n = 3,199
RWP
0.5
0.25
0
0
5
10
15
20


2001 Female
n = 3,691
RWP
0.5
0.25
0
0
5
10
15
20


2001 Male
n = 4,289
RWP
0.5
0.25
0
0
5
10
15
20

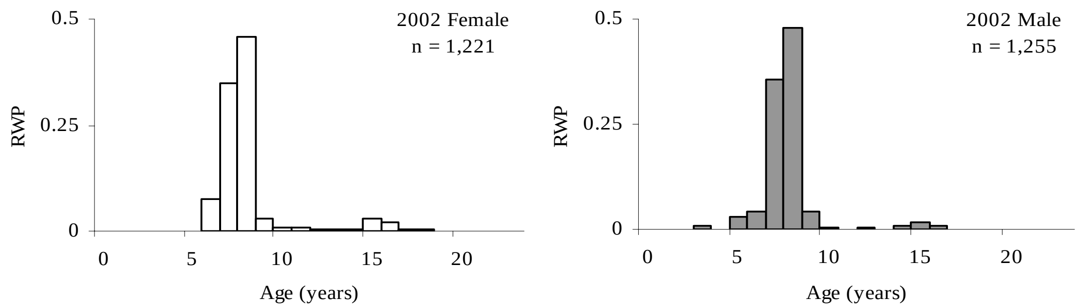


Figure 8. Sexed age composition for blue grenadier sampled from the spawning fishery, 1991-2002.

Growth

The mean length-at-age for blue grenadier was estimated by sex along with their corresponding growth curves (Figure 9). Mean length-at-age for both sexes do not follow the generated growth curves closely. Growth curves were different for female and male blue grenadier as indicated by the growth parameters. Females reach a higher asymptotic maximum and exhibit slightly higher growth rates than male blue grenadier (Table 5). The growth curve for females was similar to those previously reported (e.g. Kenchington and Augustine 1987, Smith *et al*. 1995). The male growth curve has a larger negative to than for previous studies. The strong 1994 and 1995 year classes grew slower than previous cohorts and this had a greater impact on the male growth curve (Figure 9). Punt and Smith (2001) discussed the implications of this for the stock assessment.

Table 5. Combined von Bertalanffy growth parameters for length-age relationships sampled from commercial catches of blue grenadier landed between February 1999 and August 2002 in all regions. Abbreviations: where L_∞ .= the theoretical maximum length; K = growth coefficient; t_0 = the theoretical age at zero length; n = number of individuals sampled.

Age	Overall	Female	Male
L_∞	118.7	115.2	111.6
K	0.1	0.2	0.1
t_0	-2.6	-0.9	-3.8
n	6,802	3,228	3,439
Range (years)	1-23	2-23	1-22
Average (years)	7.7	8.3	7.2

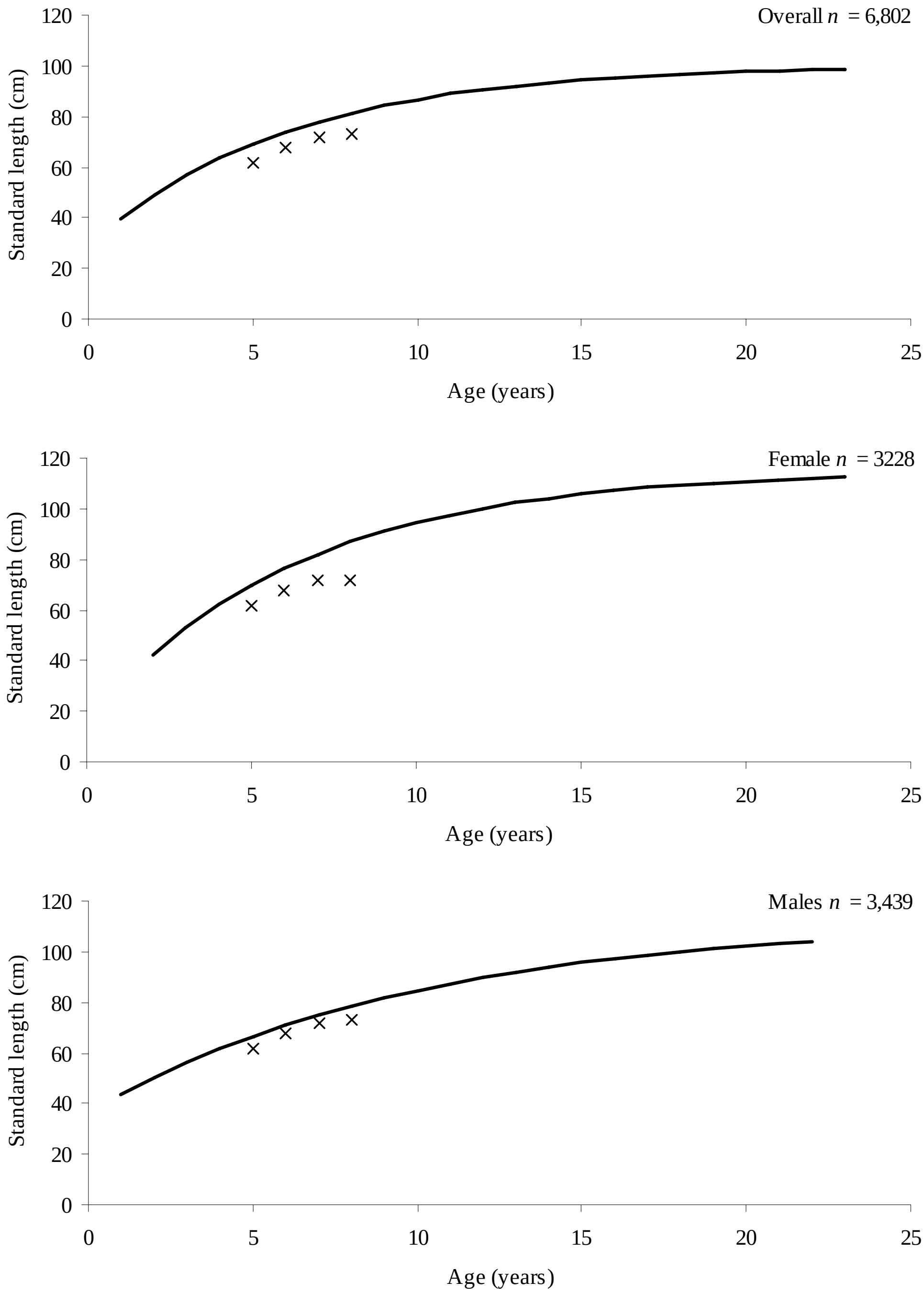


Figure 9. Von Bertalanffy growth curves for combined sexes, and female and male blue grenadier caught from 1999-2002. The mean lengths-at-age of the 1994 and 1995 year class over this period are denoted by x.

Length-weight relationships

The relationship between length (cm) and total weight (g) for female and male blue grenadier is shown in Figure 10. The weight range of females and males was 518-8445 and 420-5370g, respectively (Table 6). The overall average weight for females and males was 2909.2 and 1716.4 g, respectively (Table 6). Differences in average weight were also observed between spawning and non-spawning fish, with average weight of females and males during the non-spawning period being considerably lower than during the spawning period (Table 6). This difference was most obvious in females: on average spawning females were 1840 g heavier than their non-spawning counterparts. In contrast, spawning males were only 653 g heavier than non-spawning males.

Regression slopes of natural log-transformed weight against natural log-transformed length for females were significantly different between the non-spawning and the spawning periods (ANCOVA F=491.3, df=13,712, $p<<0.01$). Significant differences were also evident for males in the two periods (ANCOVA F=464.9, df= 18,140, $p<<0.01$).

Table 6 . Length-weight relationships of blue grenadier sampled from commercial catches landed between February 1999 and October 2001 in all regions. Spawning period corresponds to June - August; non-spawning period covers all remaining months. Abbreviations: a = intercept; b = exponent; n = number of individuals sampled; r2 = coefficient of variation.

Sex	Female			Male		
Period	Overall	Non-spawning	Spawning	Overall	Non-spawning	Spawning
n	13,716	2,589	11,127	18,144	3,773	14,371
	0.003	0.037	0.005	0.009	0.052	0.011
b	3.1	2.5	3.0	2.8	2.4	2.8
r^2	0.94	0.80	0.93	0.90	0.69	0.91
Range (g)	518-8445	559-4660	518-8445	420-5370	475-3125	420-5370
Average (g)	2909.2	1415.8	3256.7	1716.4	1199.5	1852.2

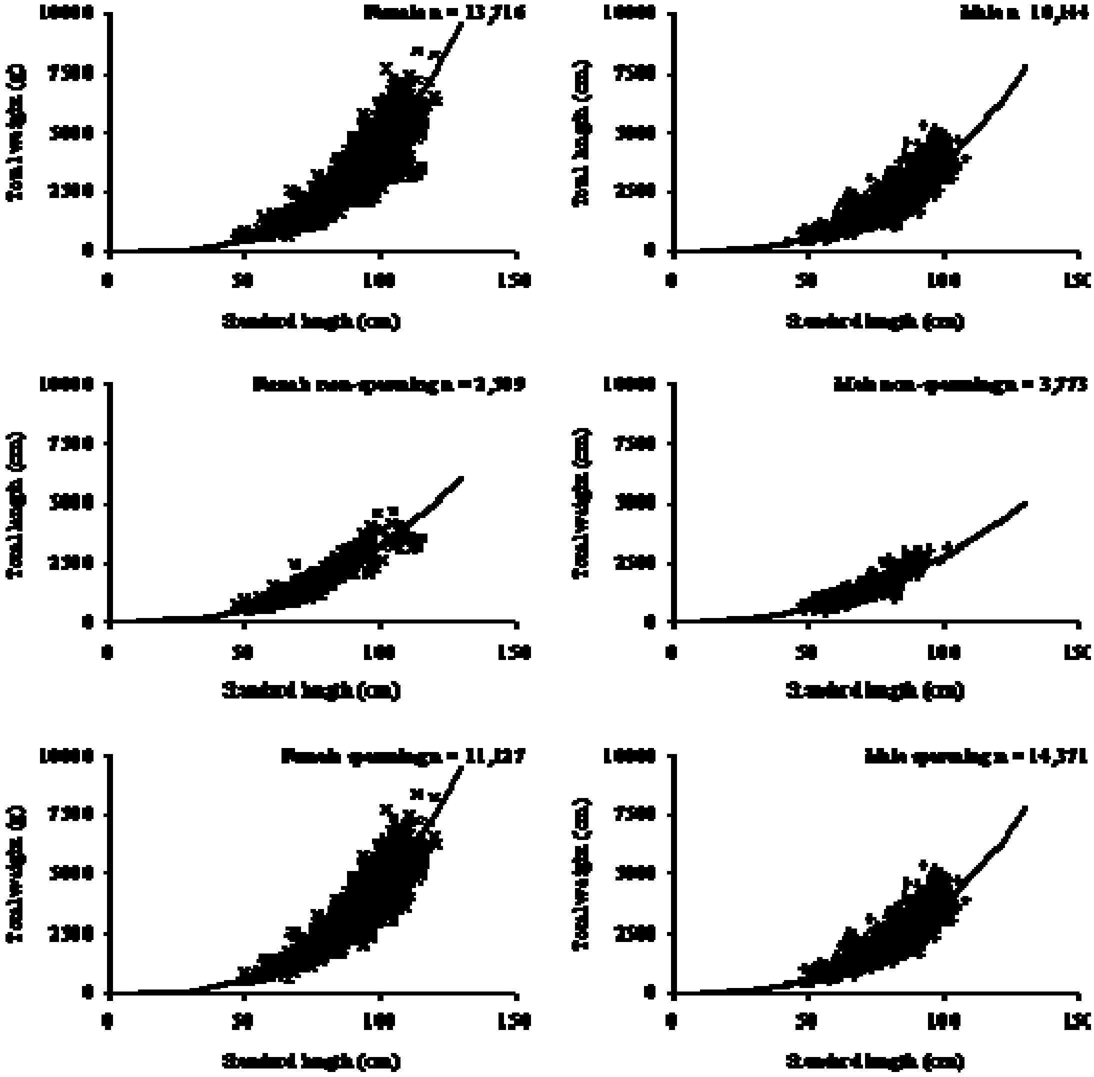


Figure 10. Length weight relationships for spawning and non-spawning blue grenadier.

Gonad development

Gonadosomatic indices

Mean gonadosomatic indices (GSIs) in female blue grenadier peaked at stage IV (running ripe) (13.6%). Mean GSIs were similar for females caught during the 2000 and 2001 spawning periods (Figure 11). The range of GSIs differed markedly between stages, particularly between stage III-V females in both 2000 and 2001.

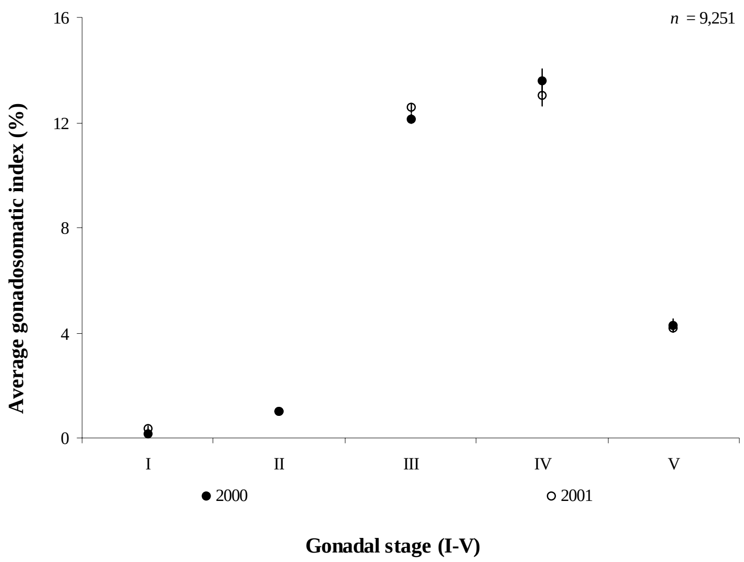


Figure 11. Mean (± 95% CL) gonadosomatic index (%) for female blue grenadier at various developmental stages in all areas 2000 and 2001.

In the WCT region, mean GSIs exceeding 10% were observed between June and August in both 2000 and 2001. Peaks in mean GSIs (>12%) were in June in 2000 and July in 2001. Mean GSIs exceeded 5% in the ECT region during July 2000 and September 2001. No change in mean GSI were recorded in EBS or WBS (Figure 12).

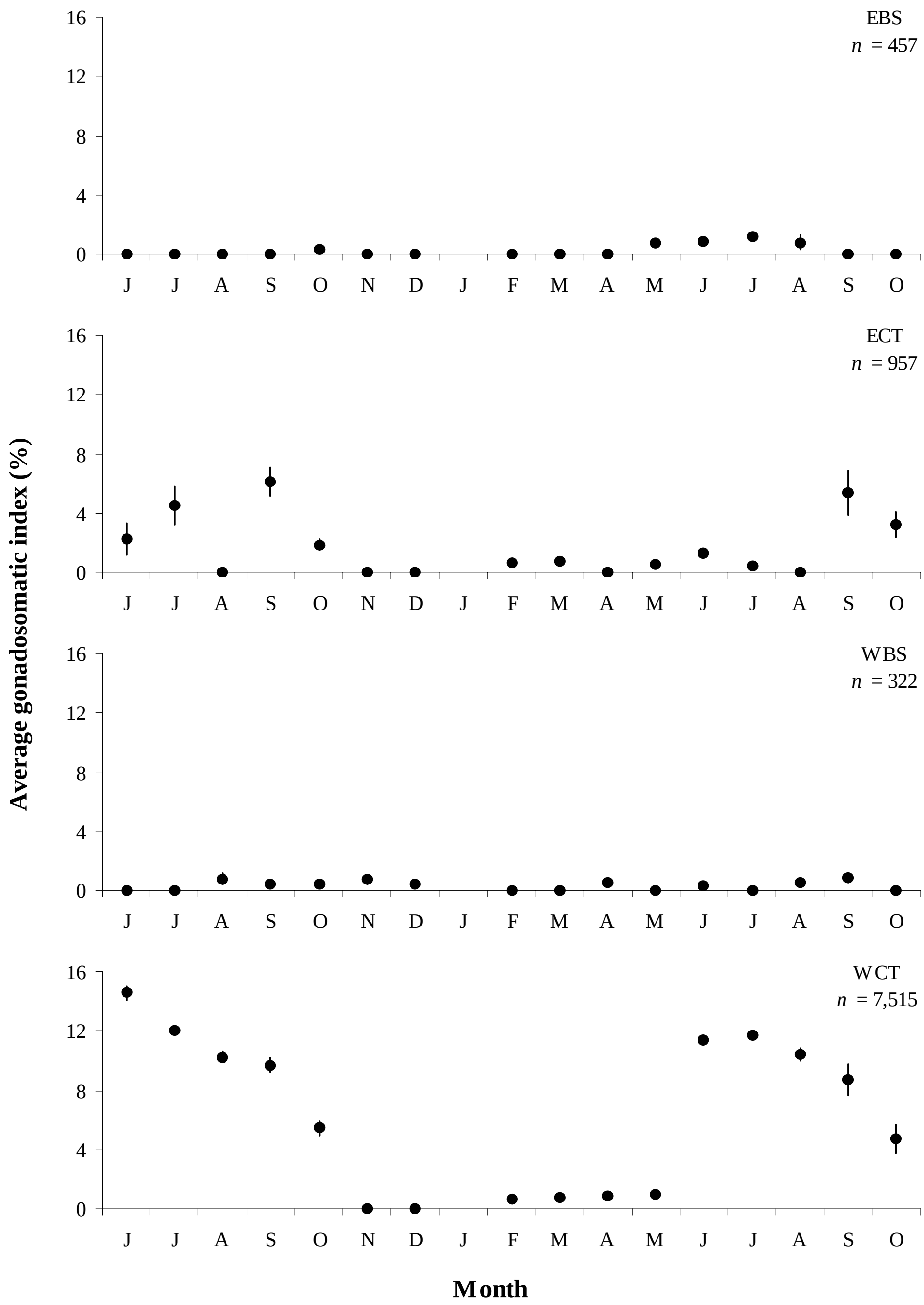


Figure 12. Mean monthly GSIs (+/- 95%CI) of female blue grenadier by area, June 2000 to October 2001.

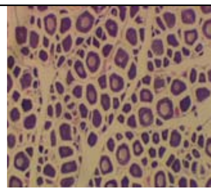
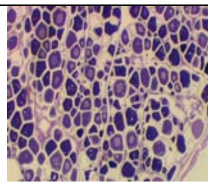
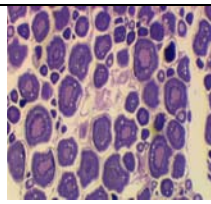
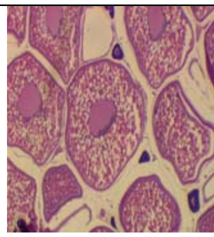
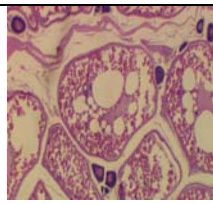
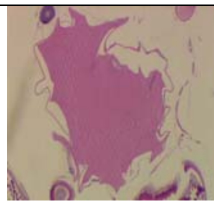
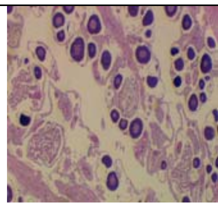
Macroscopic and microscopic description of gonads

Descriptions of macroscopic and microscopic stages for female blue grenadier are shown in Table 2 and Table 7, respectively. Oocytes are described in Table 4.

