

# Stock Assessments of Selected Northern Territory Fishes

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# Contents

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<b>EXECUTIVE SUMMARY.....</b>	<b>1</b>
GENERAL RECOMMENDATIONS .....	2
SPECIES-SPECIFIC RECOMMENDATIONS .....	2
<b>INTRODUCTION .....</b>	<b>4</b>
BACKGROUND .....	4
SPECIES BIOLOGY, STOCK STRUCTURE AND OVERVIEW OF ASSOCIATED FISHERIES .....	5
<b>MATERIALS AND METHODS.....</b>	<b>12</b>
MODELLING APPROACHES .....	12
CATCH/HARVEST RECONSTRUCTION .....	15
DETERMINATION OF SPATIALLY AVERAGED CATCH PER UNIT EFFORT (FISHES) .....	17
STOCK REDUCTION ANALYSIS (FISHES) .....	17
SIMPLE EQUILIBRIUM MODEL (GIANT MUD CRAB).....	19
SIZE-AGE-SEX MONTHLY STOCK SYNTHESIS MODEL (GIANT MUD CRAB) .....	19
<b>RESULTS.....</b>	<b>20</b>
SPANISH MACKEREL .....	20
GREY MACKEREL .....	22
COMMON BLACKTIP SHARK, AUSTRALIAN BLACKTIP SHARK AND SPOT-TAIL SHARK .....	25
BLACK JEWFISH.....	28
GOLDEN SNAPPER.....	30
GOLDBAND SNAPPER.....	32
GIANT MUD CRAB.....	34
<b>DISCUSSION .....</b>	<b>43</b>
<b>CONCLUSIONS/RECOMMENDATIONS .....</b>	<b>47</b>
<b>REFERENCES .....</b>	<b>50</b>
<b>APPENDIX A: GLOSSARY OF ABBREVIATIONS AND TERMS.....</b>	<b>54</b>
<b>APPENDIX B: SCREEN CAPTURES OF STOCHASTIC SRA OUTPUTS.....</b>	<b>55</b>

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## EXECUTIVE SUMMARY

Stocks of nine species (i.e. eight fishes and one invertebrate) caught in Northern Territory (NT) waters were assessed by world renowned fisheries scientist Professor Carl Walters (Fisheries Centre, University of British Columbia, Canada) in mid 2011 with the support of local fisheries scientists. Spanish Mackerel (*Scomberomorus commerson*), Grey Mackerel (*S. semifasciatus*), Common Blacktip Shark (*Carcharhinus limbatus*), Australian Blacktip Shark (*C. tilstoni*), Spot-tail Shark (*C. sorrah*), Black Jewfish (*Protonibea diacanthus*), Golden Snapper (*Lutjanus johnii*), Goldband Snapper (*Pristipomoides multidens*) and the Giant Mud Crab (*Scylla serrata*) were selected for analysis on the basis of existing sustainability concerns or because their current stock status was not known.

The modelling conducted in 2011 utilised catch and effort data to the end of 2010. For fish species, the analyses were repeated in late 2012 using corresponding data to the end of 2011. Two alternative modelling approaches for the Giant Mud Crab data were also tested during the intervening period (using data to December 2010 only). These models more accurately reflect the dynamics of the mud crab fishery (particularly seasonal changes in vulnerability/catchability of both sexes) than the Growth Type Group (GTG) model used in 2011. All results presented here refer to modelling work conducted in 2012.

Data for fishes were analysed using two forms of Stock Reduction Analysis (SRA; i.e. deterministic and stochastic SRA). In some cases, where fish stocks are known to span two jurisdictions, the SRA incorporated additional catch data from Western Australia (WA) or western Queensland (Gulf of Carpentaria; GoC). Data for the Giant Mud Crab were examined using a simple equilibrium model (Beverton and Holt 1956) as well as a novel size-age-sex monthly stock synthesis model. Different modelling approaches were applied to the Giant Mud Crab because i) unlike most fishes, the harvest of this species in the NT is controlled through the use of a minimum legal size (MLS) and ii) the Fisheries Division of the NT Department of Primary Industry and Fisheries (NT Fisheries) has amassed a 20 year monthly time series on Giant Mud Crab harvest sex ratio and size frequency data.

Both forms of SRA produced similar outputs, with those generated by the stochastic SRA being more accurate as they include variations in annual recruitment. Stock status determinations and the probability of current overfishing for relevant species/stocks estimated through the use of stochastic SRA are given in Table 1.

Key outputs from modelling the Giant Mud Crab data were that *annual* fishing mortality is around 1.0-1.2, similar to previous estimates of natural mortality (1.2; Knuckey 1999). However, vulnerability to fishing shows dramatic seasonal variation (the timing of which differs between sexes) such that *monthly* fishing mortality varies by more than an order of magnitude during the course of a year. The maximum body size of Giant Mud Crab in the NT also appears to have declined over the last decade, perhaps due to selection by the fishery.

The annual mortality estimates for Giant Mud Crab concur with the general rule in fisheries population dynamics that fishing mortality should be maintained at or below natural mortality to avoid overfishing and to prevent the stock from becoming overfished.

**Table 1.** Status determinations and the probability of current overfishing of selected fish stocks estimated through the use of stochastic Stock Reduction Analyses

Species	Stock or area	Stock status	Probability of current overfishing
Spanish Mackerel	All NT	Not overfished	0%
Grey Mackerel	Western NT	Not overfished	0%
	GoC	Not overfished	0%
Common Blacktip Shark	WA/western NT	Not overfished	0%
Australian Blacktip Shark	WA/western NT	Not overfished	0%
Spot-tail Shark	WA/western NT	Not overfished	4%
Black Jewfish	Accessible reefs <sup>1</sup>	Overfished	21%
Golden Snapper	Accessible reefs <sup>1</sup>	Overfished	99%
Goldband Snapper	Timor Reef	Not overfished	2%

<sup>1</sup>Accessible reefs = reefs within a day trip of major coastal population centres

Based on advice provided by Professor Walters during his visit in mid-2011 and subsequent analyses using catch and effort data to the end of 2011 (except for Giant Mud Crab), a number of general and species specific recommendations relating to fisheries research and management directions for the NT were developed for consideration. These are listed below:

#### General recommendations

- Continue or commence tagging programs to estimate current harvest rates (in fished areas) and natural mortality (in unfished areas) and expand the use of genetic tagging where practical
- Maintain fish ageing programs to assist with stock assessments and confirm the age structure of the population/s
- Where there is scope for increased harvest, it must be accompanied by rigorous monitoring and regulatory mechanisms that quickly limit the catch and/or catch rate if and when necessary
- The collection of regular and consistent catch statistics from the recreational sector is required for all species, particularly those where the recreational impact is significant

#### Species-specific recommendations

##### *Spanish Mackerel and Grey Mackerel*

- There is scope for a tightly controlled increase in the harvest of both Grey Mackerel and Spanish Mackerel (in line with the principles of ecologically sustainable development) in all areas of the NT

*Common Blacktip Shark, Australian Blacktip Shark and Spot-tail Shark*

- There is scope for a tightly controlled increase in the harvest of all three shark species (in line with the principles of ecologically sustainable development) noting the need for improved shark identification

*Black Jewfish*

- Limit both harvest and incidental mortality of Black Jewfish to prevent further overfishing of aggregations close to population centres
- Initiate a detailed study into the reproductive biology (particularly fecundity) and stock structure of Black Jewfish in northern Australia

*Golden Snapper*

- Limit both harvest and incidental mortality of Golden Snapper to prevent further overfishing close to population centres
- Reduce harvest mortality by decreasing the personal possession limit rather than applying a MLS
- Initiate a detailed study into the reproductive biology and stock structure of Golden Snapper in northern Australia and determine the incidental mortality of this species relative to depth of capture

*Goldband Snapper*

- Obtain regular fishery-independent indices of biomass (using “swept area” surveys) and use such surveys to monitor potential changes in biomass in different areas
- Retain samples of fish from these surveys to determine the degree of spatial variation in growth parameters and stock structure
- Request spatial catch and effort data for vessels targeting this species in Indonesian waters to improve the precision of future stock assessments

*Giant Mud Crab*

- Continue the mud crab market monitoring program to detect any irregularities in known patterns in mean size, maximum size and sex ratio of harvested crabs
- Find alternative methods of estimating fishing mortality that do not rely on body size data (e.g. a refined “swept area” method) to improve the precision of future stock assessments
- Review mud crab fishery management arrangements taking into account improved knowledge of trends in the fishery as well as the future development of all sectors

## INTRODUCTION

### Background

The tropical waters of the Northern Territory (NT) support a wide range of fishes and aquatic invertebrates. Of these, approximately 30 species are commercially harvested for human consumption in significant quantities; many more are harvested in small quantities by commercial aquarium fishers for the purpose of display. Almost all of the 30 primary commercial species are also harvested to varying degrees by recreational and Aboriginal fishers as well as Fishing Tour Operator (FTO) clients.

Stock assessments have been conducted for around half of the 30 primary commercial species over the last 25 years at intervals of 3-5 years (see Ramm 1994; Ramm 1997; Hay and Calogeras 2000; Buckworth 2004; Haddon et al. 2005; Ward et al. 2008). During this time there have been three Territory-wide recreational fishing surveys: the first in 1994-96 (Coleman 1998); the second in 2000-01 (which formed part of a national survey; Coleman 2004) and more recently in 2009-10 (West et al. 2012).

The series of stock assessments described herein focused on particular species (or stocks thereof) based on existing sustainability concerns (e.g. Black Jewfish and Golden Snapper; Grubert et al. 2010) or the need to update assessments where the current stock status and harvest rate was not known. These species are listed below by their Australian Standard Fish Name (Table 2). Recreational and commercial harvest controls that apply to the particular species (in addition to a range of other controls) are also presented in Table 2. Note that with the exception of the Mud Crab Fishery (MCF) all commercial fisheries examined here retain everything they “catch”. The remainder only “harvest” a proportion of their “catch” due to controls such as MLSs or personal possession limits. The annual harvest limit of 900 t of Goldband Snapper applied to the Timor Reef Fishery (TRF) has not been reached to date and so we use the term “catch” when referring to this fishery also.

**Table 2.** Recreational and commercial harvest controls for species selected for stock assessment

Australian Standard Fish Name	Recreational harvest controls		Commercial harvest controls <sup>c</sup>
	Possession limit	Minimum legal size	
Spanish Mackerel	2	NA	NA
Grey Mackerel	30 <sup>b</sup>	NA	NA
Common Blacktip Shark	Combined limit of 3 sharks (excluding protected species)	NA	NA
Australian Blacktip Shark		NA	NA
Spot-tail Shark		NA	NA
Black Jewfish	2 <sup>b</sup>	NA	NA <sup>b</sup>
Golden Snapper	5 <sup>b</sup>	NA	NA <sup>b</sup>
Goldband Snapper	30 <sup>b</sup>	NA	900 t <sup>d</sup>
Giant Mud Crab <sup>a</sup>	10	130 mm CW ♂	140 mm CW ♂
		140 mm CW ♀	150 mm CW ♀

<sup>a</sup> CW = carapace width; ♂ = male and ♀ = female

<sup>b</sup> harvest controls currently under review

<sup>c</sup> in addition to fishery-specific gear and effort controls etc.

<sup>d</sup> annual total allowable catch for Goldband Snapper



## Species biology, stock structure and overview of associated fisheries

### *Spanish Mackerel*

Spanish Mackerel are a fast-swimming pelagic predator found throughout tropical and subtropical coastal waters of the Indo-west Pacific, from Africa to Fiji (Kailola et al. 1993). Their Australian range extends from the southern tip of WA, across the north and down the east coast to southern New South Wales (NSW). Spanish Mackerel can live for up to 22 years and attain a size of over 2 m. They grow quickly and reach maturity in about two years; size at 50% maturity occurs at around 80 cm fork length (McPherson 1992; McPherson 1993; Begg et al. 2006; Buckworth et al. 2007).

Fecundity of Spanish Mackerel is presumed to be high, but is not well documented; spawning takes place several times over a protracted spawning season. Genetic studies indicate that there are three stocks of Spanish Mackerel across northern Australia (i.e. a north-west, Torres Strait and east coast stock; Buckworth et al. 2007).

Tagging studies on this species have revealed limited adult movement (at scales greater than 100 km) which, in conjunction with the results of otolith microchemistry and parasite analyses suggest that there may be a number of smaller stocks with minimal interaction (Buckworth et al. 2007). Given that the boundaries of these apparently discrete stocks are not known, the analyses presented are based on data from all NT waters.

Recreational fishers and FTO clients use a variety of methods to catch Spanish Mackerel (and Grey Mackerel) in the NT, whereas licensees in the NT commercial Spanish Mackerel Fishery (SMF) only use troll lines, rigged with either lures or baits. The primary recreational harvest control for Spanish Mackerel in the NT is a personal possession limit of two fish. Around 30% of Spanish Mackerel captures by recreational fishers in the NT are the result of targeted fishing for this species, with just over half (53%) of the (recreational) catch of this species being released (West et al. 2012).

As active pelagic fishes, without a swim bladder, mackerels are not prone to pressure change injuries (barotrauma) like demersal fishes. However, neither Spanish Mackerel nor Grey Mackerel are good candidates for catch and release fishing because they are fragile and stress easily (in relative terms) during retrieval and landing; factors important to any robust stock assessment of these species where the recreational catch is significant.

The commercial SMF takes the greatest proportion of Spanish Mackerel of any fishery operating in the NT. This species is also taken as a byproduct in the commercial Offshore Net and Line Fishery (ONLF) and Finfish Trawl Fishery (FTF). Spanish Mackerel were heavily exploited by Taiwanese drift-netters operating in NT waters during the 1970s and 1980s. This species has also been subject to illegal longline fishing (by international vessels) since about 1986, and although the exact magnitude of the illegal, unregulated and unreported (IUU) catch is not known, we have (for precautionary reasons) assumed a constant annual IUU take of 600 t of Spanish Mackerel since this time. The catch and catch per unit effort (CPUE) of Spanish Mackerel by the SMF over the last four years (2008 to 2011) has been relatively stable, at around 250 t and 350 kg/boat day, respectively.

### *Grey Mackerel*

Grey Mackerel have a smaller geographic range than that of Spanish Mackerel. They are found along the southern coastlines of eastern Indonesia, East Timor and Papua New Guinea, in parts of the Coral Sea, and also along the Australian coastline from Shark Bay, WA, clockwise to northern NSW (Kailola et al. 1993; Collette 2001).

Growth of Grey Mackerel is fast and both sexes reach maturity in less than one year. The length at 50% maturity for females (i.e. 67 cm) is slightly less than that for males (i.e. 70 cm; Welch et al. 2009). Grey Mackerel achieve a maximum length of 120 cm (as fork length for all references to this species) and weight of 10 kg, although the average weight is between 2 and 5 kg (Crofts and de Lestang 2004). Longevity is up to 12 years.

Female Grey Mackerel produce over 250 000 oocytes (eggs) per spawning and each egg mass (a string of many eggs released into the water column) can reach up to 50 cm in total length (Cameron and Begg 2002; Crofts and de Lestang 2004). The primary spawning season runs from August to December. However, there are indications of earlier spawning in the north-west of the NT. Once hatched, larvae of this species move to coastal bays and lagoon areas between the coast and outer reefs (Jenkins et al. 1985).

Around 27% of Grey Mackerel captures by recreational fishers in the NT are the result of targeted fishing for this species. Thirty eight percent of the Grey Mackerel caught by recreational fishers in the NT are released (West et al. 2012). There are no specific controls relating to the recreational harvest of Grey Mackerel in the NT, instead this species falls under the general personal possession limit of 30 fish. The effectiveness of this general personal possession limit is currently under review.

The relative harvest of Grey Mackerel by recreational fishers and FTO clients in the NT is small compared to that of the commercial ONLF. Licensees in this fishery use a combination of demersal longlines and pelagic gill nets; the latter gear type being more commonly used.

Two distinct populations of Grey Mackerel occur in the NT, one in the western side of the NT and one in the GoC (Welch et al. 2009). The two Grey Mackerel stocks have very different catch histories and are assessed separately here. Fishing of the western NT stock began in the mid-1970s with Taiwanese drift-netters harvesting thousands of tonnes per annum for about a decade. This stock has also been subjected to separate illegal longline fishing (by international vessels) since about 1986, and although the exact magnitude of IUU catch is not known, we have (for precautionary reasons) assumed a constant annual IUU take of 600 t of Grey Mackerel since this time. By contrast, fishing of the GoC stock only began in the early 1990s (it was not fished by the Taiwanese) and there has been little or no illegal fishing in this area.

*Common Blacktip Shark, Australian Blacktip Shark and Spot-tail Shark*

The Common Blacktip Shark, Australian Blacktip Shark and Spot-tail Shark are members of the family Carcharhinidae. All three species have historically been referred to as “blacktip sharks” because of their physical similarities. Indeed, even today *C. limbatus* and *C. tilstoni* cannot be reliably identified by fishers or fisheries scientists aboard their vessels. The only consistent means of distinguishing between these species is through genetic analysis or vertebral counts (Last and Stevens 2009; Morgan et al. 2011; Harry et al. 2012). The Spot-tail Shark can be distinguished from the other two species on close inspection, and has been reported as a separate species in NT commercial fishery logbooks since 1999 (Northern Territory Government 2012).

*Carcharhinus limbatus* is found globally in tropical and warm temperate areas whereas *C. tilstoni* is an Australian endemic, found only around northern Australia. *Carcharhinus sorrah* occurs in tropical areas of the Indo-West Pacific, including northern Australia. There are three genetically distinct stocks of *C. limbatus* in Australian waters, one in northern WA/western NT, one in the GoC and another on the east coast of QLD/NSW. *Carcharhinus tilstoni* forms two stocks (i.e. a northern WA/western NT stock and a GoC/eastern QLD/NSW stock). By contrast, all *C. sorrah* are part of the same genetic stock (Ovenden et al. 2007). Given the level of variation in stock structure between very similar species, the stocks are managed at the finest known scale (i.e. the three stock areas identified for *C. limbatus*) as a precautionary measure.

The longevity, maximum size and size/age at maturity are different for all three species (where known). The maximum size of *C. limbatus* is 2.5 m (as total length for all references to sharks), but the longevity of this species is not known. Male *C. limbatus* mature at 5-6 years and females at 6-7 years, with females producing pups every second year thereafter (Last and Stevens 2009). Male *C. tilstoni* live to 13 years and females to 15 years, with maximum recorded size being 2.0 m. Size at 50% maturity for males is ~1.1 m and that for females ~1.2 m, both at 5-6 years of age. *Carcharhinus tilstoni* reproduce every year and the typical litter size for both it and *C. limbatus* is one to seven pups (Stevens and Wiley 1986; Last and Stevens 2009; Harry 2011).

*Carcharhinus sorrah* attains a smaller maximum size (1.6 m) but grows faster (25 cm in the first year) and matures earlier (at two to three years and ~90 cm) than the other two species. Longevity of males is up to 9 years and females up to 14 years. Female *C. sorrah* produce one to eight pups annually (Last and Stevens 2009). The number of young produced by all three Carcharhinid species mentioned here is quite low compared to some other sharks, and orders of magnitude below that produced by fishes (noting the considerable differences in survivorship between live-born Carcharhinid sharks and fish larvae).

The commercial ONLF takes the greatest proportion of sharks (over 95% of the overall harvest) of any (legal) fishery in the NT, with *C. limbatus*, *C. tilstoni* and *C. sorrah* forming the bulk of the shark catch by this fishery. Licensees use a combination of demersal longlines and pelagic gill nets; the latter gear type being more commonly used. All three shark species were heavily exploited by Taiwanese drift-netters operating in NT waters during the 1970s and 1980s. They have also been subject to illegal longline fishing (by international vessels) since about 1986, and although the exact magnitude of IUU catch is not known, we have (for precautionary reasons) assumed a constant annual IUU take since this time (i.e. 600 t for *C. limbatus* and *C. tilstoni* combined and 200 t for *C. sorrah*).

Less than 1% of shark captures by recreational fishers in the NT are the result of targeted shark fishing (West et al. 2012). Sharks are generally considered a “nuisance” fish by this sector and the vast majority (95%) are released (West et al. 2012). The release rate of sharks by FTO clients is similar. The combined personal possession limit for sharks in the NT is three in total (excluding protected species).

### *Black Jewfish*

The Black Jewfish is a member of the Sciaenid family, a group of large sound producing fishes collectively known as “croakers”. The growth rate of Black Jewfish in NT waters is extremely fast, with fish reaching around 60 cm (as total length for all references to this species) in their first year and 90 cm in their second (Phelan 2008). The size at 50% maturity of females in the NT is 90 cm, while the maximum documented age and size in this jurisdiction is 12 years and 1.4 m, respectively (Phelan 2008).