The ovaries of immature females (stage I) are slender, thread-like, transparent and often pink in colour. Oocytes are not visible to the naked eye. Histological examination reveals very small oocytes at the chromatin nucleolar stage. As development proceeds, oocyte size increases slightly and nucleoli appear at the edge of the nucleus i.e. the perinucleolar stage. Examination of whole stage I oocytes reveal small, transparent brown oocytes with a large dark brown nucleus; these are known as the reserve oocytes.

Stage II ovaries (maturing or resting) are creamy white in colour, slightly swollen and tube like. Oocytes are visible to the naked eye and are granular in appearance. Histological sections show the appearance of cortical alveoli in the cytoplasm with the zona radiata also visible, in what is known as the cortical alveoli stage. Stage II whole oocytes under the microscope are spherical and translucent, with dark, thick cytoplasm.

Table 7. Histological sections showing macroscopic and microscopic developmental stages for female blue grenadier.

Macroscopic		Microscopic		Plates
Stage	**Status**	**Stage**	**Status**	
I	Immature	A	Chromatin nucleolar (CN)	
II	Maturing/ Resting	B	Perinucleolar (PN)	
		C	Cortical alveoli (CA)	
III	Mature	D	Yolk (YO)	
		E	Nuclear migration (NM)	
IV	Running ripe	F	Hydration (HY)	
V	Spent	G	Postovularoty follicle (POF)	

Maturing ovaries (stage III) are large and swollen, and pink in colour, with two or more sizes of eggs visible to the naked eye. Histological sections show oocytes in the yolk stage of development. Oocytes show a marked increase in size and the cytoplasm is filled with pink-stained yolk granules. Cortical alveoli and oil vesicles also increase in number. Postovulatory follicles may be present in mature sections if spawning has begun. Whole stage III oocytes are dark and completely opaque and have increased greatly in diameter from an average 0.2 to 0.7 mm.

Stage IV ovaries (running ripe) are large, swollen and generally pink to deep red in colour. Clear translucent eggs are visible to the naked eye. Histological examination of stage IV ovaries show two distinct stages of oocyte development, namely the nuclear migration stage and the hydration stage. The former exhibits migration of the nucleus to the periphery of the oocyte and fusion of yolk granules into yolk plates, whereas the latter exhibits a slight increase in size with all pink-stained yolk granules fusing to form a few large plates. Once again postovulatory follicles are visible in sections where ovulation has started. Whole oocytes are on average 1.2 mm in diameter, they are almost totally translucent, and contain large oil droplets.

Spent ovaries (stage V) appear flaccid and tube-like, are dark red to purple in colour, and have only a few eggs remaining attached to the ovary wall. Histological examination of stage V ovaries shows large numbers of postovulatory follicles and reserve oocytes. Whole oocytes examined from stage V ovaries are difficult to classify, but primarily consist of reserve oocytes and a few large translucent oocytes.

Several of the ovaries examined during the spawning period contained postovulatory follicles, together with yolked and hydrated oocytes. This provides strong evidence to suggest that blue grenadier are multiple spawners (i.e. group synchronous). That is they release their eggs in several batches during one defined spawning period (West 1990).

Oocyte development

Stage I and II females contained primarily one mode of reserve unyolked oocytes ranging from 0.05 to 0.35 mm in diameter. Reserve oocytes are defined as those oocytes which are not going to spawning in the oncoming spawning period that this the stage before cromatin nucleolar stage (Livingston *et al.* 1999).

This group of oocytes was easily distinguishable from the larger yolked and hydrated oocytes observed in more mature individuals. A bimodal distribution of yolked and hydrated oocytes was apparent in stage III and IV females, with peaks at around 0.75 and 1.15 mm diameter, respectively. The first mode of yolked oocytes was clearly differentiated from the reserve oocytes and ranged from 0.45 to 0.85 mm in diameter. These oocytes were fully yolked and ready to be shed during the oncoming spawning season. The second mode of oocytes ranged from 0.90 to 1.35 mm in diameter and were fully hydrated and ready to be released immediately. In stage V ovaries individuals had both reserve oocytes (0.05-0.35 mm) and a few yolked (0.45-0.85 mm) and hydrated oocytes (0.9-1.35 mm) (Figure 13).

A similar pattern was observed for oocyte diameters over time. Progressive peaks in mean diameter were found in May prior to spawning (0.15 mm) and in June at the beginning of spawning (0.7 mm). In July and August during peak spawning, the distribution was bimodal, exhibiting peaks at 0.7 mm and 1.15 mm respectively. All four months contained reserve unyolked oocytes (Figure 14).

The oocyte diameters mentioned above were those measured from fresh gonad samples. They were slightly larger than those in the histological samples, especially in the later stages of development because histological processing causes shrinkage of oocytes (West 1990) (Figure 15).

Oocyte size frequency indicated that females developed batches of oocytes each season, a process associated with total or isochronal spawning. This is consistent with observations made by Gunn *et al*. (1989), who determined that blue grenadier were either synchronous or group synchronous.

This study utilised a five-stage macroscopic system in contrast to other studies for SESSF species, which used a seven-stage macroscopic classification system (Livingston 1990; Baelde 1996; Knuckey and Sivakumaran 2001). Macroscopic staging is a widely used technique to determine spawning condition in fisheries studies and can be used to great success when validated by histological staging (West 1990). However, the method has certain limitations. Gonadal development is continuous, variation exists between species and within species and readings are highly subjective (Holden and Raitt 1974; West 1990; King 1996). In the field macroscopic staging requires considerable experience on part of the researcher (West 1990) and variation in gonadal development does not necessarily merit assigning an increased number of maturity stages (Treasurer and Holliday 1981). Consequently, as staging was conducted in the field by several researchers, a five-stage system was adopted to reduce some of the uncertainty associated with macroscopic staging. A five-stage macroscopic staging system has also been utilized recently by Mackie and Lewis (2005) for Spanish mackeral.

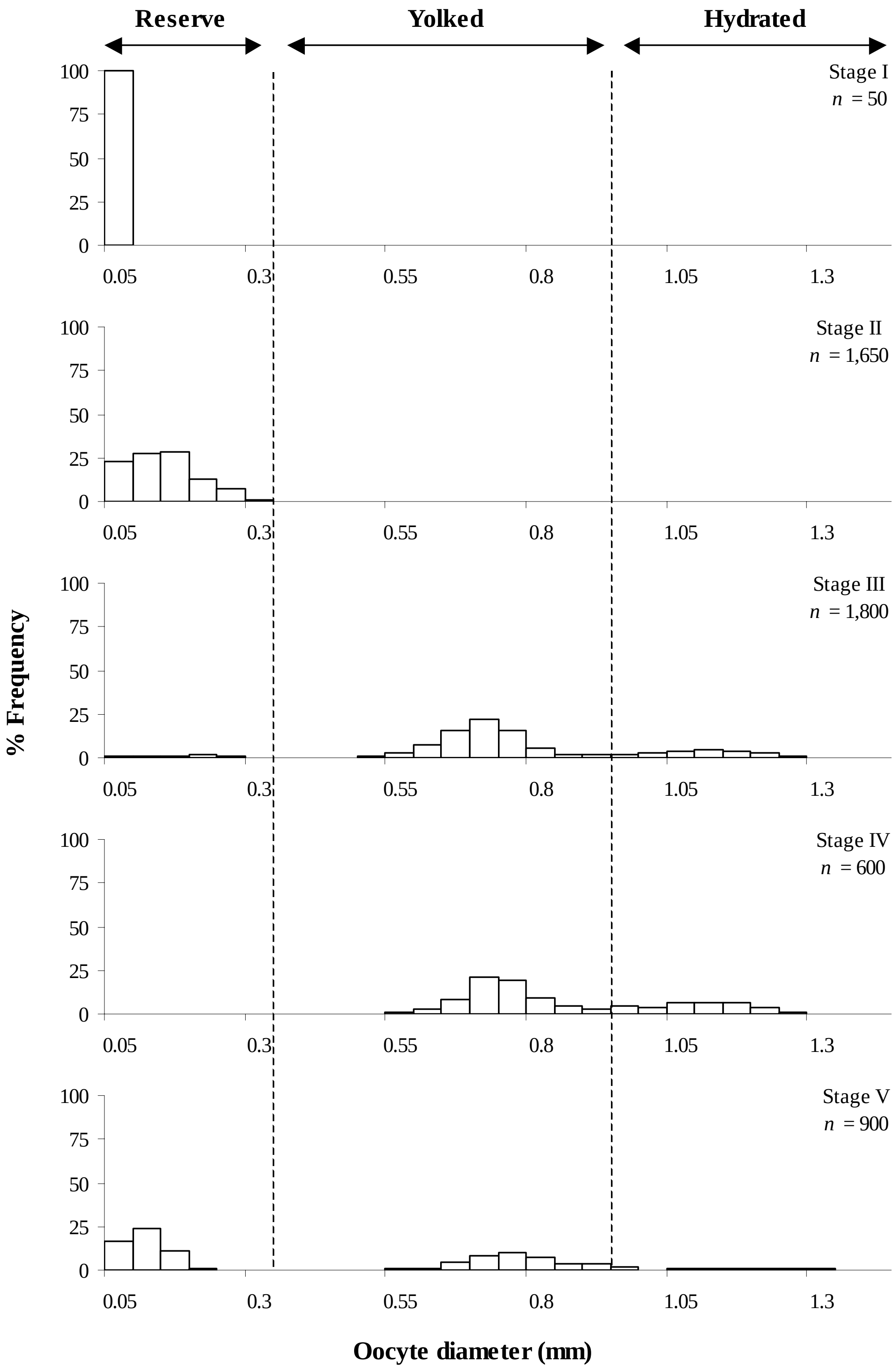


Figure 13. Percentage frequency distributions for oocyte diameter by stage (based on whole oocytes). Data for 2000 and 2001 combined.

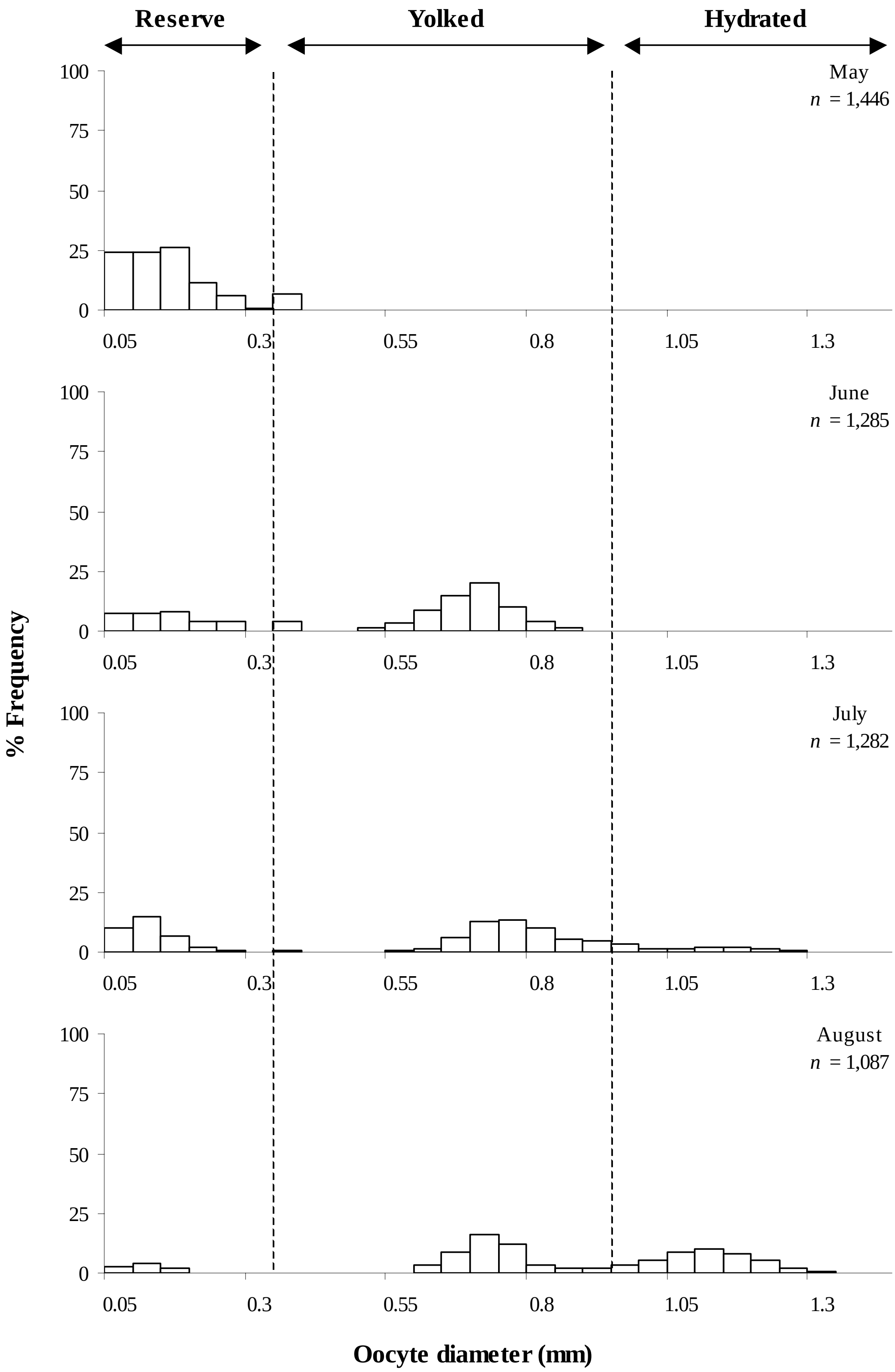


Figure 14. Percentage frequency distributions for oocyte diameter by month, Data from 2000 and 2001 combined.

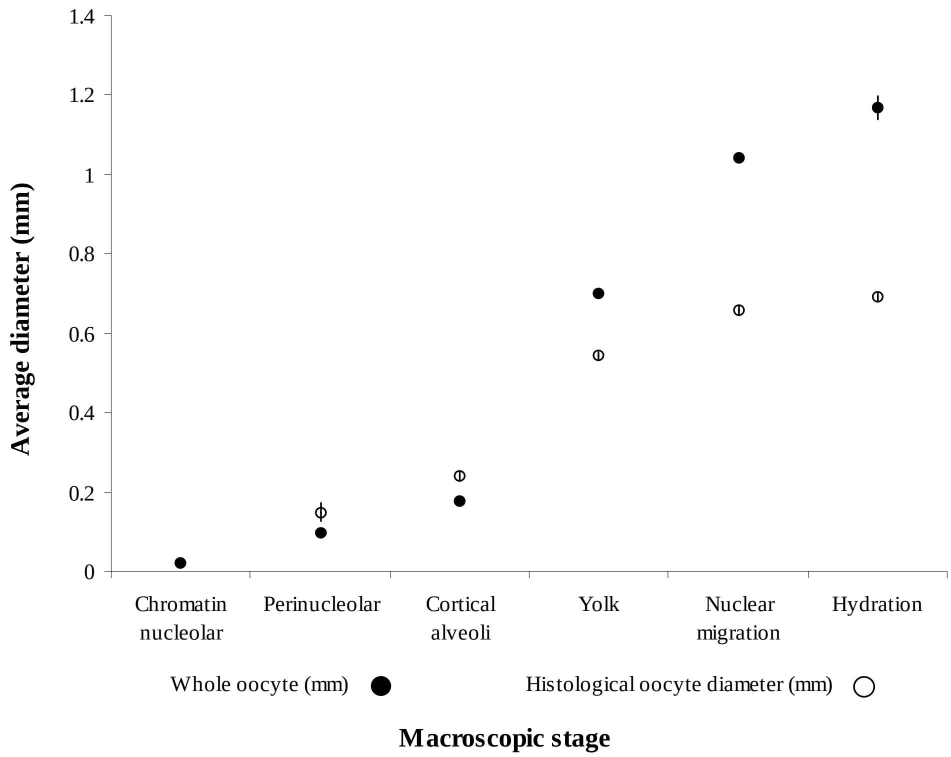


Figure 15. Mean oocyte diameter (+/- 95% CI) by stage measured from whole oocyte and histological preparation.

Length and age at maturity

Females with a GSIs >3% were usually >65 cm SL. All immature (stage I) females had GSIs <1%, with the maximum length of a stage I female reaching 74 cm SL. Only 5.7% of maturing/resting (stage II) females had GSIs >3%. Of these, all stage II females with GSIs >3%, were >80 cm SL and therefore considered to be resting, maturing females. Over 96% of mature (stage III) females had GSIs >3% and were generally >61 cm SL. Over 98% of running ripe (stage IV) females had GSIs >3%. Over 60% of spent females (stage V) had GSIs >3% and were >65 cm SL. There was considerable variation in GSIs in stages III-V, as some females had already shed an unknown amount of oocytes resulting in an overall loss of ovary mass. GSI coupled with length information indicate female blue grenadier maturity to be 65 cm SL (Figure 16). The estimated lengths at 50% maturity for females and males were 63.7 and 56.8 cm SL, respectively (Figure 17).

GSI coupled with age information indicate female blue grenadier maturity to be approximately 4 to 5 years (Figure 18). The estimated ages at 50% maturity for females and males were 5.4 and 4.3 years, respectively (Figure 19).

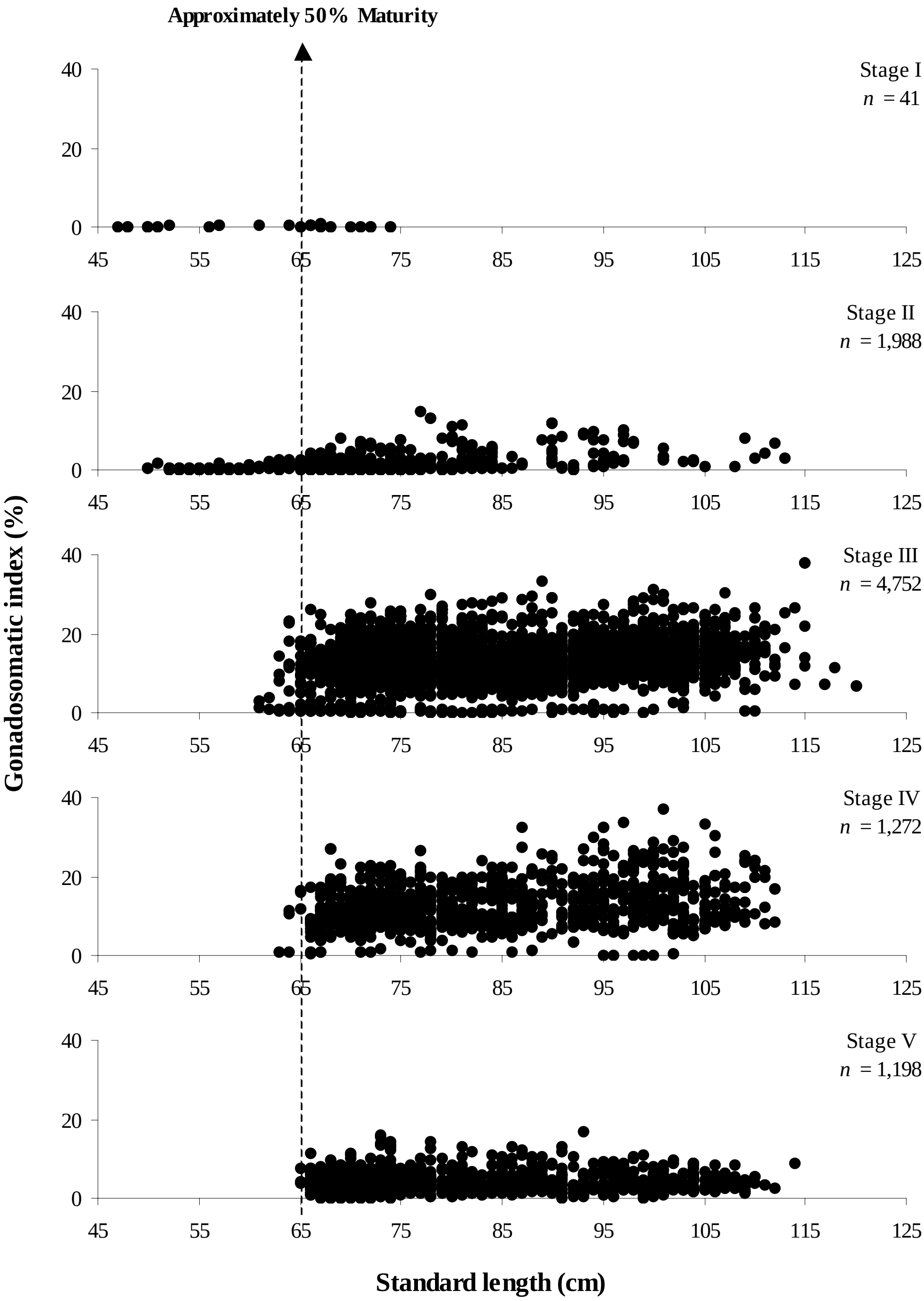


Figure 16. GSI versus length for female blue grenadier by stage. Data for 2000 and 2001 combined.