Black Jewfish form discrete and predictable aggregations at a number of sites along the NT coastline. These aggregations typically comprise mature fish over 90 cm, with a mean size of 1.0 to 1.1 m. Egg development is initiated in the dry season (July/August) and peak spawning occurs in the wet season (December to February); these events are followed by a “resting” phase spanning the intervening months (Phelan 2008). The fecundity of this species in Australian waters is not known but is presumed to be high given estimates from India (i.e. 1.7 to 6.9 million eggs for females between 85 cm and 106 cm; Rao 1963).

The aggregating behaviour of Black Jewfish makes them fairly easy to catch once the location of an aggregation is known. Heavy exploitation of this species in far north QLD led to a dramatic decline in both the number and size of sexually mature fish (to <95 cm) in a relatively short period (5 years, from 1994 to 1999; Phelan et al. 2008). While there have been observed declines of this species around populations centres in the NT they have not been to the same extent as those seen in QLD.

The stock structure of Black Jewfish in northern Australia is poorly understood. The most recent genetic study suggests there is a single homogenous population between the NT and the tip of Cape York (Phelan 2002). However, further work is required to clarify the situation given the modest sample size examined by Phelan (2002) ( $n = 109$  across three sites).

Around 85% of the harvest by the NT commercial Coastal Line Fishery (CLF) consists of Black Jewfish, with the vast majority caught using handlines. They are also taken as a byproduct species by the NT Barramundi Fishery and FTF (using nets) and are targeted by FTO clients, who like most recreational fishers, use a rod and reel to target them.

Black Jewfish are highly susceptible to severe (fatal) barotrauma when caught in waters deeper than 10 metres (Phelan 2008). Hence, a MLS is not applied to this species in the NT with the primary recreational harvest control being a personal possession limit of two fish. Almost 40% of Black Jewfish captures by recreational fishers in the NT are the result of targeted fishing for this species; around 30% of the Black Jewfish caught are released (West et al. 2012).

The commercial sector of the fishery currently harvests more Black Jewfish than the recreational sector. However, the combined effects of harvest mortality and incidental mortality (primarily through barotrauma) on this species applied by the recreational sector means that the impact of this group is significant. Comparisons of total mortality of Black Jewfish derived from the 1994-1996 (Coleman 1998) and 2000-2001 (Coleman 2004) NT recreational fishing surveys with concurrent catch data from the commercial sector suggest that (at the time) the impact of the recreational sector was roughly seven and two times greater than that of the commercial sector, respectively (using a mean recreational harvest weight of 9 kg, a mean release weight of 6 kg and assuming 50% incidental mortality over all depths).

The catch/harvest of both sectors has since declined and the total mortality imposed by the recreational sector is now roughly half that of the commercial CLF (using data from West et al. 2012 and the multipliers above). Given the sporadic nature of recreational fishing surveys in the NT, the most informative time series on the catch and CPUE of Black Jewfish comes from the commercial sector of the CLF.

### *Golden Snapper*

The Golden Snapper is considered a premium table fish and is highly prized amongst the NT fishing community. Juveniles form schools that inhabit estuarine reefs until such time as they move out to coastal reefs at depths of up to 80 m (Starling and Cappo 1996; Kiso and Mahyam 2003). The maximum documented age, size and weight of Golden Snapper in the NT is around 20 years, 80 cm (as fork length for all references to this species) and 8 kg, respectively ( $n = 2106$ ; sampling interval 1995 to 2000; Hay et al. 2005).

The first estimates of the age and size at 50% maturity of Golden Snapper in the NT were around 5 years for males (at ~50 cm) and 8 years for females (at ~60 cm; Hay et al. 2005). More recent estimates of these parameters ( $n = 679$ ; sampling interval 2009 and 2012; unpublished data) concur with those derived by Hay et al. (2005) and are within one year and 3 cm (for both sexes), respectively.

Results from the Suntag tag-recapture program on the central coast of Queensland (data courtesy of Bill Sawynok, Infotish Services) indicate that adult Golden Snapper show a high degree of site fidelity. For example, 80% of the 380 recaptures (from over 5500 fish tagged to January 2010) were caught within the same 1 x 1 km as their first capture (noting that capture depths were not recorded). The bulk of these fish (i.e. 95%) were immature, ranging in size from 20.0 cm to 44.9 cm. Fourteen percent of recaptures had moved 1 to 10 km and 5% of fish had moved 11 to 50 km. Only 1% of fish moved 51 km or more with the greatest distance travelled being 140 km. Those fish that travelled more than 10 km typically moved up and down the coast rather than inshore-offshore.

Golden Snapper are susceptible to severe (i.e. fatal) barotrauma in waters greater than 15 m depth (unpublished data). This being the case, a MLS is not currently applied to this species in the NT (although it could be considered based on habitat stratification between juvenile and adult stages). The primary recreational harvest control is a personal possession limit of five fish (currently under review). Despite its popularity in northern Australia, little else is known of the growth, reproductive biology or stock structure of Golden Snapper within its Australian range.

The contribution of Golden Snapper to the commercial CLF catch is relatively small, in the order of 2% to 9% of the total annual catch over the last ten years (to 2011). Corresponding annual tonnages range from 3.6 to 15.5 t, with the average being 7.8 t. Golden Snapper are the second most frequently caught fish by FTO clients after barramundi, with the total annual catch (as distinct from harvest) by this group over the last ten years ranging from ~13 000 to ~20 000 individuals. Using an average fish weight of 0.9 kg, this equates to between 11.7 t and 18.0 t of Golden Snapper caught, with an unknown proportion succumbing to incidental mortality (barotrauma).

Results from the 2009/10 recreational fishing survey (West et al. 2012) indicate that of the 80 000 Golden Snapper caught by recreational fishers in 12 months, around 42 000 (or 53%) were released. The 38 000 Golden Snapper harvested equate to 34 t of fish (using a multiplier of 0.9 kg), which is greater than the harvest by the commercial CLF and FTO clients combined. The total recreational harvest is likely to be substantially greater as the survey only included NT residents (and not interstate or overseas visitors). Furthermore, an unknown proportion of Golden Snapper released by recreational fishers will also succumb to incidental mortality.

Whilst the relative harvest of Golden Snapper by the recreational sector is the largest, the most informative time series on the catch and CPUE of this species comes from the FTO sector.

### *Goldband Snapper*

Goldband Snapper is a long lived, predominantly deep water species found across northern Australia. It reaches maturity at around 5 years and grows relatively quickly until 9 years. Growth then slows and the fish reach a maximum length of around 80 cm at 18 years. Natural mortality is low (0.10 - 0.14) with some individuals living to 30 years (Newman and Dunk 2003). Goldband Snapper are highly fecund serial spawners with peak spawning occurring during the Austral summer (Lloyd 2010). Notwithstanding their fecundity, Goldband Snapper are considered vulnerable to overfishing due to their extended longevity and low rates of natural mortality (Newman and Dunk 2003).

Adult Goldband Snapper occur over a wide depth range (40 m to 200 m; Lloyd et al. 1999) and suffer physical damage from barotrauma when retrieved from these depths. This being the case, a MLS is not applied to this species. Their susceptibility to barotrauma also severely limits the assessment of adult movement through conventional tagging methods. However, both genetic and otolith microchemistry analyses suggest there are several stocks of Goldband Snapper across northern Australia and Indonesia, indicating limited movement among populations (Lloyd et al. 2000; Newman et al. 2000). These findings imply that removing adults from one “stock” may have little impact on other stocks. However, the behavioural responses of adults to population reduction (through fishing) are not known, and there may also be intermixing of eggs and/or larvae such that fishing one stock does indeed impact on another through recruitment.

The majority of Goldband Snapper harvested in the NT are taken by the multi-species and multi-gear (fish traps and drop lines) Timor Reef Fishery (TRF). *Pristipomoides multidens* is one of three species harvested as “Goldband Snapper” in this fishery and makes up around 90% of the total goldband catch (unpublished data). The Goldband Snapper group currently accounts for around 50% of the total catch by this fishery, with “red snappers” (*L. malabaricus* and *L. erythropterus*) and minor byproduct species constituting the remainder.

The TRF operates offshore in the Timor Sea, a remote region extending north-west of Darwin to the WA/NT border and to the outer limit of the Australian Fishing Zone. The fishery has an area of approximately 8400 square nautical miles (nm). Prior to 1999, most operators in the fishery used drop lines, but over the next decade fishers experimented with traps, in some cases in combination with drop lines, in others not. Traps are now the predominant gear type in the fishery and take about 80% of the TRF catch.

The total allowable catch (TAC) for the Goldband Snapper group by the TRF is 900 t, whilst that for the “red snapper” and “other” groups is 1300 t and 415 t, respectively. Although the current catch of Goldband Snappers is below 900 t it is expected to approach this value in the near future.

Whilst foreign fishing vessels operated throughout northern Australian waters from the late 1950s, most of the catch was taken from the Arafura Sea rather than the Timor Sea. For this analysis, it was assumed that no fishing occurred in the Timor Reef area prior to the commencement of the domestic dropline fishery in 1987.

### *Giant Mud Crab*

Two species of mud crab are found in NT waters, the Giant Mud Crab (*Scylla serrata*) and the Orange Mud Crab (*Scylla olivacea*), with the former constituting >99% of the local commercial harvest (Hay and Calogeras 2000). Given the dominance of the Giant Mud Crab in the catch, the fishery is managed based on its biological characteristics rather than that of the smaller Orange Mud Crab.

Giant Mud Crabs reach sexual maturity at 12-18 months of age and have a lifespan of 3-4 years (Knuckey 1999). Size at 50% maturity differs between sexes and locations but is generally around 130-150 mm carapace width (CW) in the NT (Knuckey 1999). The maximum documented size and weight of Giant Mud Crabs caught in the NT is 207 mm CW and 2.0 kg for males, and 205 mm CW and 1.4 kg for females, respectively (Grubert and Lee in press). Larger crabs are known to have been caught in the NT but their size and weight has not been verified.

Two distinct genetic stocks of *Scylla serrata* have been identified in Australian waters (He et al. 2011); an endemic north-west coast stock (extending from Western Australia to the tip of Cape York) and an east-coast stock (encompassing the eastern seaboard of Australia) which is part of a larger West Pacific stock. Hence, all Giant Mud Crabs harvested in the NT appear to be part of the same stock.

The NT Mud Crab Fishery (MCF) is an input controlled fishery that has seen several management changes over time. Examples include: increases to MLSs (in 1996 and 2006), prohibition on the take of newly-moulted “commercially unsuitable” crabs (in 2001) and the unitisation of licences (in 2010). The current MLSs for commercially harvested male and female Giant Mud Crab in the NT are 14 cm and 15 cm CW, respectively. The MLSs for recreationally harvested Giant Mud Crabs in the NT are 1 cm less for each sex.

Crab traps (pots) are the primary gear type used by recreational mud crab fishers and the sole gear type used by industry. All commercial pots are constructed of 75 mm x 50 mm galvanised wire mesh whilst recreational fishers use both wire and polyethylene mesh pots.

There is some overlap in the recreational and commercial components of the MCF but most of the harvesting is spatially separated. For example, around 85% of the recreational harvest of Giant Mud Crabs occurs to the west of the Cobourg Peninsula (derived from West et al. 2012) whilst ~80% of the commercial harvest is taken to the east of this landmark (unpublished data). Annual (and seasonal) catch rates for commercial mud crab fishers operating in the NT are variable and correlated with environmental drivers such as rainfall and the La Niña-El Niño cycle (Meynecke et al. 2012a; Meynecke et al. 2012b).

Infrequent estimates of the local Giant Mud Crab harvest by recreational and Aboriginal fishers, coupled with fluctuations in the NT commercial catch make it difficult to determine the relative harvest by sector. However, where concurrent data are available it appears that the commercial fishery accounts for around 90–95% of the total Giant Mud Crab harvest in the NT. The comparatively large harvest fraction by the commercial sector and scarcity of information on other sectors means that the observations and analyses described herein refer to data collected from the commercial fishery only.

A monthly mud crab market monitoring program has been in place in the NT since the early 1990's. Between 100 and 200 crabs (contingent on availability) are sampled from key fishing areas on a monthly basis and information on sex ratio, size, weight, moult stage and mating success recorded. The monitoring database now contains records on almost 70 000 individual crabs.

## MATERIALS AND METHODS

### Modelling approaches

#### *Stock Reduction Analysis – fishes*

Stock reduction analysis (SRA) was originally developed by Kimura and Tagart (1982) and Kimura et al. (1984), and was later refined by Walters et al. (2006). SRA is a population dynamics model that consists of leading parameters on unfished recruitment, survival, recruitment compensation from harvest, growth characteristics, maximum size, age at birth, length-weight relationship and size at maturity that describes the underlying production and carrying capacity of a population over time.

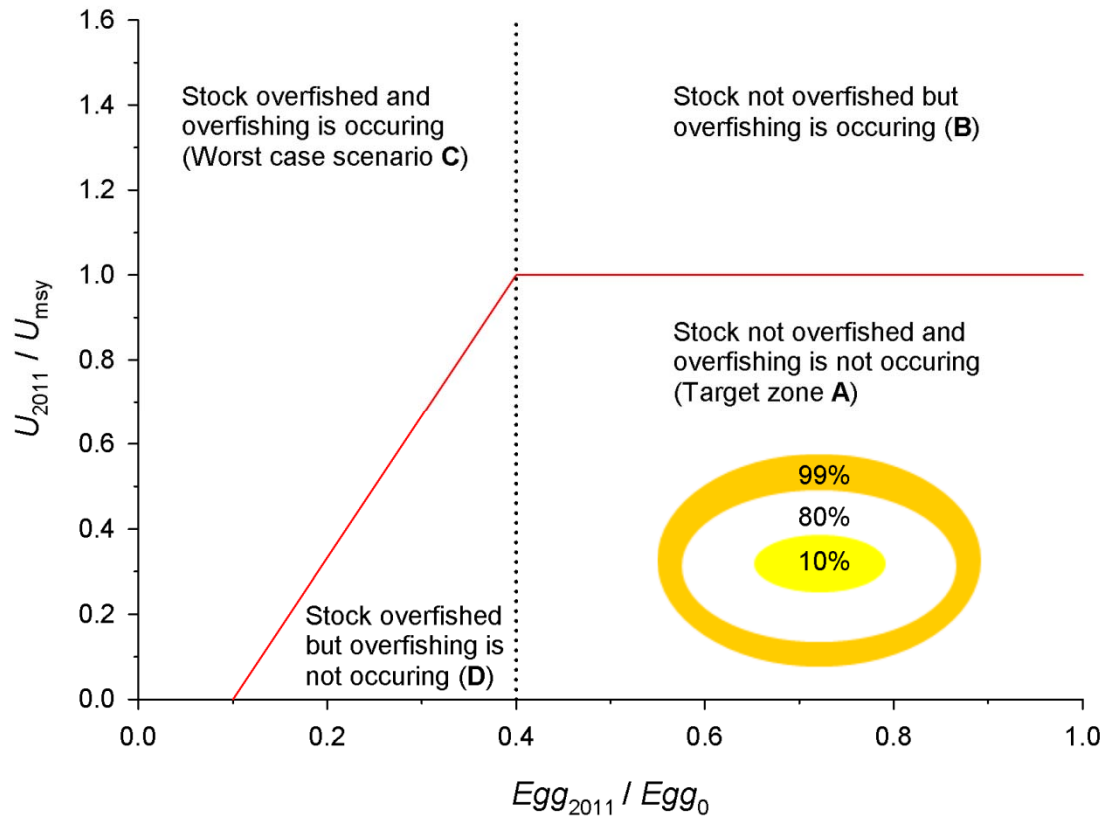
SRA simulates changes in abundance by subtracting estimates of mortality and adding estimates of new recruits, where the new recruits are a function of the current stock size and the leading parameters. Mortality includes estimates of natural mortality and known removals through harvesting. Because SRA uses historical catch information to drive the population dynamics model forward from the beginning of the fishery, it is critical to have accurate historical information on catch and effort to determine historical changes in abundance and estimate key population parameters. The key population parameters of the model are then adjusted until the simulations produce trends that are similar to those of the relative abundance estimated from catch and effort data or numbers that approach known estimates of abundance from fishery-independent data, such as abundance surveys or tagging data. SRA can also include forward projections beyond the existing time series and predict the possible impacts of alternative harvest policies.

SRA can be performed using relatively simple deterministic models created in Microsoft (MS) Excel, or more complicated stochastic models created using Visual Basic for Applications (VBA). Deterministic SRA models provide a single stock size (as biomass here) trajectory, while stochastic SRA attempts to provide probability distributions for stock size (or egg production here) over time under alternative hypotheses about unfished recruitment rates and about variability around assumed stock–recruitment relationships (Walters et al. 2006). Stochastic SRA generates these distributions by conducting large numbers of Monte Carlo simulation trials and retaining those sample trials for which the stock would not have been driven to extinction by historical catches. By resampling from these trials using likelihood weighting, it is possible to move to fully Bayesian, state–space assessment modeling through a series of straightforward steps.

The probability of overfishing can be calculated from the stochastic SRA output according to the Pacific Fisheries Management Council (PFMC) 40/10 rule, whereby the current harvest rate is targeted to be maintained below the harvest rate at maximum sustainable yield when the current egg production of the stock is <40% of the unfished egg production, and the harvest rate is targeted at zero when the stock is ≤10% of the unfished egg production (adapted from Lombardi and Walters 2011). The stock is considered overfished when current egg production is <40% of the unfished egg production. These “zones” are represented graphically in Figure 1.

The target zone for the “fried egg” probability distribution is to the right of the vertical dotted line and below the horizontal red line (Figure 1, zone A). This situation means that the stock is not overfished and overfishing is not occurring. If the “fried egg” moves vertically from this position, to above the red line (zone B), then the stock is still not overfished but the harvest rate is such that overfishing is occurring. If overfishing is allowed to continue (that is, appropriate management action is not taken), the fried egg will then shift horizontally, to the worst case scenario, where the stock is overfished and overfishing continues (zone C). When confronted with this situation, there is an obvious need to impose additional management measures to curb overfishing and rebuild the stock. If these measures are successful, the “fried egg” will then shift vertically to below the diagonal red line (to zone D) then horizontally, back to the target zone.





**Figure 1.** Diagrammatic representation of a stochastic SRA output showing four “status zones” and a “fried egg” posterior probability plot. The outer edge of each coloured (and cumulative) probability region (from inner-most to outer-most) correspond to a 10%, 80% and 99% chance that the estimated status measures fall within that region.

*Simple equilibrium model – Giant Mud Crab*

The longevity of the Giant Mud Crab is around 3-4 years and so there is no doubt that total mortality rate ( $Z$ ) of this species is high (see Knuckey 1999; Haddon et al. 2005; Ward et al. 2008), with natural mortality rate ( $M$ ) most likely around 1.0 (Knuckey 1999) and fishing mortality rate ( $F$ ) perhaps even higher (noting  $Z = F + M$ ). This being the case, average CW should remain fairly close to an equilibrium prediction of it developed by Beverton and Holt (1956). They showed that if there is knife edge selection at a minimum size  $l_r$  (see Ward et al. 2008 for examples from the NT MCF), with all fish (or crabs) above size  $l_r$  being subject to the same  $Z$ ; and if body growth follows the von Bertalanffy growth curve with metabolic parameter  $K$  and maximum theoretical length  $L_\infty$  (as CW in cm here), then  $Z$ ,  $K$ , and  $L_\infty$  should be related to mean CW of crabs harvested (i.e.  $\bar{l}$ ) through the equation:

$$Z = K \frac{(L_\infty - \bar{l})}{(\bar{l} - l_r)} \quad \text{Equation 1}$$

Beverton and Holt (1956) recommended use of this equation to estimate  $Z$  given observed  $\bar{l}$  and the growth parameters  $K$  and  $L_\infty$ . Clearly, the step-wise growth pattern of the Giant Mud Crab does not precisely conform to the von Bertalanffy growth curve; here we view it as a course approximation of this curve as have others in the past (Knuckey 1999; Haddon et al. 2005; Ward et al. 2008). The exact means by which the Beverton and Holt equation is applied to the MCF data is expanded upon below.

*Size-age-sex monthly stock synthesis model – Giant Mud Crab*

Whilst the Beverton Holt (1956) size-mortality rate equilibrium model can give some insights into long term changes in fishing mortality rates of Giant Mud Crab, there is clearly a need to look more closely at the seasonal dynamics of recruitment and fishing mortality as these interact with crab growth patterns and MLSs. In previous analyses, Knuckey (1999) and (Walters unpublished) have tried to meet this need using stock synthesis models, including the GTG model used in 2011.