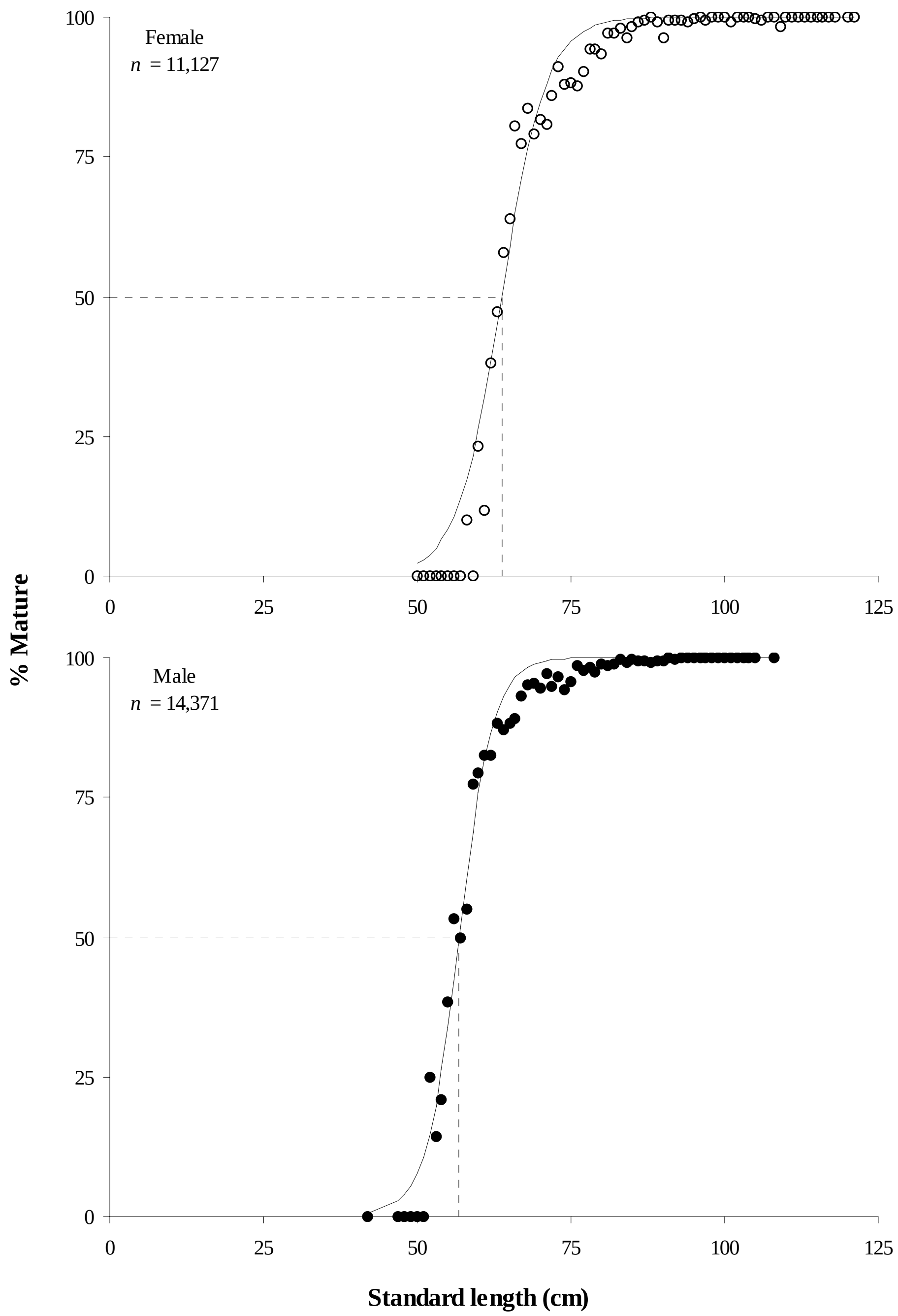


Figure 17. Maturity ogive by length for female and male blue grenadier, 1999-2001.

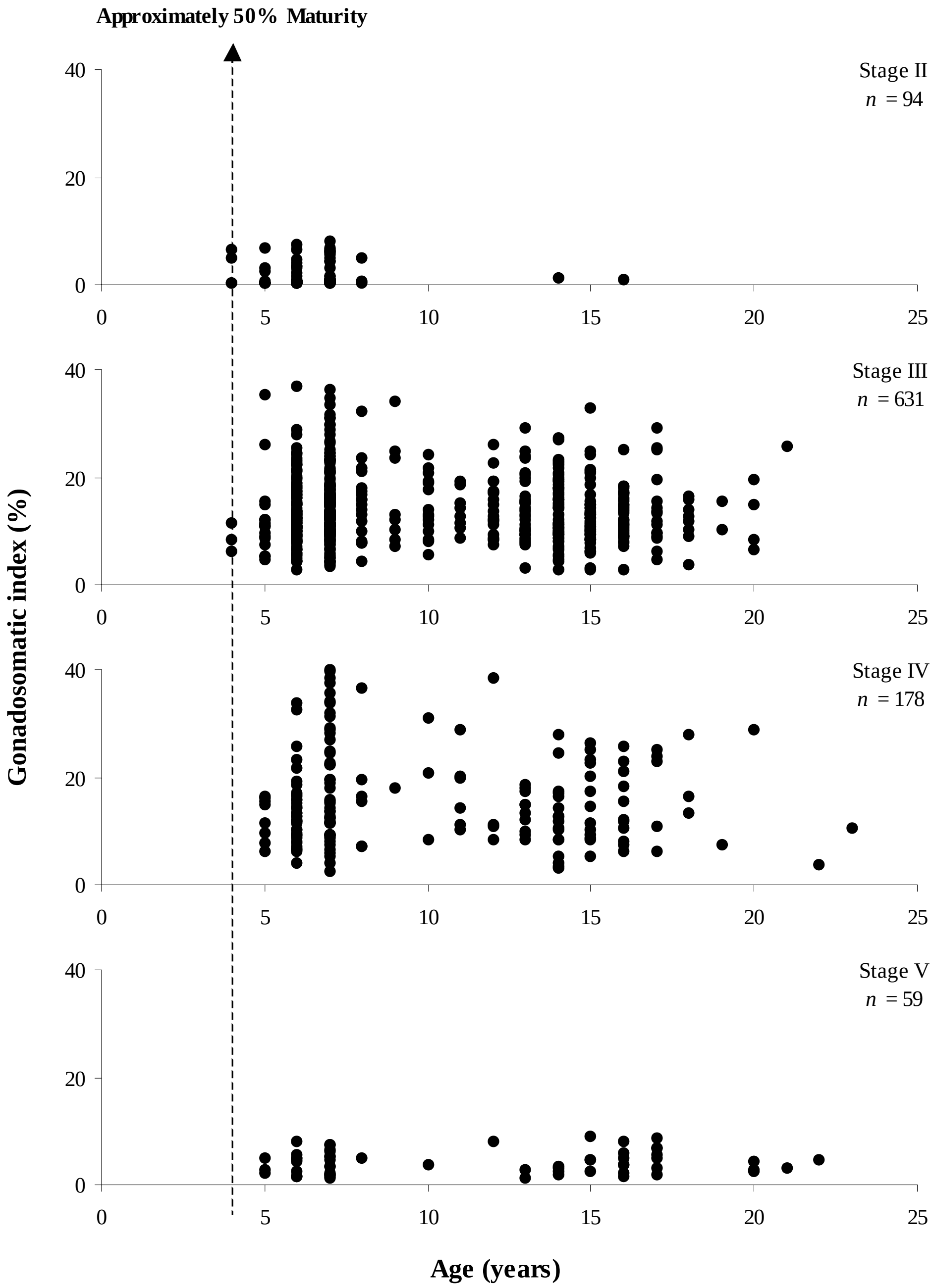


Figure 18. GSI versus age for female blue grenadier, stage II to stage V. Data 2000 and 2001 combined.

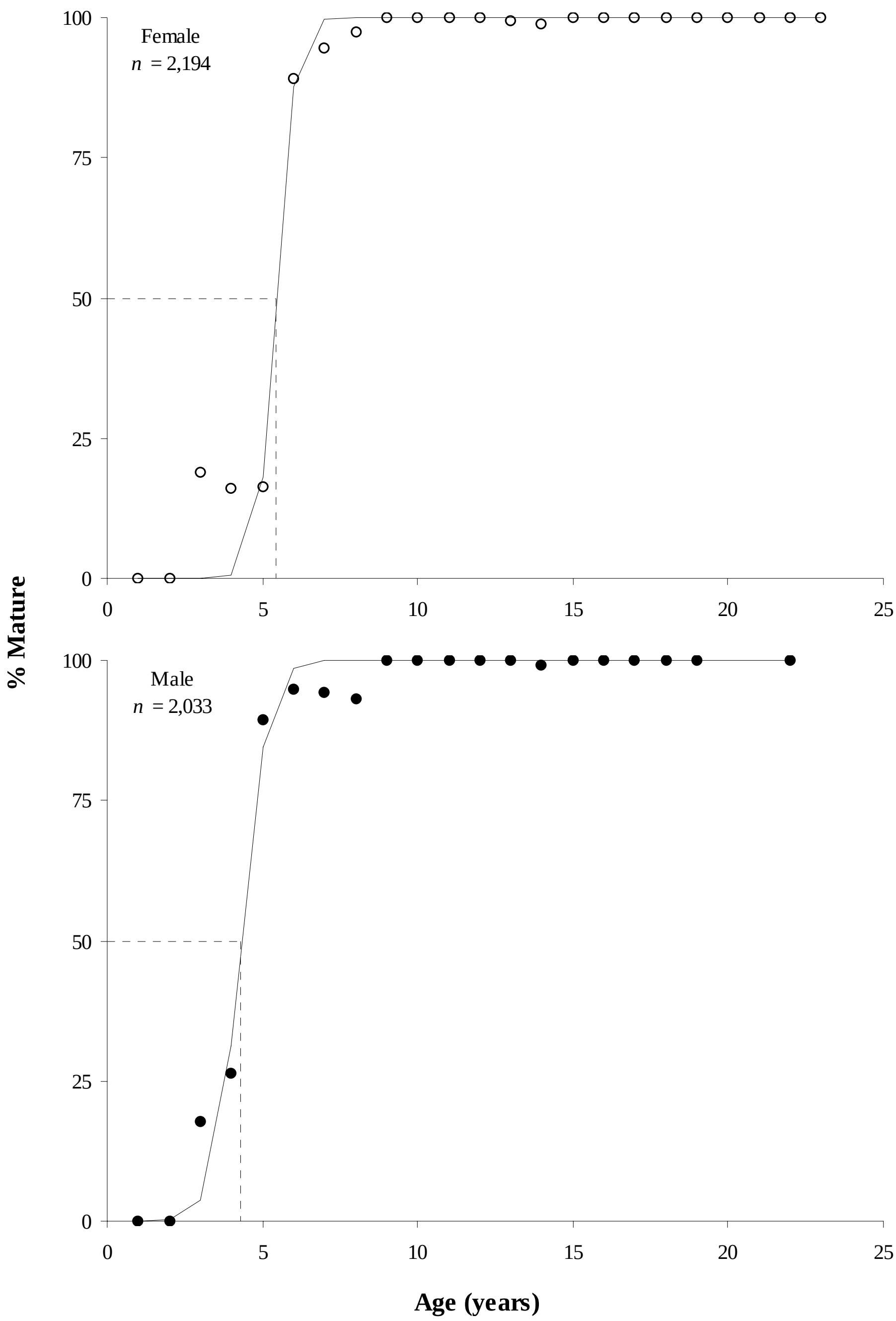


Figure 19. Maturity ogive by age for female and male blue grenadier, 1999-2001.

The length at maturity determined in the present study is marginally lower than that found in previous studies. Estimates of reproductive maturity for female and male blue grenadier in Australia are between 65-70 and 60-70 cm SL, respectively (Smith 1998, Punt *et al.* 2001; Smith and Wayte 2004). Results presented in this study are closer to New Zealand maturity estimates for blue grenadier, which are 65 and 60 cm TL for females and males, respectively (Annala *et al.* 1999, 2003).

Age estimates at 50% maturity for blue grenadier were 5.4 and 4.3 years for females and males respectively. Age and gonadosomatic information indicate female maturity corresponds to an age of 4-5 years.

Age estimates are consistent with previous studies for blue grenadier. Estimates of reproductive maturity for female and male blue grenadier in both Australia and New Zealand are 4-5 years (Annala *et al.* 1999; 2003; Smith 2000; Punt *et al.* 2001; Smith and Wayte 2004).

Variations in size and age at maturity in teleost fishes have been attributed to: (1) genetic variability (Rickey 1995; Wood and Foote 1996; Berg and Albert 2003), (2) environmental influences (Tormosova 1983; Morgan *et al.* 1994; Morgan and Colbourne 1999; Berg and Pedersen 2001) and (3) changes in population densities (Morgan and Colbourne 1999; Junquera and Saborido-Rey 1995; Belk 1995).

While all or some of these factors may have attributed to the slight reduction in the length at sexual maturity, it is most probable that fluctuations in population density were a factor. Given the entry of the two large cohorts spawned in 1994 and 1995, and the decrease in length at age (this study; Punt and Smith 2001), it is not surprising that a decrease in length at maturity was also observed.

Alternatively, the observed decrease in length at maturity may be a function of the limitations associated with macroscopic staging, specifically in differentiating between stage II and III individuals.

Fecundity

Both annual and batch fecundity were obtained from 140 and 30 female blue grenadier, respectively. Annual fecundity estimates ranged from 0.3 to 4.6 million oocytes per fish, and differed considerably by length (Figure 20). Annual fecundity increased with the length of female blue grenadier, following the equation:

$$fecundity = 1.18 \times 10^{-08} SL^{4.17}.$$

The regression between natural log-transformed data was statistically significant (F=334.9, df=138, $p<0.001$, $r^2=0.71$).

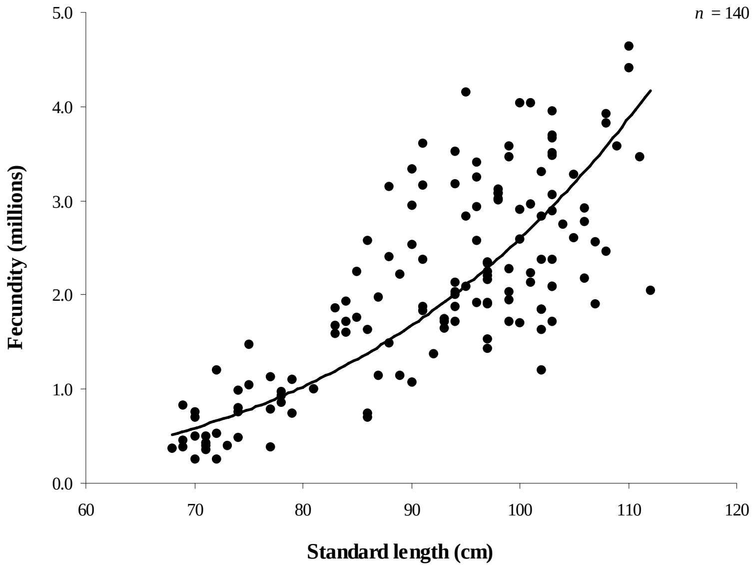


Figure 20. Fecundity versus length for female blue grenadier, data from 2000 and 2001 combined.

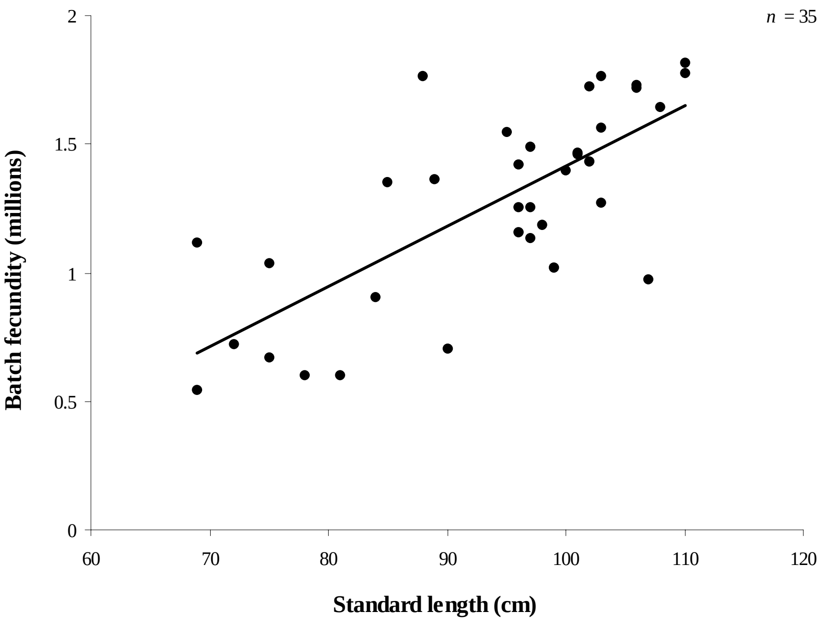


Figure 21. Batch fecundity versus length for female blue grenadier, data 2000 and 2001 combined.

Batch fecundity estimated for ripe females ranged from 0.5 to 1.8 million oocytes per fish, and also varied considerably with length (Figure 21). The relationship between batch fecundity and standard length can be represented by the following equation:

$$batchfecundity = 0.023x - 0.9276 .$$

The relationship between batch fecundity and length was significant (F=38.75, df=33, $p<0.001$, $r^2=0.54$).

The average relative fecundity in blue grenadier was 545 oocytes per gram of total weight (range 173-1179 oocytes per gram), and did not change significantly with either weight or length.

Of the 774 histological sections examined, only 51 exhibited signs of atresia. Of the 6.6% that exhibited atresia, on average only 3.7% of eggs were affected and all were from spent individuals. Postovulatory follicles were found in 8.5% of all mature ovaries examined (n = 529).

The evidence that blue grenadier is group synchronous emphasises that a reliable estimate of the fecundity of this species cannot be obtained solely by counting the number of hydrated oocytes on a single occasion and that all developing oocytes must be counted. The fecundity of blue grenadier is clearly determinate, that is several ripe batches of oocytes are formed successively from a standing stock of yolked oocytes. This is confirmed by several studies on the reproductive biology of blue grenadier (Gunn *et al.* 1989, Zeldis 1993, Schofield and Livingston 1998, Zeldis *et al.* 1998, Bulman *et al.* 1999).