The basic idea in a synthesis model is to predict changes in abundance and body sizes over time (in this case at monthly time resolution) as functions of parameters representing variable recruitment and changes in mortality rates, then vary these parameters so as to find the parameter values that best fit (predict) historical data, in this case monthly harvest ( $\text{Harvest}_{\text{sex},t}$ ) and mean CW in the harvest ( $\text{CW}_{\text{sex},t}$ ). Unfortunately, existing synthesis models, and in particular the detailed GTG model, cannot be used at present to carry out this estimation, since they do not adequately represent the complex sex-specific changes in seasonal vulnerability implied by the observed sex ratio changes (see Ward et al. 2008), and it would be a complex chore to reprogram the GTG model to do so.

For this analysis, we elected instead to develop a simpler spreadsheet based synthesis model that focuses on seasonal variation in recruitment and vulnerability to capture by sex, without accounting explicitly for variation in CW at age due to variation in growth rates (but variation in size due to variation in apparent spawning date is accounted for, by having recruitment to the population age structure for each year spread over months of the year).

### Catch/harvest reconstruction

Catch/harvest histories for each species (or stock thereof) were reconstructed using data from a range of fisheries which differed between species/stocks (described above and summarised in Table 3). Annual catch data were utilised for the SRAs on fishes whereas both annual and monthly harvest data were used in the Giant Mud Crab analyses. The latter also relied upon monthly CW and sex ratio data from NT Fisheries' mud crab market monitoring program. The year 1970 was chosen as the starting point for most catch/harvest reconstructions but in some cases (Giant Mud Crab and Goldband Snapper) later starting points were used.

Although two stocks of both the Common Blacktip Shark and the Australian Blacktip Shark are found in the NT, only data from the north-west stocks (i.e. WA/western NT) were analysed here as it is these that are most heavily fished. In the case of the Spot-tail Shark, which is known to form a single genetic stock across its Australian range, only data from WA/western NT were used as per the other sharks. Grey Mackerel was the only species to have two stocks analysed (i.e. WA/western NT and GoC). With respect to Goldband Snapper, we have assumed that the proportion of *P. multidentis* in the "Goldband Snapper" group has remained both constant and high (at 90%) over the history of the TRF and treat the catch and CPUE data as having come from a single species. This assumption is made on the basis of catch composition data collected during annual monitoring trips aboard TRF vessels over the last decade.

Spanish Mackerel, the western NT stock of Grey Mackerel and all three shark species were harvested by Taiwanese drift-netters formally operating in NT waters during the 1970s and 1980s. All five species/stocks have also been subject to illegal longline fishing (by international vessels) since about 1986, with estimates of the annual unreported catch being ~600 t for all but the Spot-tail Shark (where the estimate was ~200 t). Both the Taiwanese and illegal catches were added to each year's catch total where relevant (Table 3). The IUU catches were included to safeguard against possible under-estimation of harvest rates.

**Table 3.** Catch/harvest data sources for species selected for stock assessment (Y = yes; N = No). Domestic fisheries included commercial fisheries (Com.) operating in the NT combined with those operating in either QLD or WA (noting that area specific data were used where necessary). This category also included the NT Fishing Tour Operator (FTO) sector and the NT recreational sector (Rec.). Additional catches by illegal, unregulated and unreported (IUU) fishers were added to the catch totals in some instances.

Australian Standard Fish Name	Stock or area	International fisheries	Domestic fisheries			IUU catch
			Com.	FTO	Rec.	
Spanish Mackerel	All NT	Y <sup>1</sup>	Y <sup>2</sup>	Y	Y	600 t
Grey Mackerel	Western NT	Y <sup>1</sup>	Y <sup>3</sup>	N	N	600 t
	GoC	N	Y <sup>3,4</sup>	N	N	N
Common Blacktip Shark	WA/western NT	Y <sup>1</sup>	Y <sup>3,5</sup>	N	N	600 t
Australian Blacktip Shark	WA/western NT	Y <sup>1</sup>	Y <sup>3,5</sup>	N	N	600 t
Spot-tail Shark	WA/western NT	Y <sup>1</sup>	Y <sup>3,5</sup>	N	N	200 t
Black Jewfish	All NT	N	Y <sup>6</sup>	Y	Y	N
Golden Snapper	All NT	N	Y	Y	Y	N
Goldband Snapper	Timor Reef	N	Y <sup>7</sup>	N	N	N
Giant Mud Crab	All NT	N	Y <sup>8</sup>	N	N	N

<sup>1</sup> Taiwanese Drift Net Fishery

<sup>2</sup> NT Spanish Mackerel Fishery

<sup>3</sup> NT Offshore Net and Line Fishery

<sup>4</sup> QLD Inshore Finfish Fishery

<sup>5</sup> WA Northern Shark Fishery

<sup>6</sup> NT Coastal Line Fishery

<sup>7</sup> Timor Reef Fishery

<sup>8</sup> NT Mud Crab Fishery

The catch reconstructions for Spanish Mackerel, Black Jewfish and Golden Snapper incorporated recreational harvest estimates sourced from the three NT recreational surveys (Coleman 1998; Coleman 2004; West et al. 2012). Recreational harvests between these years were extrapolated from scaled FTO harvest data. This procedure was also applied backwards to the start of FTO catch and effort reporting in 1994. For the period 1970 to 1993, where there were no estimates of the recreational catch of these species, and no appropriate data on which to base an estimate, we applied a decay function using the 1994 catch value as the starting point and the year 1970 as an end point (where the catch approached zero). These simulations are particularly obvious in the Black Jewfish and Golden Snapper catch reconstructions.

There were several elements to the harvest reconstruction for Giant Mud Crab which ultimately lead to the derivation of estimates of monthly (and annual) harvest by number for each sex. The first step was to fit linear models to the seasonal patterns in (sex-specific) mean carapace width (denoted as  $CW_{sex,year,month}$ ) and sex ratio (as the proportion of females harvested each month;  $Pfem_t$ ) evident from data collected during the mud crab market monitoring program (sampling period May 1990 to October 2010). The aim here being to provide smoothed estimates of seasonal variation in these metrics and allow the calculation of mean sizes and the proportion of females harvested for months when there was no sampling.

Monthly sex-specific wet weight (WW) by year ( $WW_{sex,year,month}$ ) was derived from the (predicted) mean monthly CW ( $CW_{sex,year,month}$ ) using the width-weight relationships (in kg) below (from Grubert and Lee in press):

$$WW_{female} = \frac{0.0002CW_{female}^{2.979}}{1000} \text{ and } WW_{male} = \frac{0.000008CW_{male}^{3.655}}{1000} \quad \text{Equation 2}$$

Note that the CW and WW data used to construct these curves were based on live, unparasitised *Scylla serrata* only (i.e. no *Scylla olivacea*) with intact marginal spines. The equations describing these curves indicate that males grow rapidly heavier as they become wider, as evidenced by the high width-weight power (~3.6), whereas females maintain a near standard allometric pattern (power near 3.0).

Overall mean monthly wet weight ( $\overline{WW}_t$ ) was calculated using the monthly WW for each sex in combination with the (predicted) proportion of females in the catch that month ( $Pfem_t$ ), according to the equation:

$$\overline{WW}_t = Pfem_t \cdot WW_{female,year,month} + (1 - Pfem_t) \cdot WW_{male,year,month} \quad \text{Equation 3}$$

Next, the monthly harvest by number ( $Harvest\#_t$ ) was obtained from the monthly yield ( $Yield_t$ ; by weight from monthly logbook returns) divided by overall mean monthly WW ( $\overline{WW}_t$ )

$$Harvest\#_t = \frac{Yield_t}{\overline{WW}_t} \quad \text{Equation 4}$$

Finally,  $Harvest\#_t$  was apportioned to females and males to give  $Harvest\#_{female,t}$  and  $Harvest\#_{male,t}$  using  $Pfem_t$  and  $(1 - Pfem_t)$ . That is:

$$Harvest\#_{female,t} = Harvest\#_t \cdot Pfem_t \quad \text{Equation 5}$$

and

$$Harvest\#_{male,t} = Harvest\#_t \cdot (1 - Pfem_t) \quad \text{Equation 6}$$

### **Determination of spatially averaged catch per unit effort (Fishes)**

Catch per unit effort has traditionally been used to estimate the relative abundance of fish and provide an insight into stock health. However, the behaviour of both fish and fishers influences the validity of this measure as a proxy for these indicators. Conventional CPUE data derived from aggregating fishes, such as Black Jewfish, can give the misleading impression that the stock is healthy because catch rates can remain high until there is sudden and dramatic decline in both CPUE and fish size (see Phelan 2008). Likewise, aggregated CPUE data from fishers that move from one area to the next once their catch rates begin to fall gives the same misleading picture. Both scenarios are examples of what is known as CPUE “hyperstability”.

One means of overcoming the hyperstability problem is to derive an average CPUE value for all reporting areas of the fishery, producing a “spatially averaged” CPUE. Here, we refer to a 1 x 1 degree (60 x 60 nm) fishing grid as used by the NT Fisheries logbook reporting system. This CPUE standardisation method assumes that each one degree fishing grid supported large numbers of the target species prior to fishing and that initial catch rates were high; however, catch rates declined as the stock was fished down.

CPUE data for all fish species/stocks examined here were spatially averaged for prior to SRA. The CPUE time series generally ran from 1983 (i.e. the start of routine catch and effort reporting by NT commercial fisheries) to 2011. However, in the case of Golden Snapper we used CPUE data from the FTO sector which is only available from 1994. Similarly, estimates of the CPUE for Black Jewfish by the commercial CLF prior to 1994 were not considered reliable and were not used.

The standardisation procedure involved plotting the annual CPUE for each grid over time in a spreadsheet and filling in empty cells for those years where no catch was recorded. Empty cells for those years prior to fishing in a particular grid were backfilled with the highest CPUE recorded when fishing began. By contrast, empty cells for those grids where fishing had occurred, but was no longer taking place, were forward-filled with the last recorded CPUE value. Catch rates for all grids in each year were then averaged to generate a spatially averaged CPUE time series (Walters 2003). With the exception of Black Jewfish and Golden Snapper (where CPUE data were expressed in kg/hook hr and kg/line hour, respectively) the CPUE of all fishes was expressed as kg/boat day.