Mean annual fecundity estimates ranged from 0.3 to 4.6 million oocytes per ovary in females ranging from 68 to 112 cm SL. Annual fecundity increased with both length and weight. These estimates compare favourably with previous estimates for blue grenadier assessed in Australia (Gunn *et al.* 1989, Bulman *et al.* 1999) and New Zealand (Schofield and Livingston 1998). Estimates ranged from 0.5 to 1.8 million oocytes per ovary in females ranging from 69 to 110 cm SL. Batch fecundity has not been previously estimated for blue grenadier. The average relative fecundity found in this study (545 oocytes/g) appears to be consistent with estimates produced by Bulman *et al*. (1999) at 520 oocytes/g).

Comparison of annual and batch fecundities suggest that females spawn all their oocytes in 2-3 large batches over the spawning season. However, this may vary depending on both the length and weight of the fish. The findings are consistent with previous research conducted on blue grenadier in New Zealand (Langley 1993, Zeldis 1993, Schofield and Livingston 1998).

The simultaneous occurrence of postovulatory follicles and ripe oocytes in ovaries of blue grenadier suggests that hydration and ovulation of consecutive batches could take place within a brief period. However, numerous samples taken at regular intervals during the spawning season would be required to age postovulatory follicles precisely (Macewicz and Hunter 1993, Oda *et al.* 1993, Baelde 1996).

The rate of atresia appears to be negligible and is thought not to affect fecundity estimates. The fact that female blue grenadier are partial spawners constitutes more of a problem for estimating fecundity, even more so because spawning batches are quite large. Partially spent females cannot be identified macroscopically and to avoid underestimating annual fecundity it is necessary to check microscopically for the presence of postovulatory follicles in every female before estimating the number of oocytes. In addition, during the capture process females may release some of their eggs due to the pressure applied to individuals during trawling. Therefore appropriate samples for fecundity and batch fecundity are often difficult to collect.

Spawning location and period

The majority of male blue grenadier caught in WCT from February to May were either at immature or maturing/resting stages of development. From June to September running ripe individuals dominated this area. The bulk of male blue grenadier in EBS, ECT and WBS were at the immature or maturing/resting stages of development; however, a small proportion of maturing, running ripe and spent males were present between June and October in these areas (Figure 22).

The gonadal developmental stages of females in the different regions paralleled those of male blue grenadier. The bulk of female blue grenadier caught in WCT from February to May were either at immature or maturing/resting stages of development. From June to September mature, running ripe and spent individuals were most dominant in this area, with large numbers of spent individuals occurring in October. The majority of female blue grenadier caught in EBS, ECT and WCT were either at the immature or maturing/resting stages of development. Despite this, a small number of mature, running ripe and spent females were present between June and October in these areas (Figure 23).

The majority of reproductively active (stages III-V) female and male blue grenadier indicate that spawning occurs primarily on the WCT from June to August. Beyond that the majority of fish are at the maturing/resting (stage II) phase of development. However, in ECT and WBS regions there are small proportions of fish at the maturing, running ripe and spent stages of development, around the primary spawning period. Similarly, GSI information from females indicated that spawning occurs primarily on the WCT from June to August. However, average GSIs in the ECT region were slightly elevated during June to August in both 2000 and 2001 (Figure 12).

These results are consistent with previous studies which indicate that blue grenadier spawn primarily on the WCT from late May to early September (Wilson 1981, 1982, Thresher *et al.* 1989, Gunn *et al.* 1989, Bulman *et al.* 1999). However, while larval abundances have been found to be consistently highest off the WCT (Bulman *et al.* 1999), there is some evidence to suggest small scale sporadic spawning elsewhere based on larval sampling and adult reproductive morphology (Thresher *et al.* 1988, 1989, Gunn *et al.* 1989, Bruce *et al.* 2001).

Evidence for a secondary spawning area

While this study has found little evidence of spawning aggregations outside the WCT, reproductively active male and female blue grenadier were found in both ECT and WBS regions during the primary spawning period. Similar observations were noted by Gunn *et al.* (1989). The existence of reproductively mature fish outside the main spawning area may be a result of (*i*) individuals captured during their migration to and from the WCT or (*ii*) intermittent small scale spawning outside the WCT.

It is known that blue grenadier migrate annually from their extensive distribution around southern Australia in autumn to the primary spawning area (WCT) and disperse again during spring (Gunn *et al.* 1989, Smith *et al*. 1995). Arrival on the spawning grounds is size-dependent, with large fish arriving early in the spawning period and smaller fish arriving later (this study, Sullivan and Coombs 1989, Sullivan and Cordue 1990). Reproductively active blue grenadier found outside the primary spawning area during the spawning period may be a function of this migration to and from the WCT.

Alternatively, blue grenadier larvae have been collected off north-eastern Tasmania (Thresher *et al.* 1988, 1989, Gunn *et al.* 1989) and in coastal waters off eastern Victoria and southern New South Wales (Bruce *et al.* 2001). Potential sources of these larvae suggest spawning may occur in north-eastern Tasmania or eastern Bass Strait (Thresher *et al.* 1988, 1989, Gunn *et al.* 1989, Bruce *et al.* 2001). Leading to the suggestion of a second smaller spawning area beyond the limits of the WCT (Thresher *et al.* 1988, 1989, Gunn *et al.* 1989, Bruce *et al.* 2001).

This evidence is supported by biochemical genetic analyses, which showed that Australian blue grenadier exhibited greater genetic variability within regions than between regions (Milton and Shaklee 1987). This type of variation has been observed in several other groups of marine fish, and is thought to be a result of strong schooling tendencies by year class, or the existence of two or more stocks, which overlap both spatially and temporally (Milton and Shaklee 1987).

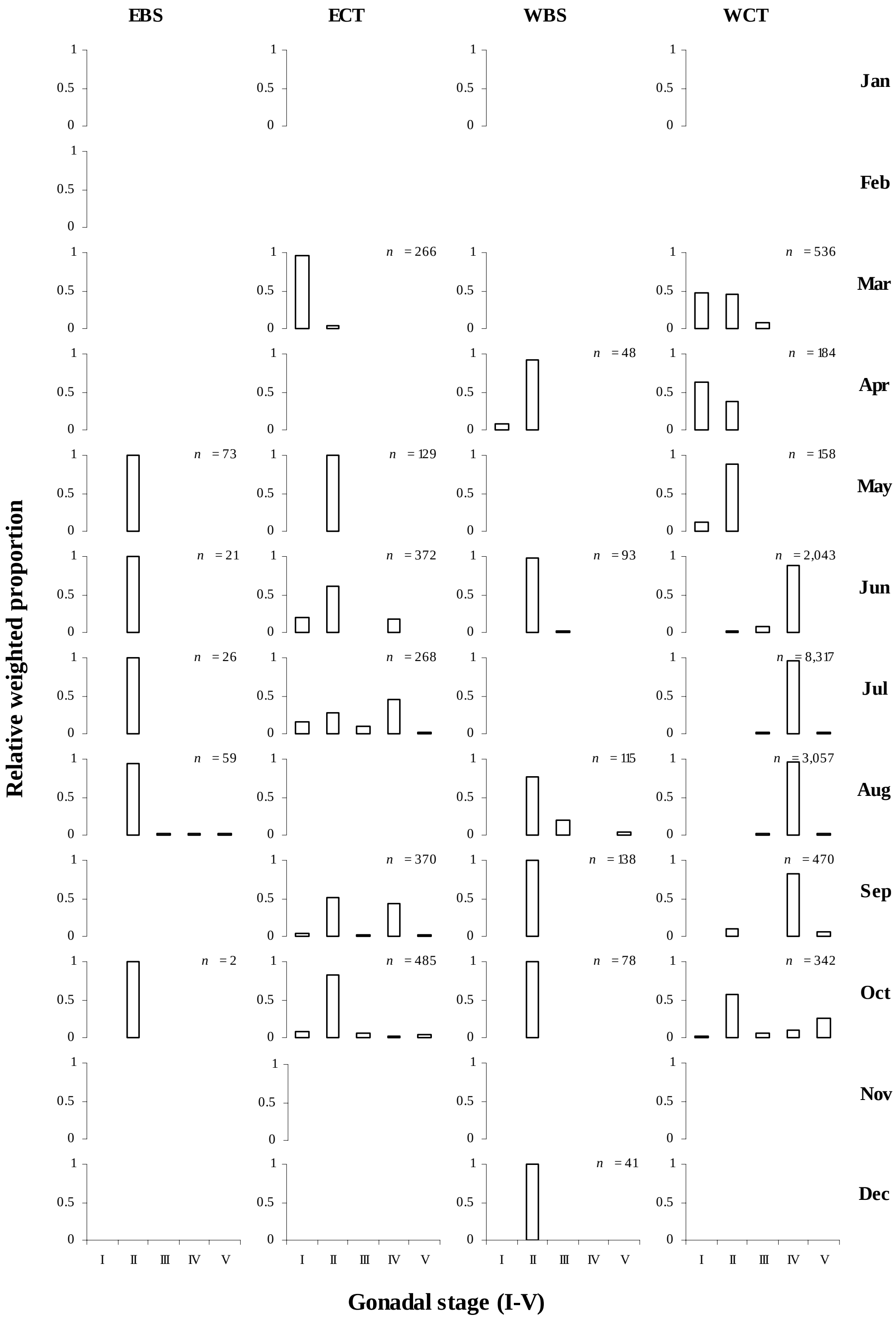


Figure 22. Monthly frequency of male blue grenadier at various gonad stages in all areas (data from 2000 and 2001 combined).

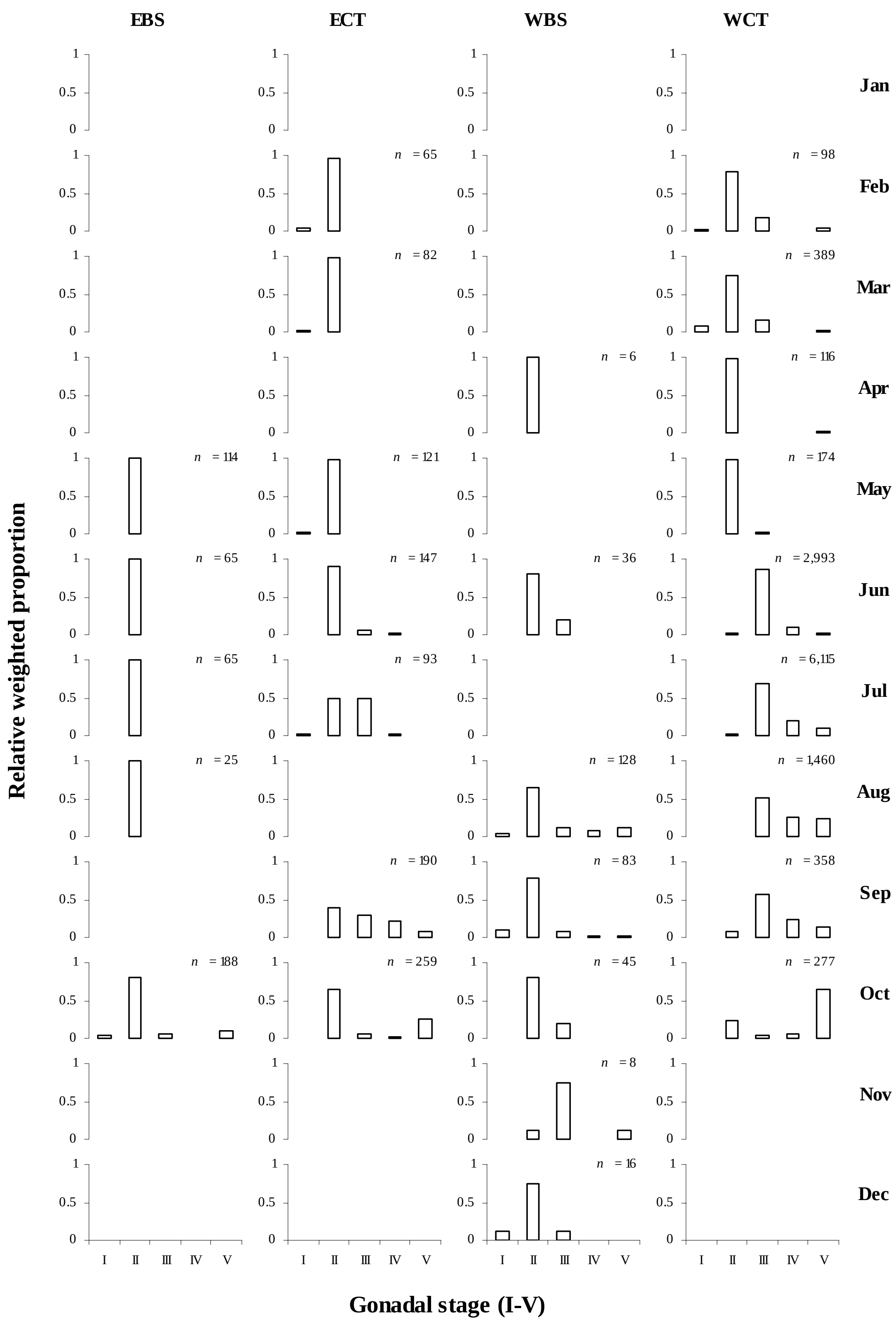


Figure 23. Monthly frequency of female blue grenadier at various gonad stages (data 2000 and 2001 combined).

There are several spawning areas for blue grenadier in New Zealand. The major spawning area is located on the west coast of the South Island (Patchell 1982, Kuo and Tanaka 1984), and additional spawning occurs in Cook Strait and Puysegur Bank (Murdoch and Chapman 1989, Livingston 1990, Livingston *et al.* 1991, Ballara and Sullivan 1994, Zeldis *et al.* 1998).

However, while the existence of a secondary spawning area or small scale sporadic spawning outside the WCT in Australian waters cannot be discounted, the primary spawning area for blue grenadier is the WCT, with peak spawning occurring between June and August.

Proportion of non-spawners

In total, of the 491 ovaries classified macroscopically as stage III-IV (adult spawner) only 1 was classified histologically as a non-spawner giving macroscopic staging an accuracy level of 99.7%. However, of the 283 ovaries classified as stage I-II (adult non-spawner) 39 were classified histologically as spawners giving macroscopic staging; an accuracy level of 86.2% (Table 8).

Table 8. Numbers of blue grenadier classified in each histological stage compared with macroscopic stage in all areas between 2000 and 2001 (data pooled by year).

Classification	Microscopic Stage (A-G)	Macroscopic Stage (I-II)	Macroscopic Stage (III-IV)
	A Chromatin nucleolar	0	0
	B Early perinucleloar	95	0
	C Late perinucleloar	93	0
	D Early cortical alveoli	56	1
Non-spawner		**244**	**1**
	E Late cortical alveoli	25	6
	F Yolk	3	221
	G Nuclear migration	0	133
	H Hydration	0	96
	I Early perinucleolar plus POF	11	34
Spawner		**39**	**490**
Grand Total		**283**	**491**

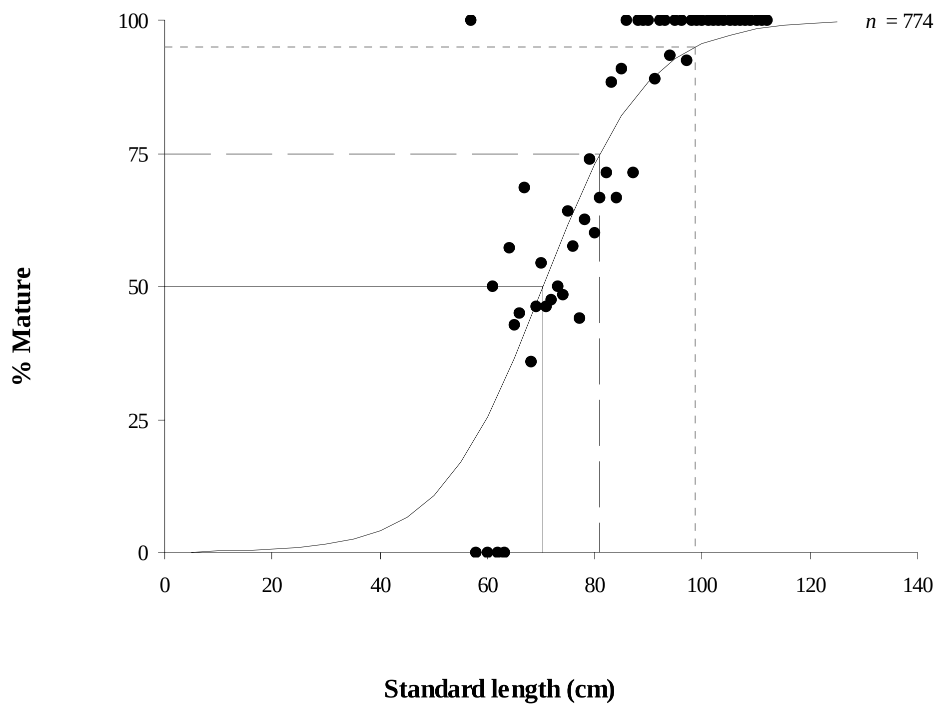


Figure 24. Maturity ogive for female blue grenadier based on histological examination. Horizontal and vertical lines represent size at 50%, 75% and 95% maturity.

The smallest mature female staged histologically during the present study was 57.0 cm SL. The estimated length at 50, 75 and 95% maturity for female blue grenadier were 70.3, 80.9 and 98.7 cm SL, respectively (Figure 24).

Based on histological examination exclusively, the highest proportion of 'non-spawners' was found in EBS (44%), followed by WCT (30%), WBS (20%) and ECT (15%). Of fish classified as 'non-spawners', 35% were found in non-spawning areas (EBS, ECT and WBS), 30% were found in the primary spawning area (WCT) and 32% were found to be 'non-spawners' overall (Table 9).

When 'non-spawning' fish were classified as 'immature' or 'adult non-spawner' based on their length at 50% maturity (70.3 cm SL) 1% (*n* = 2) of individuals were classified as 'immature'. Following exclusion of these 'immature' fish from the data set, proportions of adult non-spawners did not change significantly from initial histological classification (Table 10, Figure 25).

Table 9. Reproductive status of female blue grenadier based on histological examination exclusively in all areas between 2000 and 2001 (data pooled by year).

Reproductive status		Non-spawner		Spawner	
Area		*n*	%	*n*	%
NS	EBS	74	44	93	56
	ECT	4	15	23	85
	WBS	13	20	51	80
	Total	91	35	167	65
SP	WCT	154	30	362	70
Grand total		**245**	**32**	**529**	**68**

Abbreviations: *n* = number of individuals sampled;
NS = non-spawning; SP = spawning

Table 10. Reproductive classification of female blue grenadier based on length at maturity (50, 75, 95%) in all areas between 2000 and 2001 (data pooled by year).

Sensitivity	Samples	Reproductive status	NS area				SP area	
			EBS	ECT	WBS	Total	WCT	Grand total
50%	All	Immature	1	0	0	0	0	0
		Adult non-spawner	44	15	20	35	30	31
		Adult spawner	56	85	80	65	70	68
	Immature excluded	Adult non-spawner	44	15	20	35	30	31
		Spawner	56	85	80	65	70	69
75%	All	Immature	40	15	19	32	15	21
		Adult non-spawner	4	0	2	3	15	11
		Adult spawner	56	85	80	65	70	68
	Immature excluded	Adult non-spawner	7	0	2	5	18	14
		Spawner	93	100	98	95	82	86
95%	All	Immature	44	15	20	35	24	28
		Adult non-spawner	0	0	0	0	6	4
		Adult spawner	56	85	80	65	70	68
	Immature excluded	Adult non-spawner	0	0	0	0	8	5
		Spawner	100	100	100	100	92	95

Abbreviations: NS = non-spawning; SP = Spawning

At 75% maturity (80.9 cm SL), 21% (n = 159) of fish were classified as 'immature'. Subsequent exclusion from the data set revealed, of the fish classified as 'adult non-spawners,' 5% were found in non-spawning areas (EBS, ECT and WBS), 18% were found in the primary spawning area (WCT) and 14% were found to be 'adult non-spawners' overall (Table 10, Figure 25).

At 95% maturity (98.7 cm SL), 28% (n = 215) of fish were classified as 'immature'. Consequent elimination of immature fish from the data set showed, of the fish classified as 'adult non-spawners,' none were found in non-spawning areas (EBS, ECT and WBS), 8% were found in the primary spawning area (WCT) and 5% were found to be 'adult non-spawners' overall (Table 10, Figure 25).

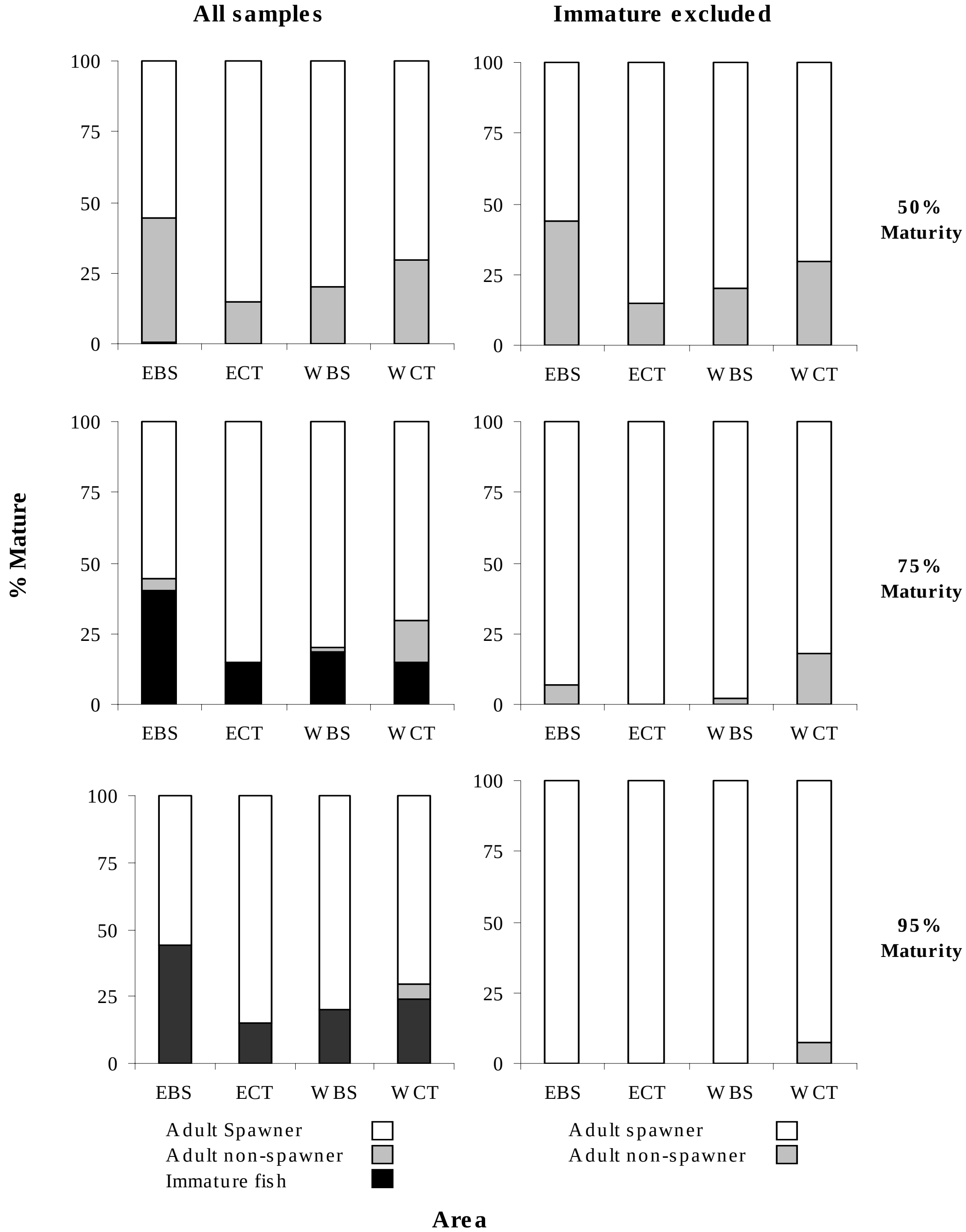


Figure 25. Percentage of spawning, non-spawning and immature blue grenadier estimated at 50%, 75% and 95% length at maturity by area, data pooled across years.

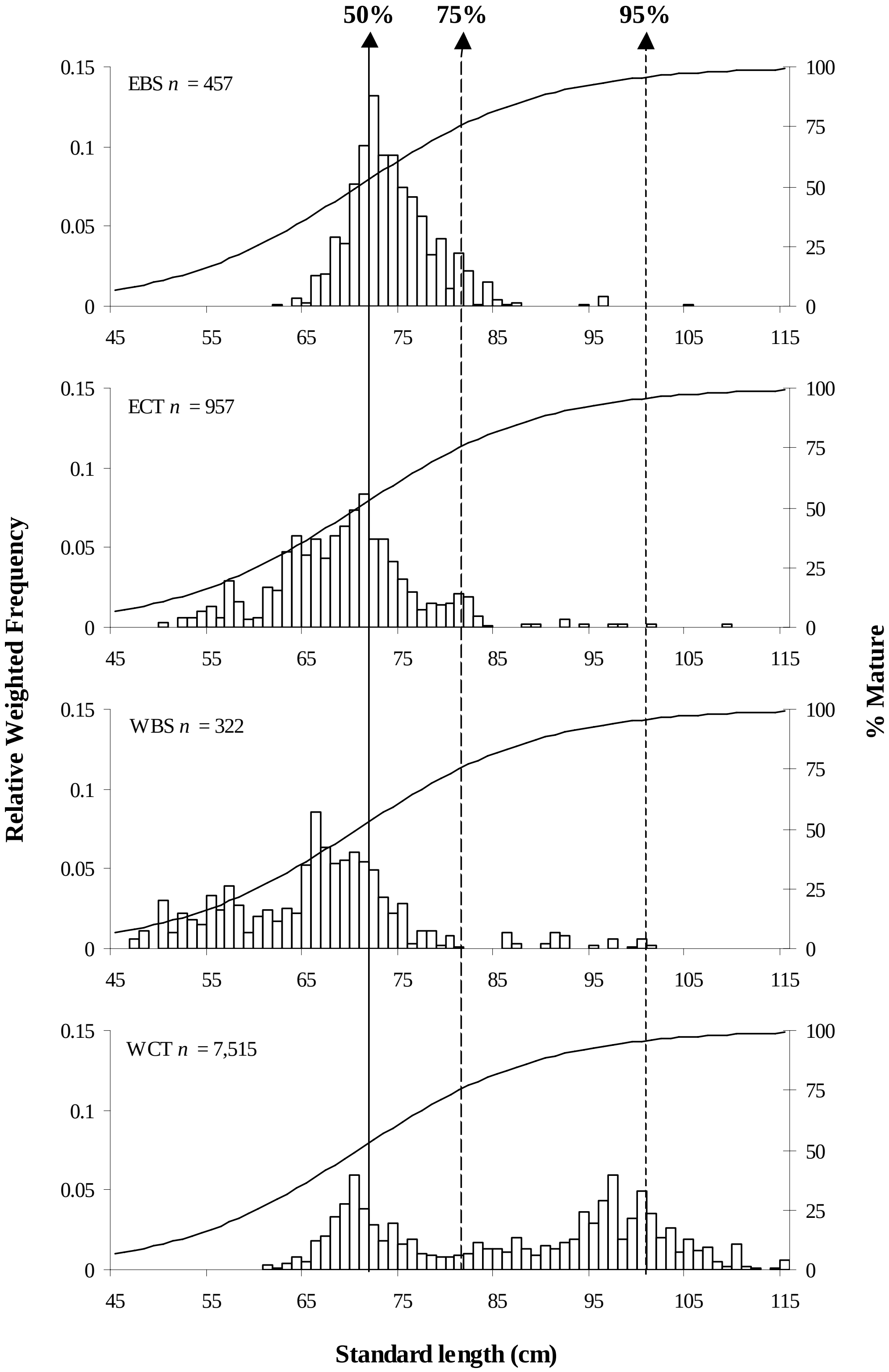


Figure 26. Maturity ogives overlaid over female length frequency distributions by area, data pooled. Vertical lines represent lengths at 50%, 75% and 95% maturity.

Weighted length frequency data from all sampling locations indicate that the majority of females in non-spawning areas were below 80 cm SL, with a large modal peak at 65-70 cm SL. This corresponds to approximately 50% maturity. Fish in the WCT exhibited a bimodal distribution with peaks around 70 and 90 cm SL. The overlaid maturity ogive placed on the length frequency histograms indicate that the majority of fish sampled outside the main spawning area were below 75% length at maturity. Fish in the WCT were abundant above and below the 95% length at maturity (Figure 26).

The overall level of accuracy associated with macroscopic staging was around 85%. The majority of error was associated with classification of stage II individuals at the maturing/resting phase of development. Similar levels of macroscopic staging error have been reported, confirming the need for validation of macroscopic staging when determining the proportion of non-reproductive adults (Livingston *et al.* 1997).

Histological maturity ogives indicate that at 70.3 cm SL 50% of the population is mature. Despite the limitations associated with macroscopic staging, results from maturity ogives based on macroscopic staging do not differ considerably (i.e. 63.7 cm SL) and are consistent with previous estimates (65-70 cm SL) in Australia (Smith 2000, Punt *et al*. 2001, Smith and Wayte 2004) and New Zealand (65 cm SL) (Annala *et al.* 1999, 2003).

This study showed that there is evidence of 'adult non-spawners' based on (*i*) histological examination, (*ii*) length at maturity , (*iii*) classification of 'adult spawners' and 'adult non-spawners' and (*iv*) length frequency analysis.

However, there are several potential sources of error associated with determining 'adult spawners' and 'adult non-spawners' including:

i. The number of under developed fish, which were classified as non-spawners, which may have developed late, and gone on to spawn, leading to an overestimate of adult non-spawners (Livingston *et al.* 1997).

ii. Fish which have already spawned (i.e. resting stage) and postovulatory follicles have degenerated and moved back to a resting state, leading to an overestimate of adult non-spawners (Macewicz and Hunter 1994).

iii. The number of spawning developing fish that could have resorbed their eggs and failed to spawn, leading to a potential over estimation of the total proportion of fish spawning (Yamamoto 1956, Gokhale 1957).

iv. The changes in catchability and vulnerability between trawl surveys and the difficulty of detecting any bias or size selectivity when sampling a population with commercial trawl data (Livingston *et al.* 1997).

v. The number of non-spawning fish, which are simply immature rather than non-spawners, leading to an overestimate of the proportion of adult non-spawners.

Of the potential sources of error listed above the latter (v) is of most concern, given that the majority of samples taken outside the spawning area were small <80 cm SL.

The above estimates of the proportion of non-spawning adults in each sample need to be weighted to the overall population given different abundances in each zone, particularly during the spawning season.. Fishery independent data are not available to provide relative biomass indices. Consequently, a different method was used. As a proxy for abundance in each zone the mean winter catch rate (kg/hr from the SEF logbook) was multiplied by the area of the main blue grenadier depth strata (derived by GIS, David Ball, PIRVic *personal communication*). In broad terms this is an area swept approach. The period selected to estimate catch rates was from 1991-1996. From 1997, the introduction of factory trawlers made catch rate comparisons between areas inappropriate. The overall proportion of non-spawining adults was then derived from the following:

$$P = \frac{\sum_{a=20}^{50} p_a N_a}{\sum_{a=20}^{50} N_a}$$

where:

p_a is the proportion of non-spawning adults in zone *a*,

N_a is the estimated biomass in zone *a*, $N_a = CR_a.A_a$,

CR_a is the catch rate in zone a,

A_a is the area in zone *a*

The total proportion of adult non-spawners estimated using the above relationship was, for the 50% maturity ogive 29% (cf 30%) and for the 75% maturity ogive, 16% (cf 18%). The 95% ogive was not used because it excludes most fish in the population.

These estimates are not inconsistent with previous estimates of the proportion of non-spawning adult blue grenadier in New Zealand. Initial estimates suggested that only 60-75% of the total adult blue grenadier population would spawn in a given year (Hurst and Schofield 1995). Further trawl estimates indicate that approximately 77% (68-85%) of the potential spawners spawn in a given year. That is, the population contains about 23% of non-spawning adults (Livingston *et al.* 1997). This value is currently used in blue grenadier 'base case' stock assessment (Punt *et al*. 2001, Tuck *et al*. 2004).

There is considerable uncertainty around our results. Few studies have been conducted to determine the degree of adult non-spawning in fish populations. Fish species which have been documented to contain adult non-spawning fish these include: orange roughy (Bell *et al.* 1992), the brackish water butbot in Baltic Sea (Pulliainen and Korhonen 1990), the estuarine surf bream, (Pollock 1984) and blue grenadier (Hurst and Schofield 1995, Livingston *et al.* 1997). However, all of these studies were based on the assumption that all fish sampled were fully mature (i.e. approaching 100% maturity).

The blue grenadier fishery during the study period was dominated by small fish and there were few large fish (>80 cm SL) sampled outside the spawning area. It seems likely that the large proportion that was estimated for non-spawning adults off the west coast of Tasmania during the spawning season could be resident immature fish. But for the reasons given above, it is hard to give definitive estimates. Consequently, we recommend the proportion of non-spawners derived from the 75% maturity ogive (as this removes some of the uncertainty due to small fish) of 16% be used in future blue grenadier assessments.

Turn-over rates

Annual and monthly sex ratios

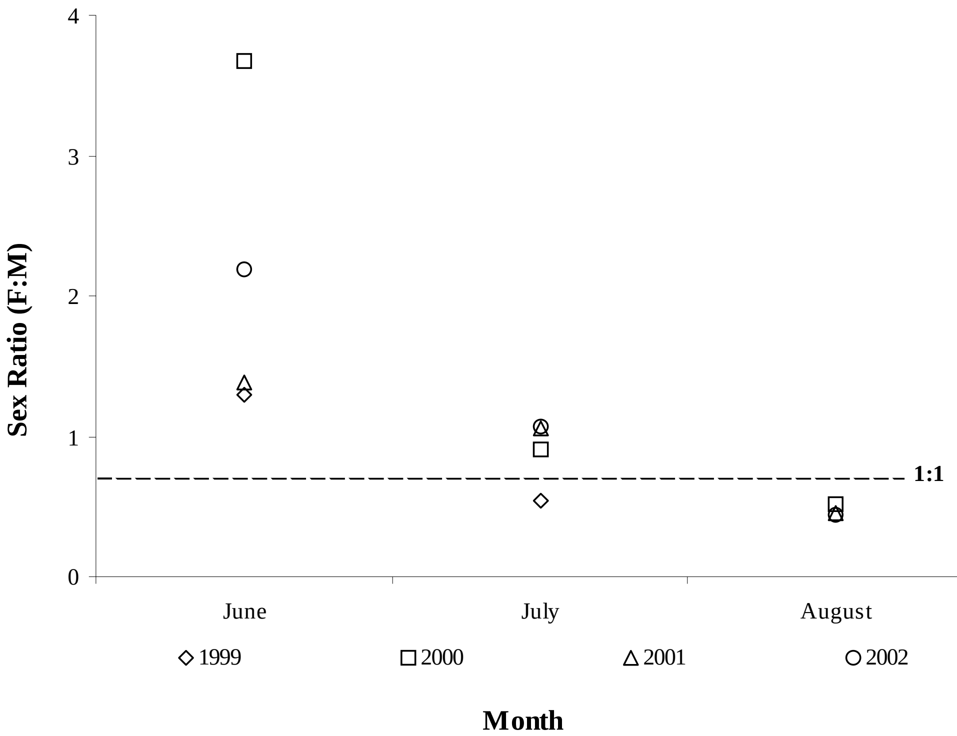


Figure 27. Monthly sex ratio (F:M) of blue grenadier examined from the WCT spawning period during 1999 and 2002.

The monthly sex ratios (F:M) of blue grenadier throughout the June-August spawning period from the WCT between 1999-2002 fluctuated between 3.7 and 0.4. In all years sex ratios were highest (>1:1) in June, decreased to approximately 1:1 in July, and continued to decline in August to <1:1 (Figure 27).

Sex ratios for each spawning year differed significantly from 1:1 with the exception of 2002. Similarly, sex ratios for each month differed significantly from 1:1 excluding July 2001 and 2002 (Table 11).

Table 11. Summary statistics of chi-squared goodness of fit test for sex ratio information sampled from commercial catches obtained during each spawning period in the WCT between 1999 and 2002.

Year	Month	*n*	X^2	*df*	*p*
1999	Overall	10076	314.8	1	***
	June	2845	46.57	1	***
	July	7231	636.89	1	***
2000	Overall	5929	36.94	1	***
	June	570	185.31	1	***
	July	3368	7.51	1	***
	August	1991	201.89	1	***
2001	Overall	7980	44.66	1	***
	June	1621	41.06	1	***
	July*	3833	2.82	1	NS
	August	2526	365.61	1	***
2002	Overall*	2476	0.44	1	NS
	June	501	69.05	1	***
	July*	1285	1.51	1	NS
	August	690	101.78	1	***

Abbreviations: *n* = number of samples, X^2= chi-squared value; *df* = degrees of freedom; *p* = significance value.

Significant effects: NS = not significant; * = <0.05; ** = <0.001; *** = <0.0001

The sex ratio of blue grenadier was in favour of females at the beginning of the spawning period and decreased towards the end of the spawning period, when males became more abundant.

This contrasts previous work, which indicates that sex ratios were consistently in favour of males during each month of the spawning period (Bulman *et al.* 1999). However, like the present study, the proportion of females also declined towards the end of the spawning period (August) (Bulman *et al*. 1999).

A study of spawning dynamics of blue grenadier in the Hokitika Canyon in New Zealand by Langley (1993) found no apparent trend in mean daily sex ratio over the spawning season. However, yearly differences in sex ratio were observed (Langley 1993). Sex ratios were approximately 1:1 at the beginning of the study, but declined in subsequent years (Langley 1993). Fluctuations in sex ratio have been attributed to (*i*) differences in residence time on the spawning grounds between the sexes, (*ii*) availability to fishing gear during the spawning season (Bulman *et al.* 1999) and (*iii*) differential maturity for males and females (Langley 1993). A further reason could be differential movement of each sex to the spawning grounds.

A difference in residence time of females and males on the spawning grounds has not been clearly established. However, given that females potentially release all their eggs in 2-3 batches (Langley 1993) and males appear to release milt continuously over a prolonged time frame, a difference in residence time of the sexes may be plausible.

Given the differences in length and weight of female and male blue grenadier during the spawning period (see Figure 10), their susceptibility to the fishing gear may also vary. In addition spawning behaviour may also differ between the sexes, making them more or less susceptible to fishing gear at certain times during the spawning period. While spawning behaviour has not been investigated for blue grenadier in detail, it has been suggested that blue grenadier show marked spatial sex segregation during spawning, however the vertical distributions remain to be described (Patchell and Hurst, unpublished data in Pankhurst 1988).