### **Stock Reduction Analysis (Fishes)**

Two forms of SRA were used during the modeling exercises on fishes; deterministic SRA models were constructed and manipulated in MS Excel spreadsheets, while stochastic SRA models were run using an executable VBA file (Lombardi and Walters 2011). Both approaches required information on historical catches, CPUE and population parameters (as per Table 4 for the latter).

Age estimates of Goldband Snapper sampled during 1990-95 and 1999-2001 were used to generate catch curves and construct age schedules for the SRAs on this species. Examination of these data (prior to running the deterministic SRA) revealed some apparent contradictions between the age structure and catch history.

The catch curve analyses indicated that the total mortality rate ( $Z$ ) for both data sets was almost identical (at 0.55), yet growth data indicated that natural mortality ( $M$ ) was around 0.15. With a consequently high fishing mortality ( $F$ ) rate of 0.40 (given  $Z = M + F$ ), the population should not have supported the stable CPUE seen over the years. Two possible explanations for the apparent lack of old fish were proposed:

1. That fish become much less vulnerable to the fishing gear as they get older, because of changes in schooling behaviour or emigration from the TRF. The assumption in this scenario was that the old fish would still be contributing recruits to the population.
2. That  $F$  is high because the older fish have been harvested elsewhere (potentially in Indonesian waters) at a very high rate for a long time. This scenario assumed that old fish are absent and unable to produce recruits.

Given the above, the deterministic SRA on Goldband Snapper was run using two different scenarios (Table 4); the first assuming low  $M$  with dome-shaped vulnerability (i.e. older fish are less vulnerable to fishing), and the second assuming a high  $M$  with flat vulnerability (i.e. all recruits are equally vulnerable to fishing). These analyses indicated that the best fitting model was a combination of the two scenarios, where older fish became less vulnerable to the fishing gear,  $M$  was low (0.16) and  $F$  was moderately high (0.2); conditions that were then applied to the stochastic SRA on Goldband Snapper.

**Table 4.** Values of leading parameters for deterministic Stock Reduction Analyses (SRA) of Spanish Mackerel (*Scomberomorus commerson*, **S.c.**), Grey Mackerel (*S. semifasciatus*, **S.s.**), Common Blacktip Shark (*Carcharhinus limbatus*, **C.l.**), Australian Blacktip Shark, (*C. tilstoni*, **C.t.**), Spot-tail Shark (*C. sorrah*, **C.s.**), Black Jewfish (*Protonibea diacanthus*, **P.d.**), Golden Snapper (*Lutjanus johnii*, **L.j.**) and Goldband Snapper (*Pristipomoides multidens*) under two different scenarios (**P.m.(1)** and **P.m.(2)**).

Parameter	Values								
	<b>S.c.</b>	<b>S.s.*</b>	<b>C.l.</b>	<b>C.t.</b>	<b>C.s.</b>	<b>P.d.</b>	<b>L.j.</b>	<b>P.m.(1)</b>	<b>P.m.(2)</b>
$R_0$	2.55	6.00	0.82	1.8	0.90	0.20	0.20	150	1600
Surv	0.700	0.670	0.730	0.730	0.730	0.726	0.755	0.852	0.670
recK	3.00	3.00	3.00	3.00	2.66	5.48	5	10.00	10.00
vbK	0.21	0.35	0.21	0.14	0.34	0.32	0.27	0.14	0.14
$L_\infty$	141.0	86.0	193.6	199.2	123.0	136.6	67.0	73.6	73.6
alw	0.010	0.010	0.010	0.010	0.010	0.013	0.025	0.010	0.010
$t_0$	0.00	0.00	-1.20	-1.80	-1.90	0.18	0.00	0.00	0.00
$W_{mat}$	3504	795	40200	18300	12064	4078	1624	498	498

$R_0$  = Unfished natural recruitment rate

Surv = Survival rate

recK = Recruitment compensation ratio

vbK = von Bertalanffy  $K$  growth coefficient

\*  $R_0$  value for GoC Grey Mackerel stock was 2.90

$L_\infty$  = Maximum theoretical body length (cm)

alw = Length weight relationship

$t_0$  = Hypothetical age at fish length 0

$W_{mat}$  = Weight at maturity (g)

The catch and effort data for the Common Blacktip Shark and the Australian Blacktip Shark were the same as these species cannot be differentiated by fishers. Separate stochastic SRAs were initially run on both species. However, the use of species-specific parameter values had almost no impact on the stochastic model outputs and so the inputs for the Australian Blacktip Shark were used thereafter (as they were from Australian studies and were considered more accurate).

### Simple equilibrium model (Giant Mud Crab)

In the case of the Giant Mud Crab,  $\bar{l}$  in the Beverton-Holt relationship (Equation 1) corresponds to the MLS by sex, corrected upward by about 0.7 cm for the male MLS of 13 cm, and 0.4 cm for the female MLS of 14 cm, to account for reduced vulnerability of smaller crabs. These correction factors represent the knife-edge selection lengths of 13.7 and 14.4 that give the same as crabs taken with continuously variable size-vulnerability following the width-vulnerability relationship:

$$V(CW) = \left( e^{\frac{-1.7(CW-13.9)}{1.6}} \right)^{-1} \quad \text{Equation 7}$$

Parameters for this logistic vulnerability relationship have been estimated by comparing catch rates from crab pots with and without escape gaps (Grubert and Lee in press), and interestingly do not appear to differ substantially between males and females.

The Beverton-Holt (1956) size-mortality rate equilibrium equation can now be used in several ways with annual average CW and MLSSs, along with growth parameters, for example:

- a) It can be solved for  $Z$  over time given  $K$ ,  $L_{\infty}$  and time-varying MLSSs ( $l_t$ ), and  $Z$  can be plotted against effort ( $E$ ) where we expect  $Z = M + qE$ ; we can then get  $M$  from the regression intercept and  $q$  from the slope. This is the “standard” use advocated by Beverton and Holt.
- b) Given an assumed constant  $M$  and assumed constant growth parameters  $L_{\infty}$  and  $K$ , it can be used to calculate apparent changes in catchability  $q$ , using  $q = (Z - M) \div E$ .
- c) Given an assumed  $q$  based on average  $F$  and  $E$ , along with stable growth parameters, it can be used to calculate apparent changes in  $M$ , given  $Z - M = F = qE$ .
- d) Given an assumed  $q$  and  $M$ , implying an assumed time series of total mortality rates  $Z$ , and an assumed  $K$ , the equation can be solved for  $L_{\infty}$  for each year, as  $L_{\infty} = Z \div K(\bar{l} - l_t) + \bar{l}$ . This use of the method provides a way to detect possible changes in growth due to changes in food availability, competition when recruitments have been strong, or genetic selection against faster growing, larger crabs.

Here, we examined four scenarios using annual mean  $\bar{l}$  and size limits by sex, assuming  $K = 0.8$  and  $L_{\infty} = 20$  cm (from Haddon et al. 2005; except for case **d**),  $M = 1.0$  (from Knuckey 1999; except for case **c**), and  $q = 1.58$  (except for cases **a** and **b**, where  $q$  is estimated) to examine changes in mortality, catchability and  $L_{\infty}$  of Giant Mud Crabs over time.

### Size-age-sex monthly stock synthesis model (Giant Mud Crab)

The derivation of the various elements of the stock synthesis model is complex and is not presented here. However, a summary of the mechanics of the MS Excel spreadsheet model is available from the lead author or Professor Carl Walters. Likewise, spreadsheets containing the model (and model outputs) are available in a zip file at the following Dropbox public link (noting that the monthly catch data accessible through this link have been aggregated by licence and fishing grid and are not considered commercially sensitive):

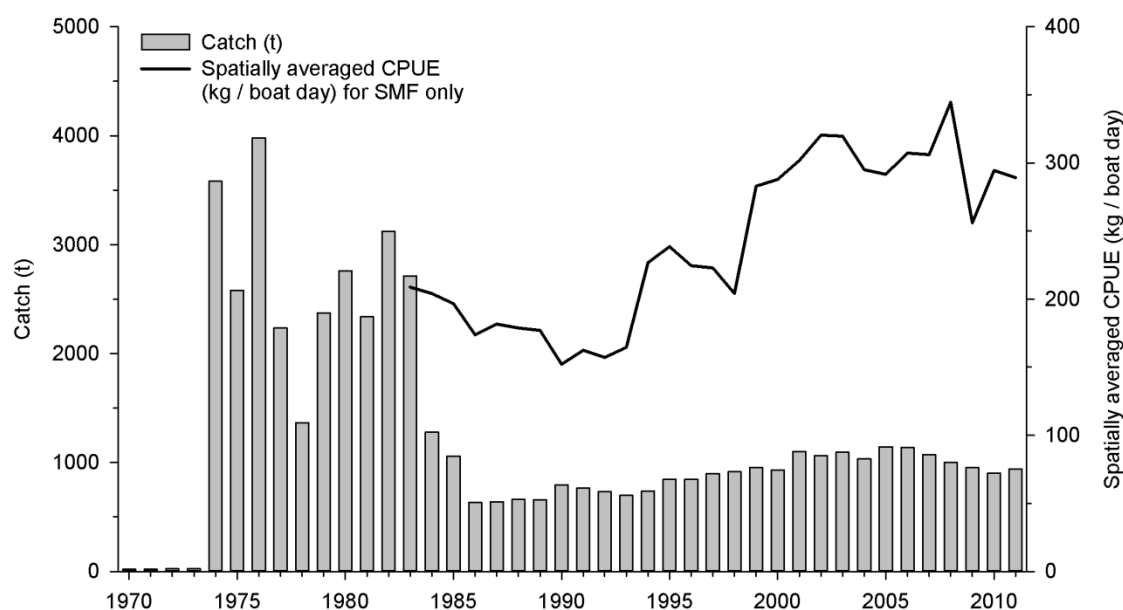
<http://dl.dropbox.com/u/51142274/length%20sex%20dynamics%20model.zip>

## RESULTS

### Spanish Mackerel

#### *Catch reconstruction and spatially averaged CPUE*

Spanish Mackerel in NT waters were heavily exploited by Taiwanese drift-netters from around 1974 (Figure 2). These operators were excluded from this area in the mid 1980s and the annual catch since that time (including IUU fishing) has varied between 600 t and 1100 t. The spatially averaged CPUE of Spanish Mackerel by the SMF has increased about 50% over the past 25 years.