Gonad development

Stage III female blue grenadier were the most dominant group on the spawning grounds containing between 45-95% of the total proportion at any given time. Relative proportions of stage III females were highest in June and decreased steadily until August. Stage IV and V females were present but did not contribute greatly to the overall proportion of gonadal stages during the spawning period. However, both stages IV and V females showed a similar trend during the period 1999-2001, with relative proportions being low in June and increasing slightly in August. Stage I and II females did not add significantly to the relative proportion of gonadal stages at any time during the spawning period (Figure 28).

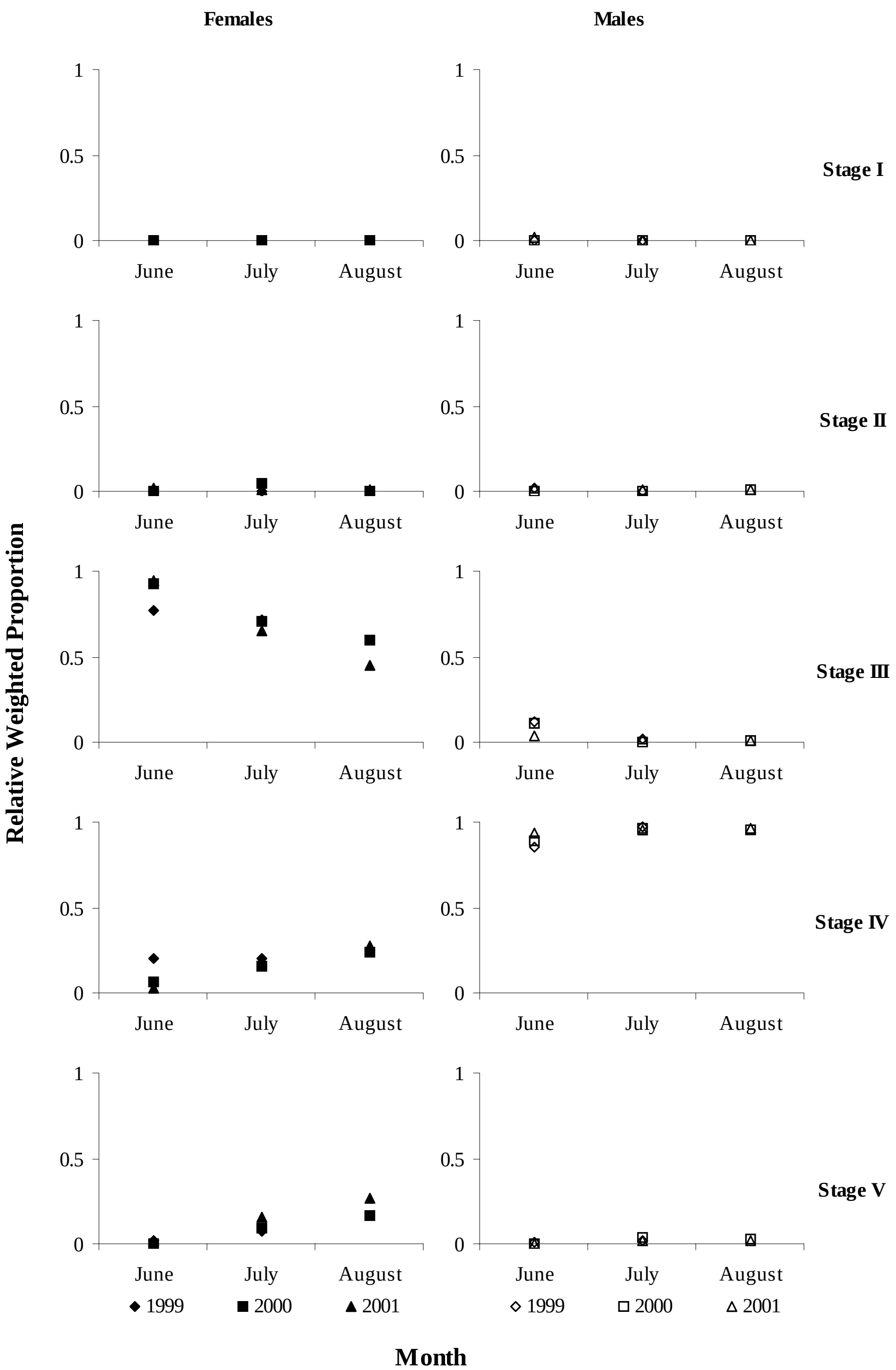


Figure 28. Relative weighted proportion (RWP) of different gonadal stages (I-V) of female and male blue grenadier examined from the WCT spawning period during 1999 and 2001.

Stage IV male blue grenadier were the most common group on the spawning grounds, comprising between 85-96% of the total proportion at any given time. Relative proportions of stage IV testes were lowest in June, and increased slightly from July to August. Low proportions of stage III males were present in June and did not appear in the remaining months of the spawning period. Stage I, II and V males did not contribute significantly to the relative proportion of gonadal stages during the spawning period (Figure 28).

As stated previously, histological studies indicate that female blue grenadier are total spawners, that is they shed all their eggs during the spawning period (Gunn *et al.* 1989, Zeldis 1993). However, they are also termed multiple spawners, releasing all their eggs in two or three batches during this well defined spawning period (Langley 1993, Zeldis 1993, Schofield and Livingston 1998).

If all fish arrived at the beginning of the spawning period in June, it would be expected that the proportion mature (stage III) female and running ripe male (stage IV) gonads would decrease dramatically by the end of August, and as a result the number of spent (stage V) fish would increase. This was not observed. The proportion of mature (stage III) females declined only slightly and the proportion of running ripe (stage IV) and spent (stage V) fish increased only slightly towards the end of the spawning period. In contrast, the majority of males were consistently running ripe (stage IV) for the whole spawning period.

The constant number of female mature fish (stage III), as well as the low numbers of running ripe (stage IV) and spent (stage V) fish caught during the spawning period may suggest that females spawn and then leave the area soon after they complete spawning. Similarly, male blue grenadier may also leave the area after spawning ceases, as the majority of gonads collected were running ripe (stage IV) and there were very few spent individuals on the grounds at any given time.

Alternatively, spawning behaviour of blue grenadier may differ between sexes and/or reproductive stage. This behavioural shift may cause blue grenadier to be less or more susceptible to the fishing gear at different times during their spawning cycle.

Length and age composition

The length composition of female and male blue grenadier during the 1999-2002 spawning period was bimodal. With the proportion of fish contained within each mode shifting throughout this period.

In June-July 1999, female length distributions were dominated by fish >80 cm SL. In 2000, females exhibited a major transition in the modes represented during the spawning period. Catches in June consisted primarily of females >80 cm SL, whereas in August, catches yielded mostly females <80 cm SL. In 2001 and 2002 there was a large overlap between the two modal groups. Females >90 cm SL did not contribute greatly to the overall length distribution in any month but were most common in June and July. Fish <90 cm SL dominated in all months but were most common August (Figure 29).

In June 1999, male length distributions consisted primarily of fish >80 cm SL, with the proportion of males <80 cm SL increasing considerably in July. Males <80 cm SL also dominated catches during the 2000-2002 spawning period, with the proportion of fish <80 cm SL increasing steadily from June to August. Although the proportion of males >80 cm SL was low in all months, they were most common in June and July (Figure 30).

In both June and July 1999, catches of female blue grenadier consisted essentially of females >6 years old. In June 2000, catches were dominated by females >7 years old, whereas females <7 years old were most common in August. Females <8 and <9 years old dominated during the entire spawning period in 2001 and 2002, respectively. Older fish (e.g >10 years old) did not contribute greatly to the overall distribution in any month, but were present in June and July (Figure 31).

Catches in June 1999, were dominated by males >6 years old, before declining considerably in proportion by July. Males <7, <8, and <9 years old dominated during the entire spawning period, in 2000, 2001 and 2002, respectively. However, the proportion of smaller males increased steadily between June and August. Males >9 years old were rare in all months, although they appeared June and July and declined August (Figure 32).

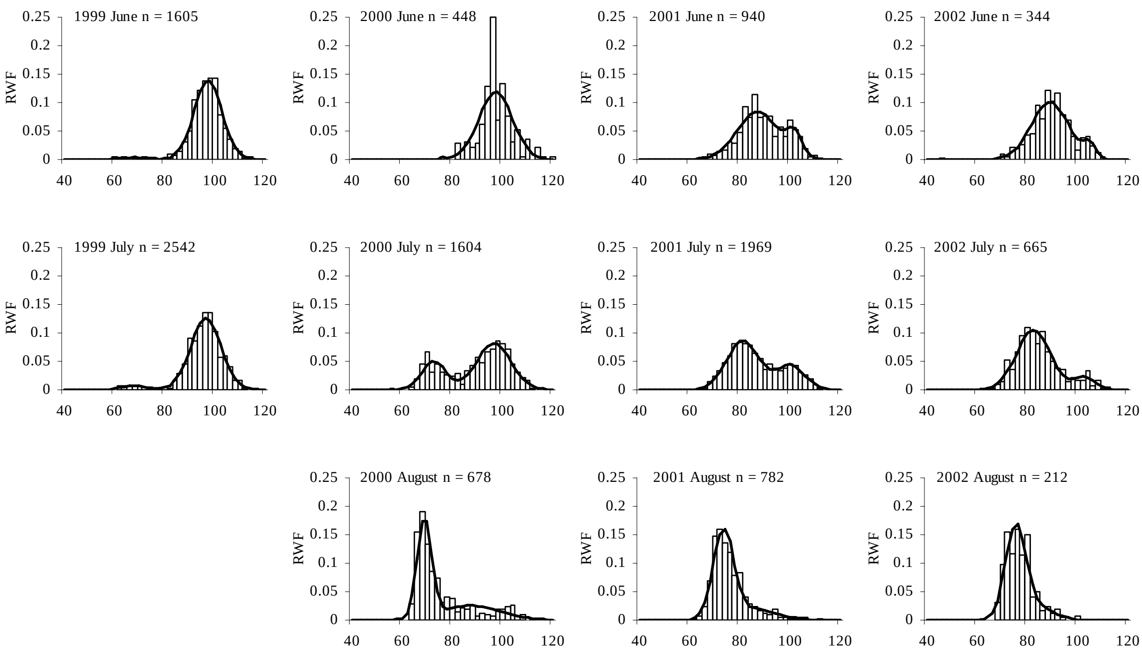


Figure 29. Relative weighted proportion (RWP) by length (SL, cm) of female blue grenadier examined from the WCT spawning period during 1999 and 2002.

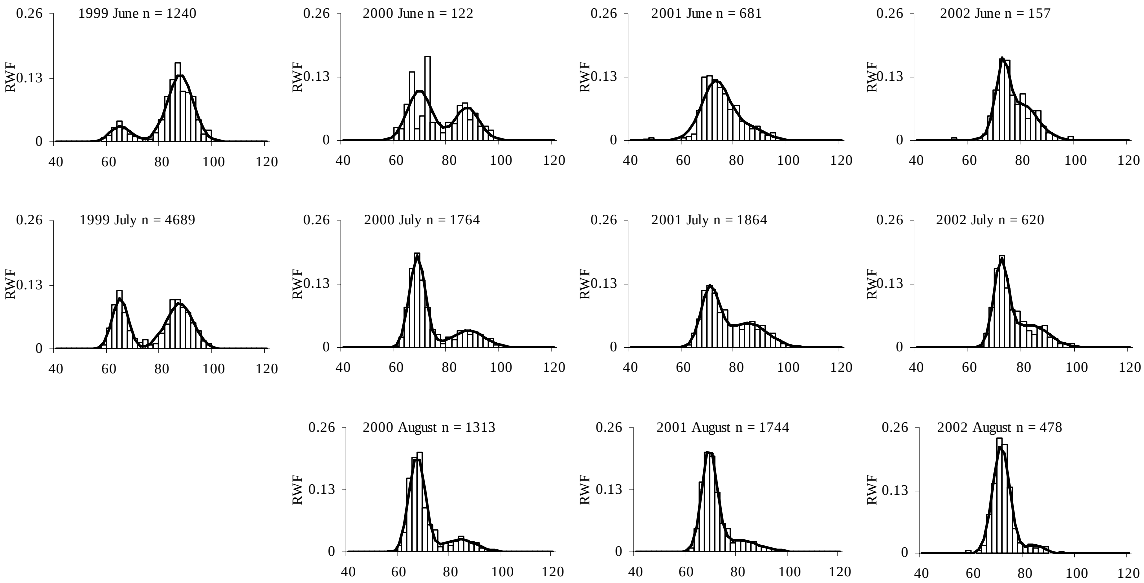


Figure 30. Relative weighted proportion (RWP) by length (SL, cm) of male of blue grenadier examined from the WCT spawning period during 1999 and 2002.

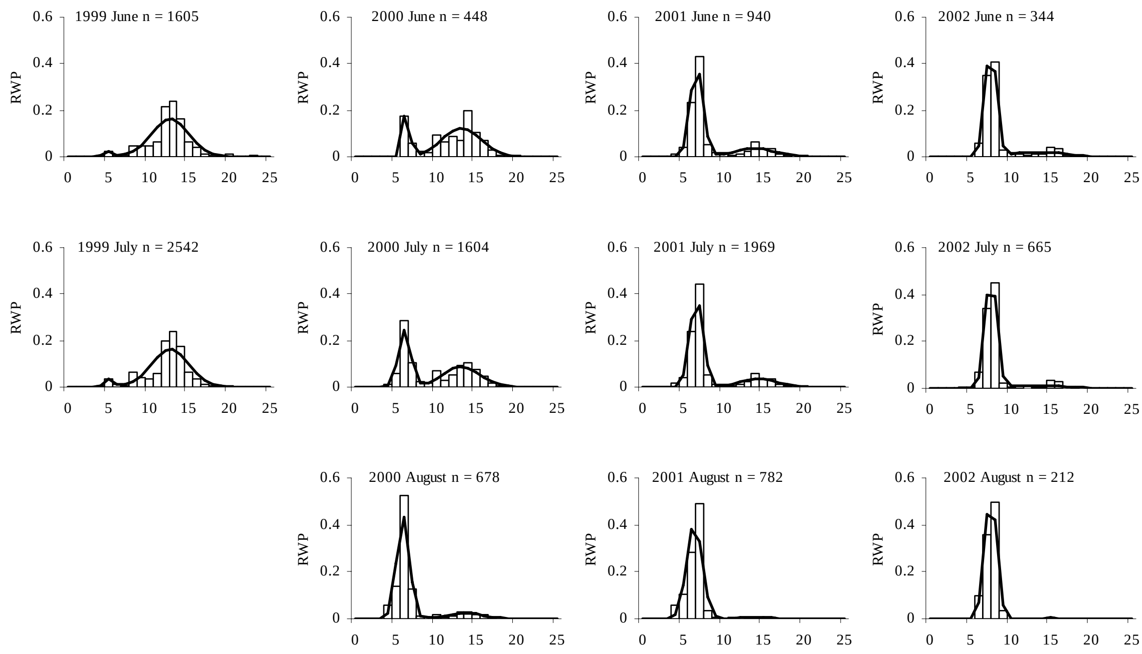


Figure 31. Relative weighted proportion (RWP) by age (years) of female blue grenadier examined from the WCT spawning period during 1999 and 2002.

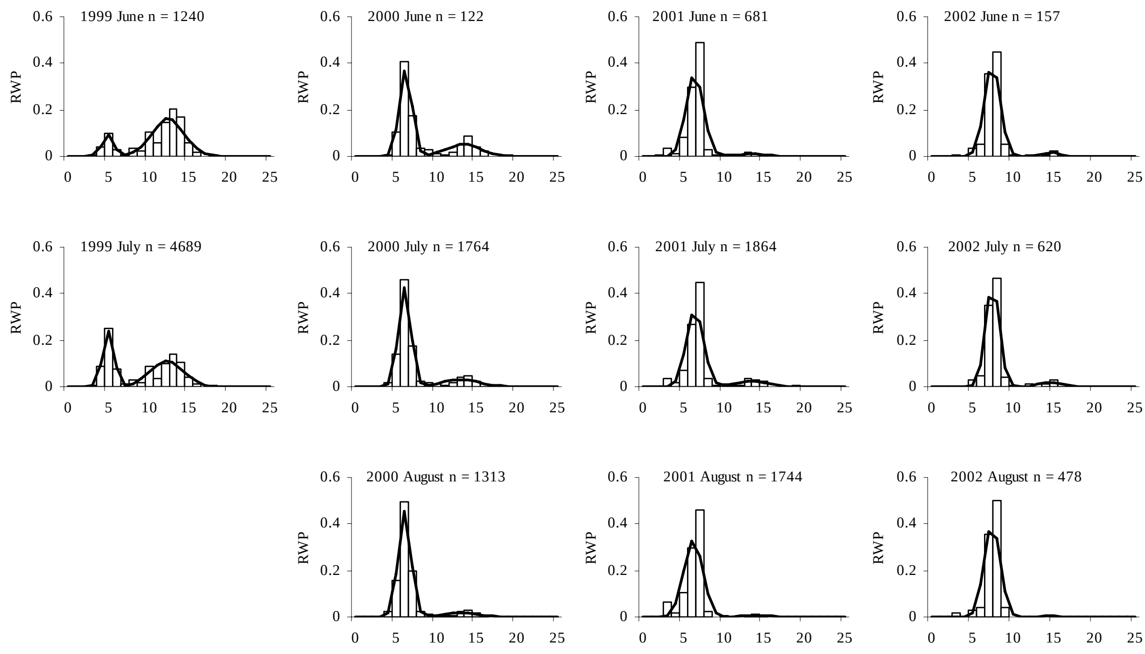


Figure 32. Relative weighted proportion (RWP) by age (years) of male blue grenadier examined from the WCT spawning period during 1999 and 2002.

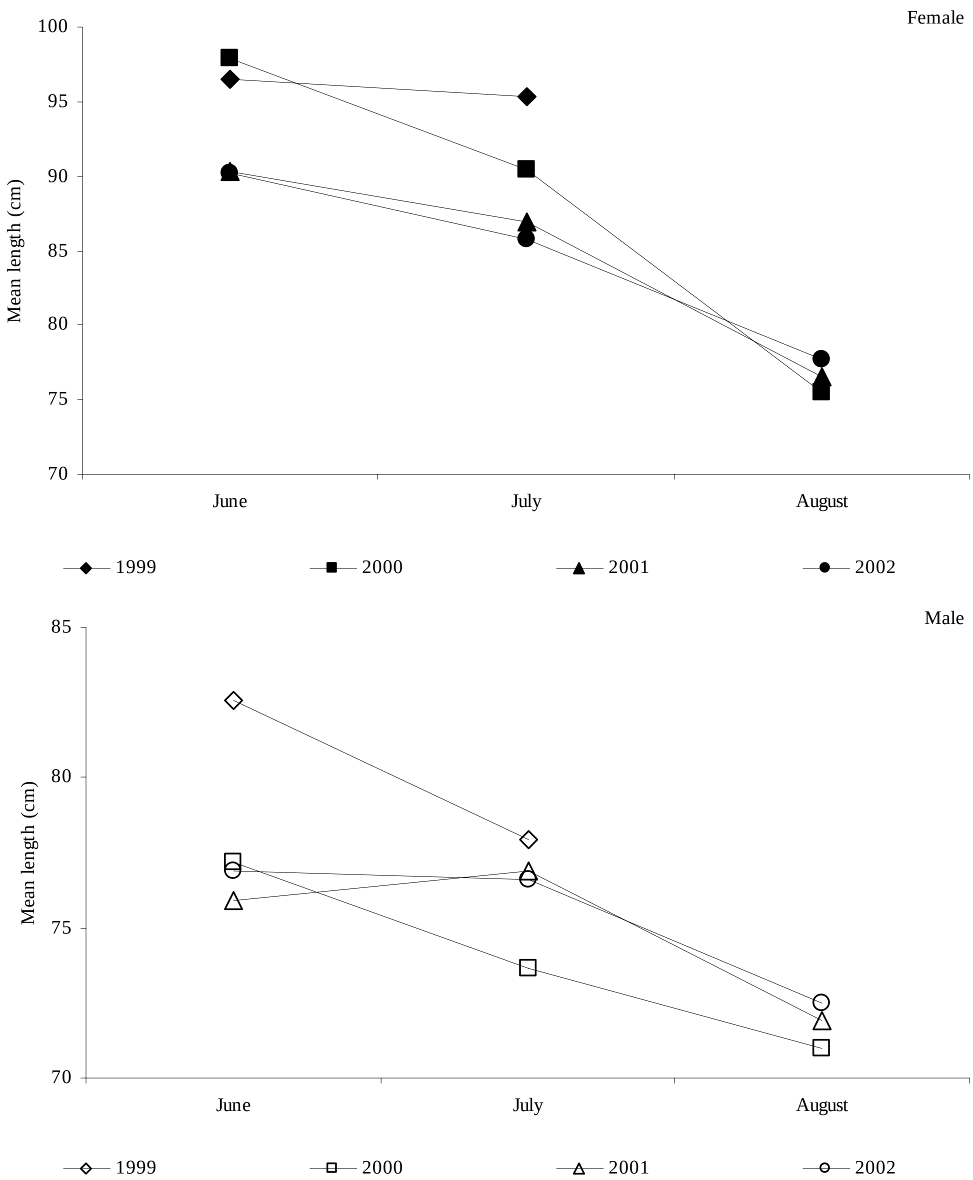


Figure 33. Monthly mean standard length estimates for female and male blue grenadier examined from the WCT spawning period during 1999 and 2002.

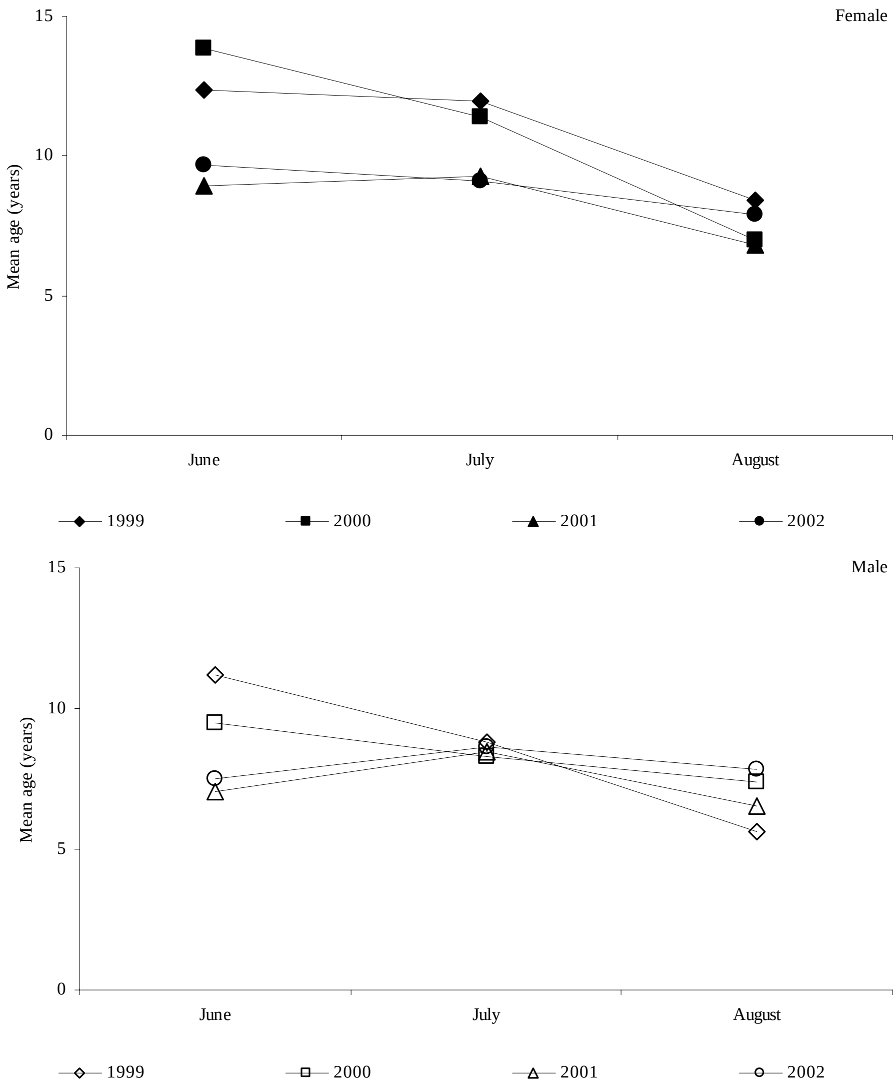


Figure 34. Monthly mean age estimates for female and male of blue grenadier examined from the WCT spawning period during 1999 and 2002.

Transitions in the lengths of fish present on the spawning grounds are reflected by an overall monthly decline in mean length of females and males by month during the 1999-2002 spawning period (Figure 33).

An overall decrease in mean age of females occurred during the 1999-2002 spawning period, with the decline being most prominent in 1999 and 2000. Likewise, an overall decline in mean age of males was evident through the 1999-2000 spawning period, whereas no decline was apparent in 2001 and 2002 (Figure 34).

As stated previously, the length and age distribution for female and male blue grenadier were bimodal. Length distributions showed that the first mode was comprised of smaller fish (<80 cm SL) and second mode contained larger fish (>80 cm SL). Similarly, age distributions revealed that the first mode contained younger fish (<10 years old) with second mode including older fish (>10 years old). The relative numbers or proportions of female and male blue grenadier contained within each length and age modal group changed considerably during the spawning period (Table 13).

Calculations of the relative number or proportion of female blue grenadier within each mode were similar for both length and age. In 1999, over 95% of catches contained larger older females. In June 2000, larger females were most abundant comprising around 100% of the population; this decreased to around 38% by August. Similarly age distributions indicate that in June, 77% of females present was considered old; by August, however, only 14% of old females remained. In 2001 and 2002, small young females dominated the distribution, estimates of small young females ranged from 93-70% and 99-70%, respectively. The number of smaller younger females increased in August in both years (Table 13).

Assessments of the relative number or proportion of male blue grenadier within each mode varied for both length and age. In 1999, large old males were most common in June (around 84%) and decreased in proportion in July (60%). In 2000, smaller, younger males dominated the distribution, ranging from 60-70% and 72-90%, respectively. The proportion of smaller, younger males increased substantially in August. In 2001, smaller (84-53%) younger (97-88%) males were most abundant. In 2002, however, large males dominated the distribution in June (63%) and small males dominated in July (60%) and August (92%). Young males were most common in 2002, accounting for 93-99% of the catch (Table 12).

Table 12. Relative numbers of female and male blue grenadier contained within each length/age modal group sampled from commercial catches obtained during each spawning period in the WCT between 1999 and 2002.

Sex		Length				Age			
		Female		Male		Female		Male	
Year	Month	1st mode Small	2nd mode Large	1st mode Small	2nd mode Large	1st mode Young	2nd mode Old	1st mode Young	2nd mode Old
1999	June	0.03	0.97	0.16	0.84	0.03	0.97	0.17	0.83
	July	0.04	0.96	0.40	0.60	0.05	0.95	0.42	0.58
2000	June	0.00	1.00	0.60	0.40	0.36	0.77	0.72	0.28
	July	0.30	0.70	0.73	0.27	0.47	0.53	0.82	0.18
	August	0.62	0.38	0.79	0.21	0.86	0.14	0.90	0.10
2001	June	0.85	0.15	0.84	0.16	0.77	0.23	0.95	0.05
	July	0.70	0.30	0.53	0.47	0.79	0.21	0.88	0.12
	August	0.78	0.22	0.76	0.24	0.97	0.03	0.97	0.03
2002	June	0.93	0.07	0.37	0.63	0.84	0.16	0.96	0.04
	July	0.89	0.11	0.60	0.40	0.86	0.14	0.93	0.07
	August	0.81	0.19	0.92	0.08	0.99	0.01	0.99	0.01

The length at age distribution for female and male blue grenadier shows a wide range of lengths for any given age, particularly in the younger age classes. However, it appears that larger old fish enter the spawning grounds in June. Larger, old fish and large, younger males and females were present in July, whereas small, younger males and females dominate in August (Figures 35, 36).

A summary of the overall length and age dynamics exhibited by female and male blue grenadier during each spawning period is given in Figure 37.

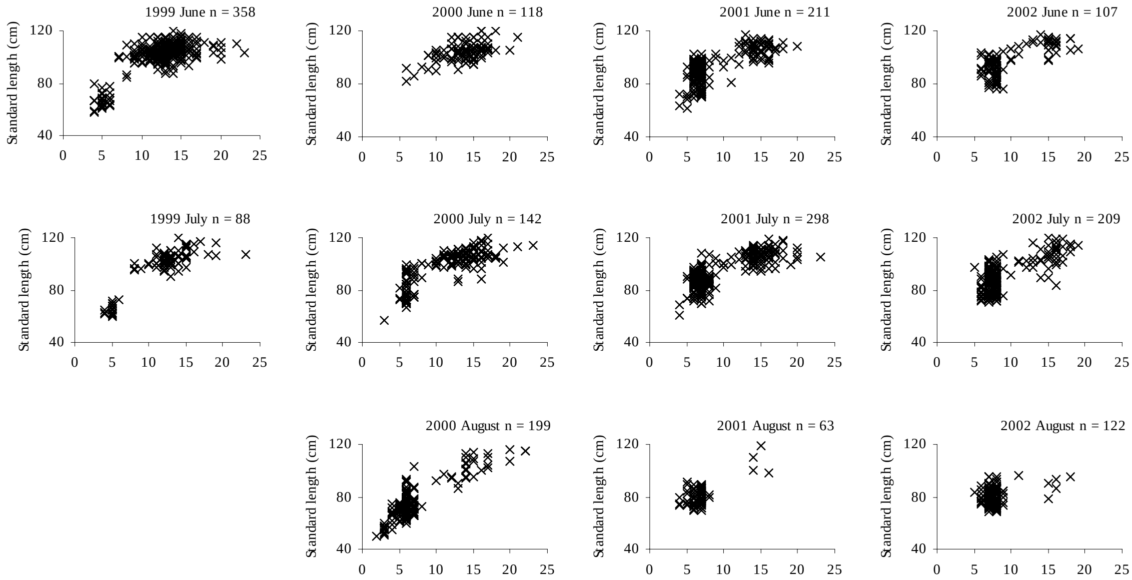


Figure 35. Length at age information for female blue grenadier examined from the WCT spawning period during 1999 and 2002.

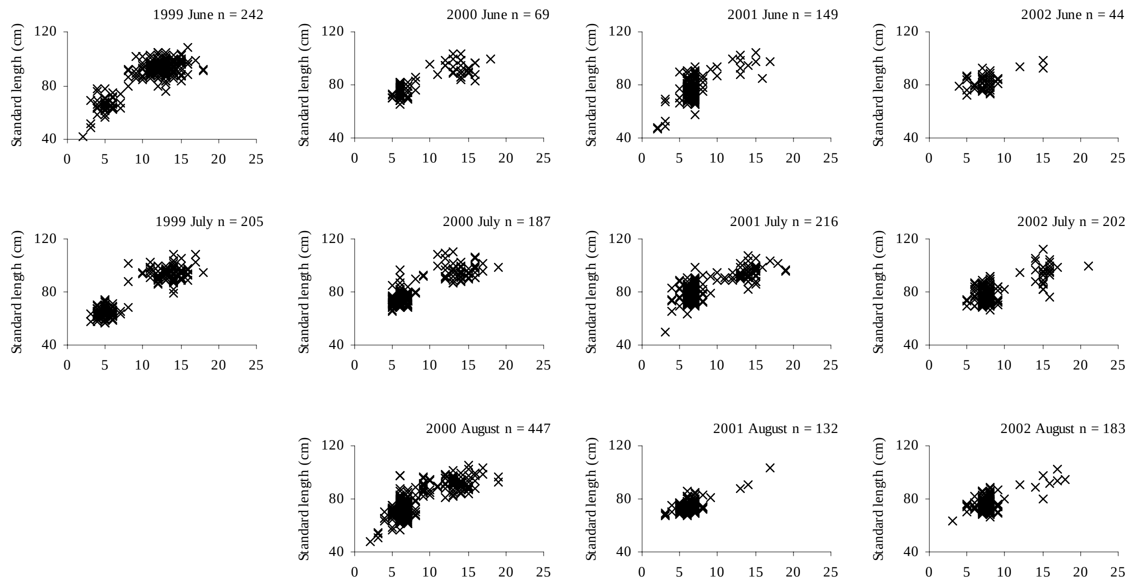


Figure 36. Age and length information for male blue grenadier examined from the WCT spawning period during 1999 and 2002.

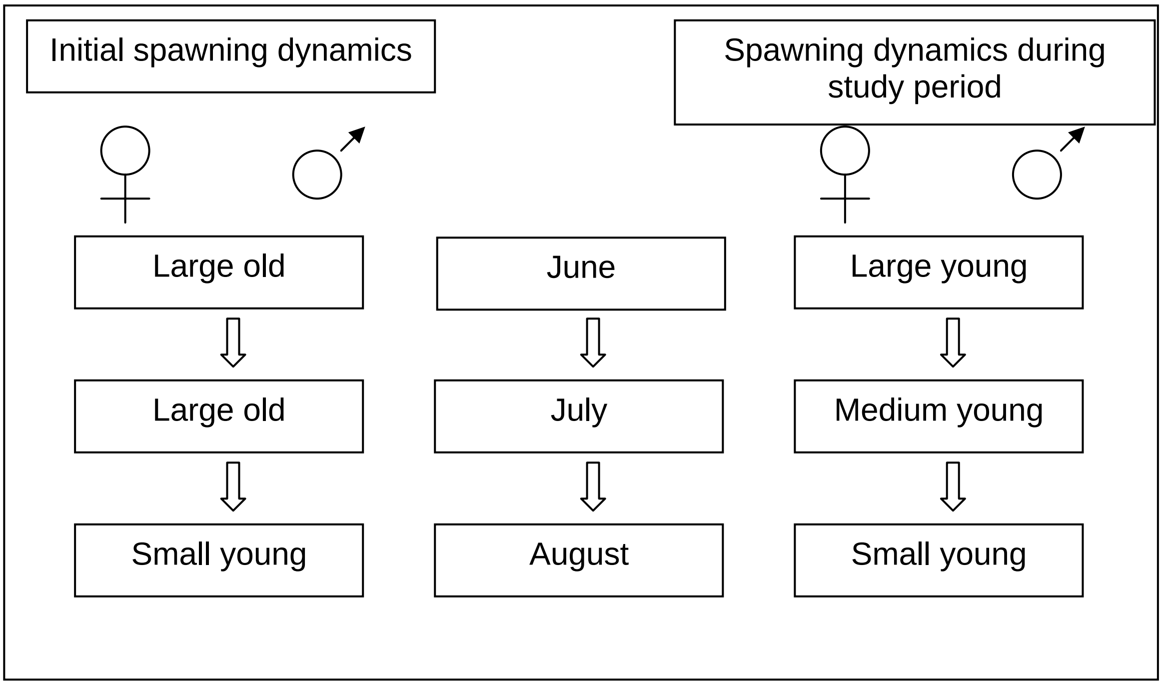


Figure 37. Summary of spawning dynamics for blue grenadier.

The timing of these two large cohorts into the spawning fishery was slightly different between sexes. Thus, new cohorts of males entered the spawning fishery before new cohorts of females; smaller, young males were present in significant numbers in 1999, while the same could only be detected for females in the 2000 spawning period. It is generally agreed in both Australia and New Zealand that males and females reach sexual maturity after 4 and 5 years, respectively (Annala *et al.* 1999, 2003, Smith 2000). This staggered entry of males and females provides further evidence of differential recruitment to the fishery.

In addition, the appearance of new cohorts in the fishery was also spread over different months in the two sexes. Larger, older males occurred only in the spawning period in significant numbers in 1999. By contrast in 2000, 2001 and 2002, the proportion of larger, older fish became increasingly smaller, both through each spawning period and across years. Larger, older females were present in large numbers in both 1999 and 2000. Like males, their numbers declined through the spawning period and across the years.

Between 1999 and 2001 there is a significant transition in the length and age-frequencies. Larger, older fish dominated in 1999 whereas smaller, younger fish dominated in 2002. These smaller, younger fish spawned in 1994 and 1995 represent two new cohorts entering the fishery (Punt *et al.* 2001).

The steady decline in the mean length of female and male blue grenadier as the spawning period progresses shows that the spawning population is constantly altering.

Length and age data suggests that size within age has significant influence on when a fish arrives on the spawning grounds. This is supported by the fact that larger spawning fish arrive earlier in the spawning grounds than smaller fish, despite the fact that in the latter years of the study the age structure consisted primarily of young fish and remained so for the duration of the spawning period. Thus, while age will influence the maturity of an individual, size will influence when a fish arrives on the spawning grounds, which implies that the turn-over of fish on the spawning grounds appears to be a function of both age and size.

As the two large cohorts dominating the distribution of blue grenadier grow, the evidence for turn-over may disappear as only a single age mode (normal distribution) will be present on the grounds. Whether will still be a turn-over of bigger fish arriving followed by smaller fish needs to be observed. However, there is a large size range of fish currently contained within these cohorts. Nevertheless, once the fish become more homogenous with respect to size, the spawning period length may shorten again as turn-over decreases.

The evidence presented in this study indicates that not all fish arrive on the grounds at once, and that a turn-over of fish on the spawning grounds occurs. It has been suggested by Langley (1993) that the minimum time which New Zealand female blue grenadier spends on the spawning grounds is between 20-27 days (spawning duration), as this is the time between the first occurrences of immediately pre-spawning and spent fish in trawl catches. Harley *et al.* (2004) derived a residency time of 40 days for female blue grenadier, giving an estimate of spawning duration of about 32 days. The results of this study are consistent with the above studies.

On the basis of this study, SlopeRAG has endorsed the use of a 2x turn-over rate in the blue grenadier assessment, although sensitivities are undertaken for a 1x and 3x turn-over (Tuck and Punt 2006).

Per-recruit analyses

Parameter values used in the following analyses are given in Table 13. Morison (1996) was used for von Bertalanffy parameters in preference to growth curves developed here because blue grenadier sampled during the study period were dominated by the 1994 and 1995 year classes which exhibited atypical slow growth.

Table 13. Summary of parameter values used in per-recruit analyses for blue grenadier.