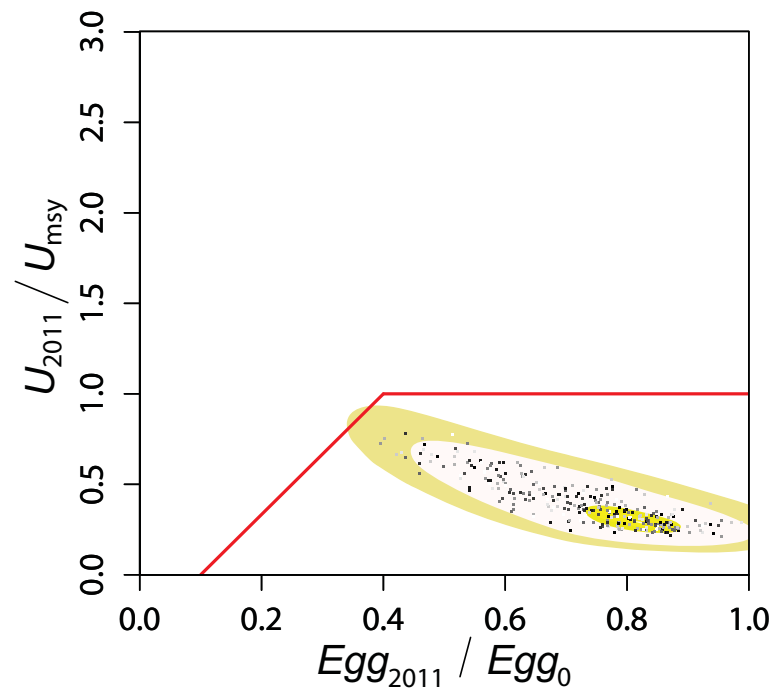
**Figure 2.** Total catch (t) of Spanish Mackerel (*Scomberomorus commerson*) by all fisheries operating in NT waters and the spatially averaged CPUE (kg / boat day) of this species by the Spanish Mackerel Fishery only

#### *Outputs from deterministic and stochastic SRA models*

Deterministic SRA produces a single estimate for the status measures used to describe stock health and fishing intensity employed here (see above). In the case of the Spanish Mackerel stock, the deterministic model indicated that current biomass is 79% of that prior to any fishing activity (i.e. before fishing commenced) and that the current harvest rate is 21% of that required to achieve maximum sustainable yield (MSY).

The outputs of the stochastic SRA (which produces a probability distribution of the two status measures and expresses relative egg production rather than relative biomass) on Spanish Mackerel agreed with those of the deterministic model. The stochastic SRA model suggest that the stock has recovered to the extent that egg production is around 85% of that prior to any fishing activity and the current harvest rate is approximately 20% of that required to achieve MSY (Figure 3 and Plate i, Appendix B). This recovery is attributed to the rapid growth and relatively high fecundity of Spanish Mackerel in association with tight controls on the fishery.



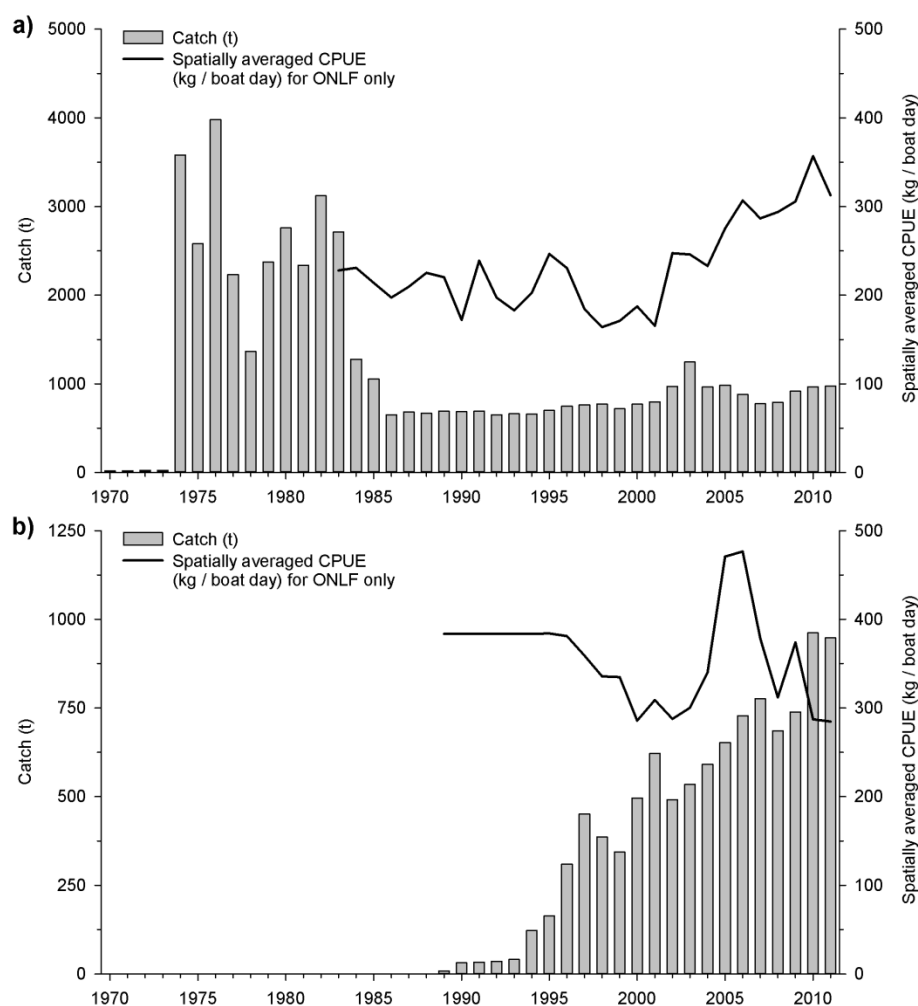


**Figure 3.** Output from the stochastic SRA for Spanish Mackerel (*Scomberomorus commerson*). The position of the probability distribution indicates a high degree of certainty (i.e. 99% probability) that the Spanish Mackerel stock is not overfished and that the current harvest rate is below that necessary to achieve the maximum sustainable yield (i.e. overfishing is not occurring).

## Grey Mackerel

### *Catch reconstruction and spatially averaged CPUE*

The catch histories of the two stocks of Grey Mackerel straddling the NT are quite different. The western stock was subject to heavy fishing pressure by Taiwanese drift-netters from 1974 to 1985 (Figure 3a). Since the exclusion of these operators the catch has gradually increased from around 700 t to 900 t. The spatially averaged CPUE of the western Grey Mackerel stock by the ONLF has shown a modest increase over the last decade. Specific targeting of the GoC Grey Mackerel stock only began in the early 1990s (Figure 3b). The catch since that time has increased, while the spatially averaged CPUE has fluctuated widely.

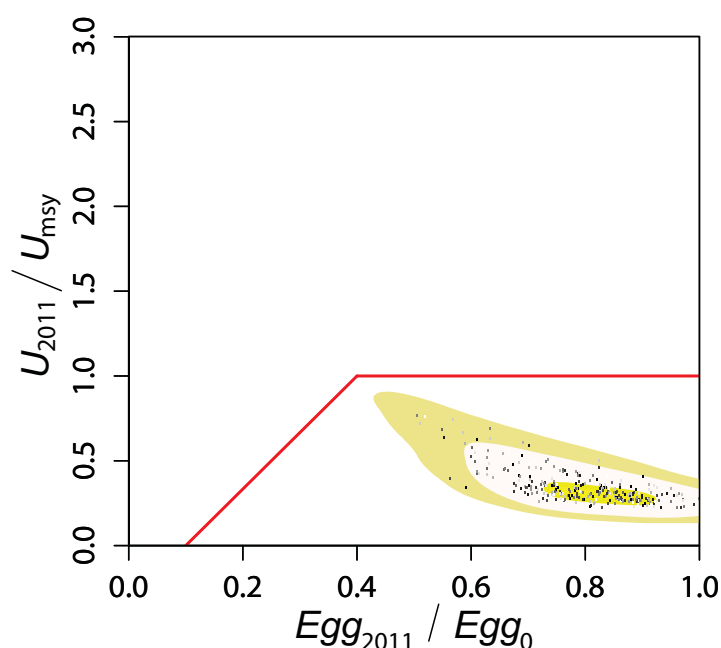


**Figure 4.** Total catch (t) of **a)** western NT and **b)** GoC Grey Mackerel stocks by all fisheries operating in northern Australia and the spatially averaged CPUE (kg / boat day) of these stocks by the Offshore Net and Line Fishery only. Note difference in left y-axis scales between **a)** and **b)**.

### Outputs from deterministic and stochastic SRA models

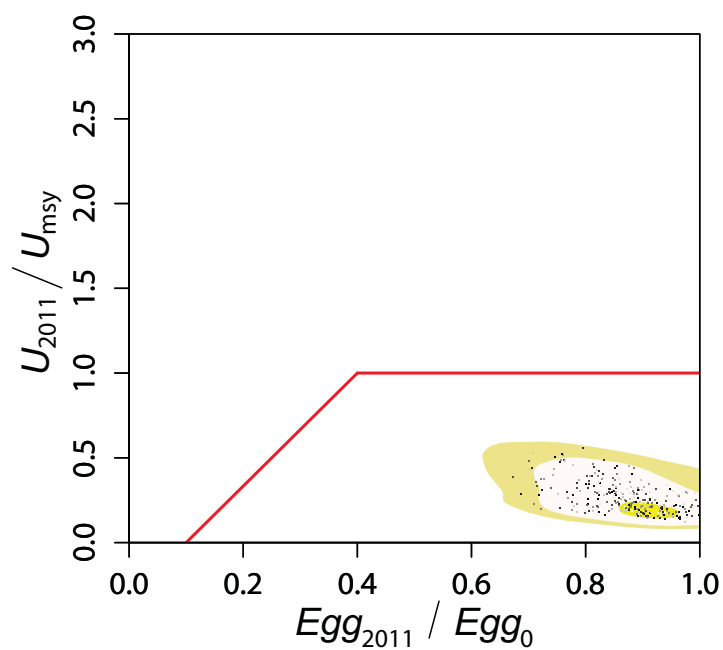
The deterministic SRA on the western NT Grey Mackerel stock advised that it has recovered from the high historical catches in the 1970s and 1980s and that the current harvest rate is 12% of that required to achieve MSY. The biomass of the stock is also at 81% of the unfished level. The outputs from the deterministic SRA on the GoC Grey Mackerel stock indicated that it is being fished well within sustainable limits, with biomass at 74% of the unfished level and the harvest rate at 26% of that required to achieve MSY.