Equations	Parameters	YPR	EPR	Source
Von Bertalanffy growth function	L_∞	100.190	115.510	Morison 1996
	K	0.168	0.160	
	t_0	-2.000	-0.940	
Length-weight relationship	a	0.004	0.003	This study
	b	3.013	3.104	
Non-spawning selectivity	L_{50}	52.427	52.427	Punt *et al.* 2001 *a*, *b*
	L_{95}	78.514	78.514	
	b	0.095	0.095	
Spawning selectivity	L_{50}	75.145	75.145	
	L_{95}	93.765	93.765	
	b	0.000	0.000	
Fecundity	a		0.000	This study
	b		4.172	
Length at maturity	a		0.275	This study
	b		63.718	
Natural mortality	M	0.275	0.250	Punt *et al*. 2001 *a*, *b*
Number of recruits	N_0	1	1	-
Age at first capture	t_c	2-9	2-9	-
Fishing mortality non-spawning	F_{ns}	0.1-2	0.1-2	-
Fishing mortality spawning	F_{sp}	0.1-2	0.1-2	

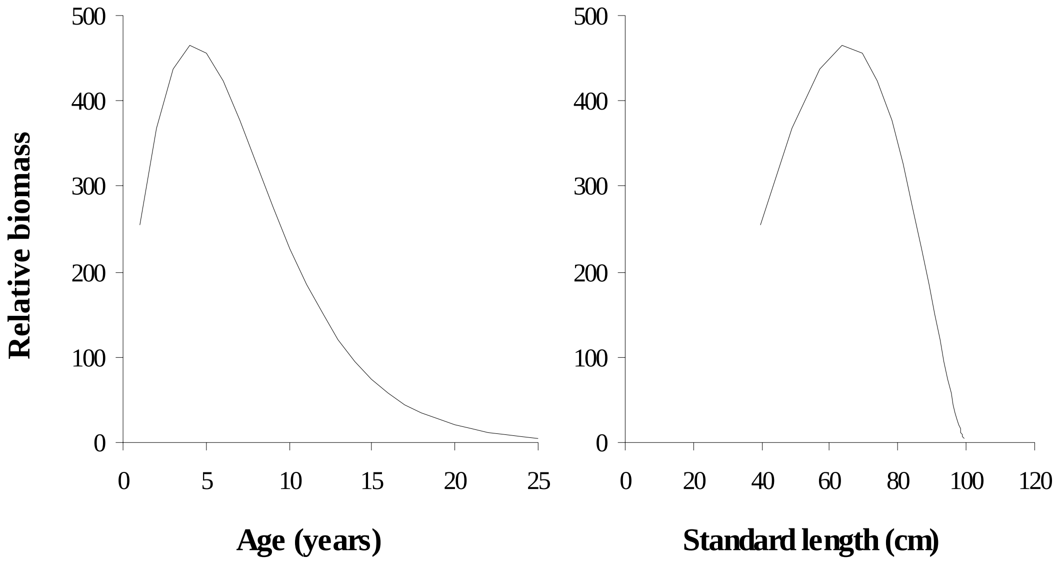


Figure 38. Relative biomass per recruit for blue grenadier by age (years) and standard length (cm).

The maximum biomass per recruit, in the absence of fishing (with natural mortality, *M*, set at 0.275), occurs at 4 years of age corresponding to a length of around 63 cm SL (Figure 38).

The values of YPR generated by the model are shown across a range of fishing mortalities (F = 0 to F = 2 $year^{-1}$) for various ages at first capture (t_c = 2 to t_c = 9). With natural mortality set at 0.275, YPR values peaked between ages 4-5 but at high fishing mortalities. However, overall YPR values were relatively insensitive to increasing the age at first capture (t_c) except at high ages (7-9), when YPR estimates were considerably lower (Figure 39).

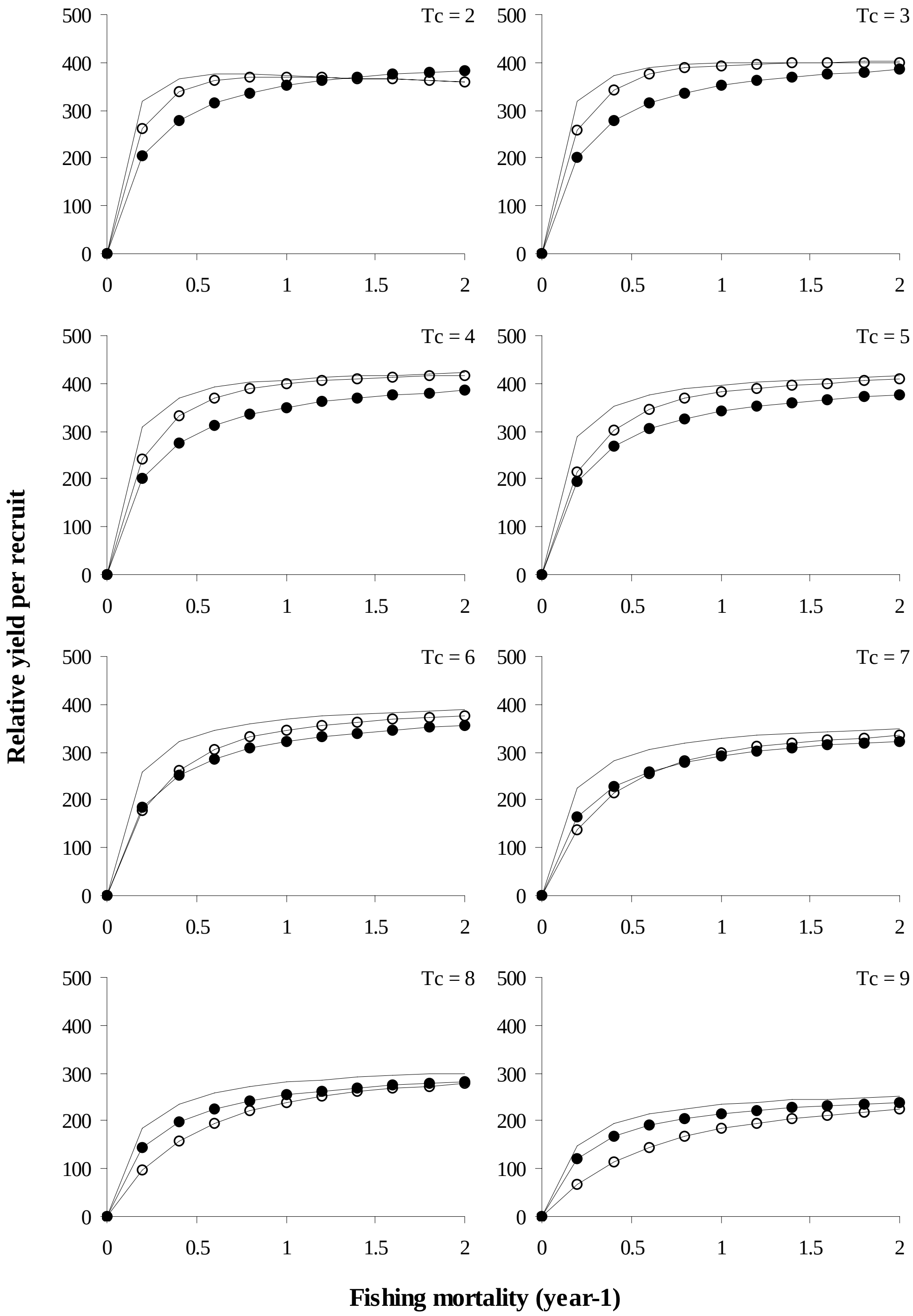


Figure 39. Yield per recruit versus fishing mortality for blue grenadier for a range of age at first capture (tc). Closed circle – spawning fishery; open circle - non- spawning fishery; solid line – combined.

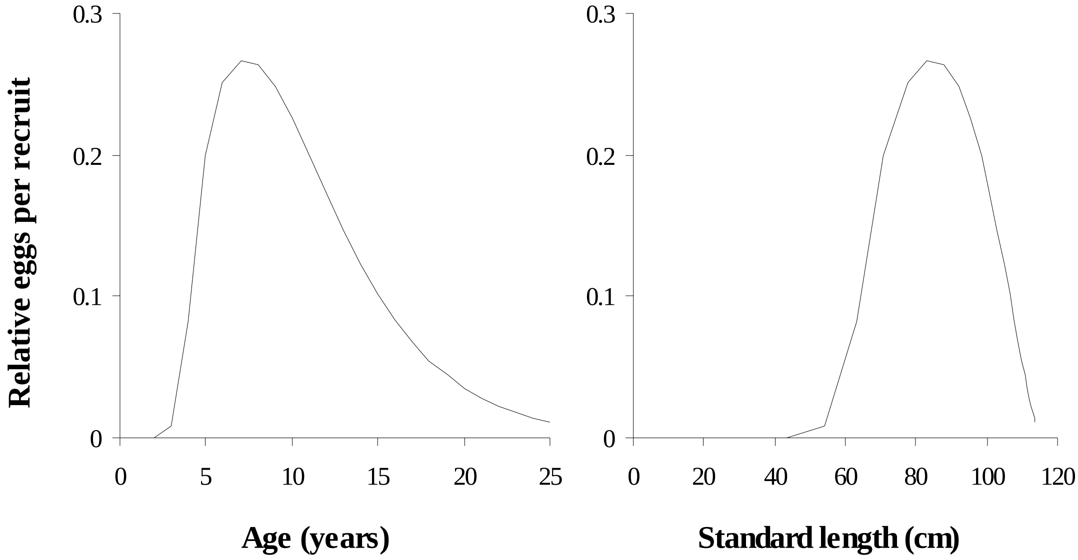


Figure 40. Relative eggs per recruit for blue grenadier by age (years and standard length (cm).

Eggs per recruit for female blue grenadier, in the absence of fishing (with natural mortality (*M*) set at 0.25), peaked at 7 years of age corresponding to a length of about 83 cm SL (Figure 40).

The values of EPR generated by the model are shown for a range of fishing mortalities (*F* = 0 to F = 2 year^{-1}) for various ages at first capture (t_c = 2 to t_c = 9). Natural mortality (*M*) was set at 0.25. Not surprisingly, increasing the age at first capture increased the relative eggs per recruit and this was most pronounced at higher levels of fishing (Figure 41).

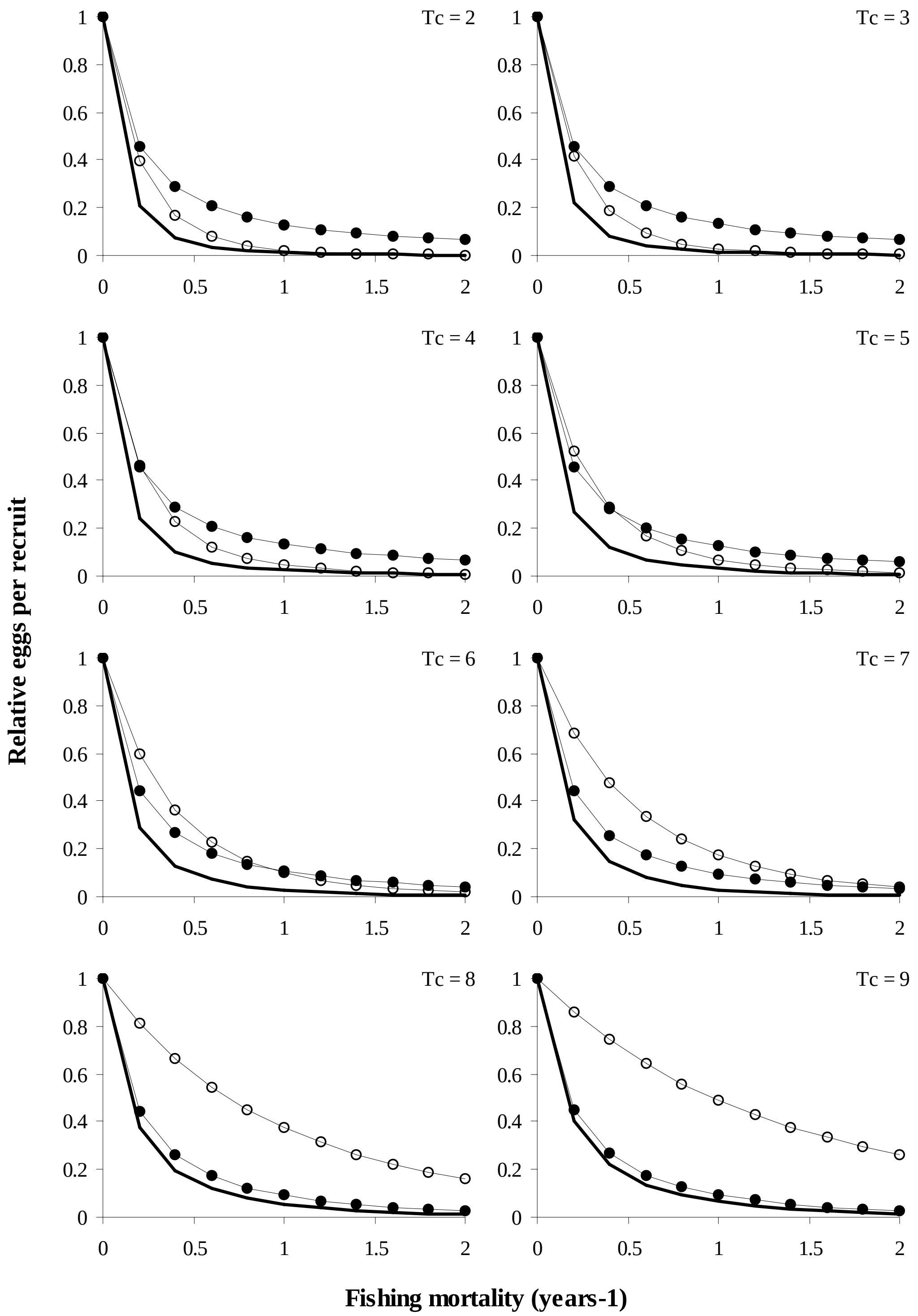


Figure 41. Relative eggs per recruit versus fishing mortality for a range of age at first capture (tc). Closed circle – spawning fishery; open circle - non- spawning fishery; solid line – combined.

The per recruit analyses indicate that while yield is maximised with ages at first capture of 4-5 years, increasing the age at first capture would benefit the reproductive potential of the population, particularly at high levels of fishing. During the study period, the age at which blue grenadier entered the non-spawning and spawning fisheries was around 4-5 years which closely corresponded to their age at 50% maturity. However, the population was dominated by the 1994 and 1995 year classes passing through the fishery.

Historically, while 4-5 year old fish were entering the spawning fishery it was dominated by older fish. The major issue concerns the non-spawning fishery. In previous years, large numbers of 3 year olds and in some years 2 year olds have been caught and during 1996-1998 very large numbers of young fish (1-2 year old fish) were also discarded (Punt *et al*. 2001). Clearly, this not only reduces potential yield but also has more pronounced impact on potential egg production. However, it should be noted that industry has adopted the use of larger meshes particularly in the western part of the fishery which should result in reduced capture and discarding of small fish.

Benefits

The main and most direct beneficiaries of this research will be the trawl sector of the SESSF. Knowledge of the spawning, the proportion of fish that spawn, turn-over rates during the spawning season, and reproductive parameters will assist in the development of improved stock assessments, and in the identification of harvest strategies for the trawl sector which represent the best compromise between maximising yield and minimising the impact of fishing on egg production (ie recruitment).

Determining turn-over rates has enabled industry-based acoustic snapshots to be used as absolute fishery independent biomass estimates, improving their utility and giving greater certainty to the blue grenadier assessments.

Further Development

Further estimation of the proportion of adult non-spawners is required. This would best be done during a period of 'normal' age composition and through fishery independent surveys. Whether this proportion is density dependent, i.e. changes with stock size, should also be examined.

Spawning dynamics and their interaction with fleet dynamics should be considered/modelled explicitly in the assessment of blue grenadier. This should include the varying duration of the spawning fishery, sex dependent data such as monthly changes in size and age composition during the spawning season and varying length weight relationships.

How to better estimate turn-over rates is unclear and requires further consideration, but would benefit from explicit modelling integrated into the assessment.

Any future egg surveys should take into account the results of this study and it may be possible to re-visit the earlier biomass estimates derived from egg surveys in the light of findings from this study.

It is unlikely that secondary spawning areas contribute significantly to total egg production, but this should be better estimated through the prospective fishery independent surveys.

Planned Outcomes

The main outcome of this project is the refinement in reproductive parameters for blue grenadier and estimates of the proportion of non-spawners and the turnover rate during the spawning season. Importantly, the latter enables acoustic 'snapshots' to be used as absolute estimates in the assessment. These results will provide greater certainty to the blue grenadier assessment and are already being used by the resource assessment group responsible for the assessment.

Conclusions

Blue grenadier were sampled on board commercial fishing vessels off western Tasmania between June 1999 and August 2002 during the spawning season (June to August). Blue grenadier were also sampled during the non-spawning period and also throughout the year in three other fishing zones within the SESSF boundaries: east coast of Tasmania, eastern Victoria and western Bass Strait. The latter sampling was conducted with support of the Integrated Scientific Monitoring Program (ISMP).

The body weight and length of each fish was recorded. Fish were sexed, the gonads macroscopically staged and otoliths collected for ageing. A sub-sample of gonads was taken for histological examination. SETF logbook data (SEF1) were examined for the period 1986 to 2003.

By 1997, following the introduction of 'factory' trawlers, landings from the spawning fishery exceeded that of the non-spawning fishery. Catches by these vessels quickly contributed over 90% of total catches with average monthly catches peaking in July at over 2,500 t. Catches from all other areas remained low during the spawning season. During the study period the fishery, both spawning and non-spawning, was dominated by the 1994 and 1995 year classes passing through the fishery.

This study confirmed that the major spawning area was off the west coast of Tasmania. This was supported by fisheries data. However, a few reproductively active male and female blue grenadier were sampled off the east coast of Tasmania and in western Bass Strait during the primary spawning period. These individuals may have been captured during their migration to and from this area or possibly reflect intermittent very low level spawning outside the west coast.

The length and age at 50% maturity based on macroscopic examination of gonads was 63.7 cm SL and 5 years for females and 56.8 cm SL and 4 years for males. These lengths are somewhat lower than previous estimates but most likely reflect the influence of the slower growth of the strong 1994 and 1995 year classes. Blue grenadier are batch spawners with determinate annual fecundity. Estimates of fecundity ranged from 0.3 million eggs to 4.6 million eggs for fish ranging from 68 cm SL to 112 cm SL.

Based on histological examination exclusively, 35% fish were classified as 'non-spawners' in non-spawning areas, 30% were found in the primary spawning area and 32% were found to be 'non-spawners' overall. However, it is also difficult to distinguish between immature fish and non-spawning adults. The blue grenadier fishery during the study period was dominated by small fish and there were few large fish (>80 cm SL) sampled outside the spawning area. Consequently, to remove uncertainty about these estimates, the 75% maturity (80.9 cm SL) ogive was applied to the data. 21% of fish were classified as 'immature' and of the fish classified as 'adult non-spawners', 5% were found in non-spawning areas and 18% were found in the primary spawning area. These estimates were weighted to the overall population given different abundances in each zone, particularly during the spawning season.

There is considerable uncertainty around our results. Few studies have been conducted to determine the degree of adult non-spawning in fish populations. However, all of these studies were based on the assumption that all fish sampled were fully mature (i.e. approaching 100% maturity). Consequently, we recommend the weighted proportion of adult non-spawners derived from the 75% maturity ogive (as this removes some of the uncertainty due to small fish) of 16% be used in future blue grenadier assessments.

Turn-over rates were assessed through an examination of sex ratios, gonad development, and size/age composition during the spawning period. Large, older fish enter the spawning area first followed by a steady decline in the mean length of female and male blue grenadier as the spawning period progresses, indicating that the spawning population is constantly altering. The best estimate of turn-over rate is 2x and this has been endorsed by SlopeRAG for use in the base case blue grenadier assessment.

The results of this study have refined our understanding of the reproductive biology of blue grenadier and provided estimates of the key areas of uncertainty; the proportion of non-spawning adults and the turn-over rate during the spawning season. Most of the results of this study have already been adopted by SlopeRAG for the assessment of blue grenadier in Australian waters.

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Appendix 1: Intellectual Property

No intellectual property has arisen from this project that is likely to lead to significant commercial benefits, patents or licences. Any intellectual property associated with the project will be shared between the Fisheries Research and Development Corporation, Fisheries Victoria and the AMC.

Appendix 2: Staff

Sarah Russell	Project Scientist, AMC
David C. Smith	Principal Investigator, Fisheries Victoria