The outputs from the Stochastic SRAs on the two Grey Mackerel stocks were similar to those obtained from the deterministic models. Current egg production by the western NT stock was estimated at about 80% of that by the unfished stock and the current harvest rate at approximately 20% of that required to achieve MSY (Figure 5 and Plate ii, Appendix B).



**Figure 5.** Output from the stochastic SRA for the western NT Grey Mackerel (*S. semifasciatus*) stock. The position of the probability distribution indicates that the western NT Grey Mackerel stock is not overfished and that the current harvest rate is below that necessary to achieve the maximum sustainable yield (i.e. overfishing is not occurring).

The Stochastic SRA of the GoC Grey Mackerel stock suggested that despite the increasing catches, the current harvest rate is less than 10% of that required to achieve MSY and that current egg production is over 90% of that by the unfished stock (Figure 6 and Plate iii, Appendix B). This being the case, neither stock is considered overfished and the current harvest rate of both is considered sustainable.

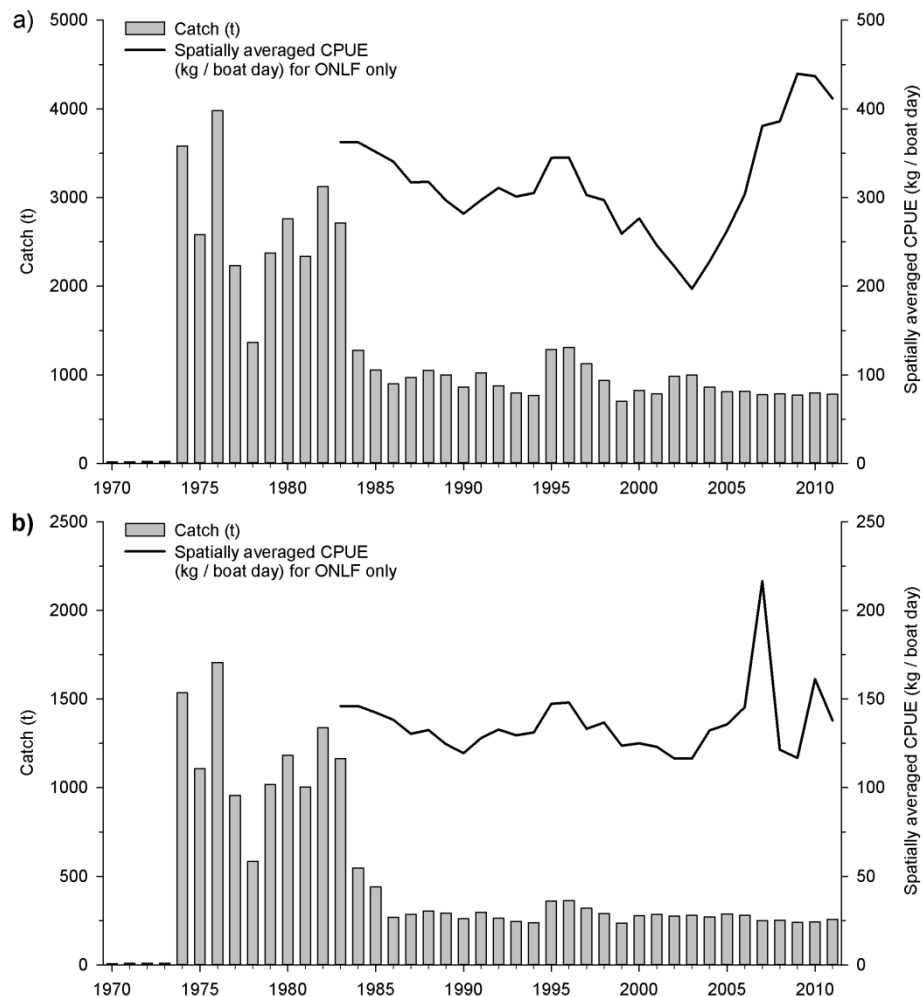


**Figure 6.** Output from the stochastic SRA for the GoC Grey Mackerel (*S. semifasciatus*) stock. The position of the probability distribution indicates that the GoC Grey Mackerel stock is not overfished and that the current harvest rate is below that necessary to achieve the maximum sustainable yield (i.e. overfishing is not occurring).

## Common Blacktip Shark, Australian Blacktip Shark and Spot-tail Shark

### Catch reconstruction and spatially averaged CPUE

Similar to both mackerel species, the Common Blacktip Shark, Australian Blacktip Shark and Spot-tailed Shark were taken in large quantities in the 1970s and 1980s (Figures 7a and 7b). Catches since the mid-1980s have stabilised. The spatially averaged CPUE of Common Blacktip Shark and Australian Blacktip Shark gradually declined from 1984 to 2003, but has shown a noticeable increase thereafter. The spatially averaged CPUE of the Spot-tail Shark has been more stable over time, with the exception of an abrupt peak in 2007.



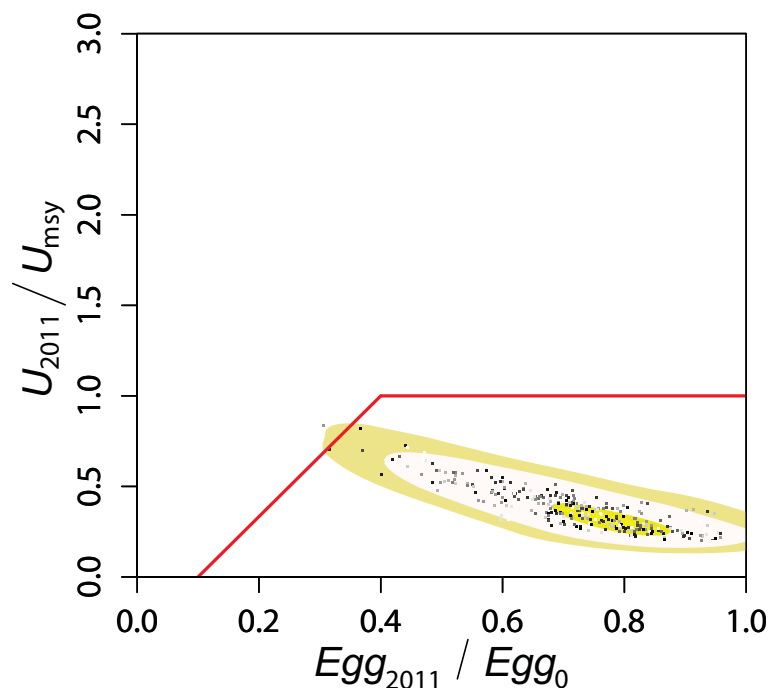
**Figure 7.** Total catch (t) of “western” stocks of **a)** Common Blacktip Shark (*Carcharhinus limbatus*) and Australian Blacktip Shark (*C. tilstoni*) (combined) and **b)** the Spot-tail Shark (*C. sorrah*) by all fisheries operating in northern Australia and the spatially averaged CPUE (kg / boat day) of these stocks by the Offshore Net and Line Fishery only. Note difference in both y-axis scales between **a)** and **b)**.

### Outputs from deterministic and stochastic SRA models

The deterministic SRAs on the Common Blacktip Shark and Australian Blacktip Shark indicated that they have recovered from the high historical catches in the 1970s and 1980s. The current harvest rates of these species were estimated at 19% and 12% of that required to achieve MSY, respectively. The current biomass estimates for each species are now at 81% and 90% of the unfished biomass, respectively.

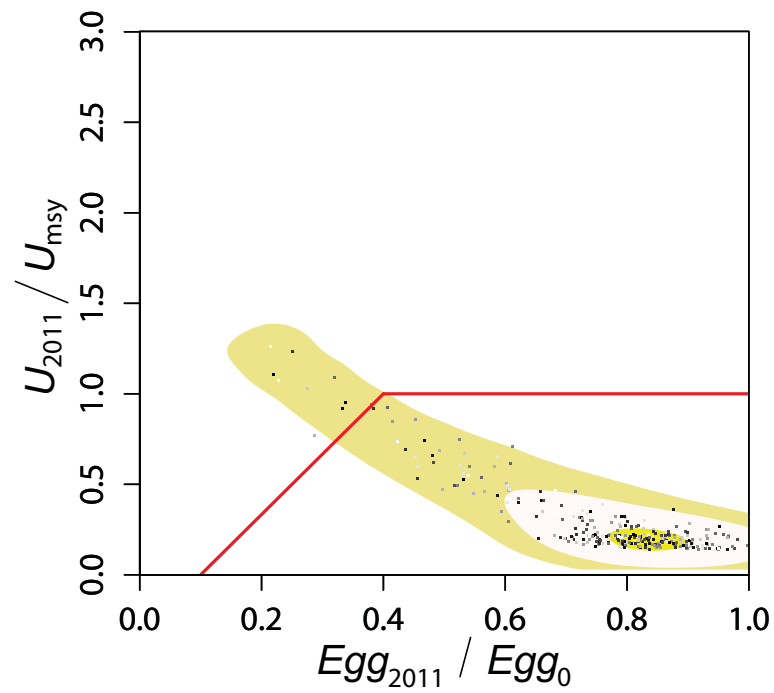
The outputs from the deterministic SRA on the Spot-tail Shark suggested that it is being fished within sustainable limits, with biomass now at 93% of the unfished biomass and the current harvest rate at 13% of that required to achieve MSY.

The results of the Stochastic SRA on the Common Blacktip Shark and Australian Blacktip Shark were similar to those obtained from the deterministic model. That is, there is a high degree of certainty (i.e. 99% probability) that neither stock is overfished and that the current harvest rate is below that necessary to achieve MSY (Figure 8 and Plate iv, Appendix B).



**Figure 8.** Output from the stochastic SRA for both the Common Blacktip Shark (*Carcharhinus limbatus*) and Australian Blacktip Shark (*C. tilstoni*). The position of the probability distribution indicates that there is a high degree of certainty (i.e. 99% probability) that neither stock is overfished and that the current harvest rate is below that necessary to achieve the maximum sustainable yield (i.e. overfishing is not occurring).

The Stochastic SRA on the Spot-tail Shark indicated a high degree of certainty (i.e. 95% probability) that the stock is not overfished and also that the current harvest rate is below that necessary to achieve MSY (i.e. a 96% chance that overfishing is not occurring; Figure 9 and Plate v, Appendix B).

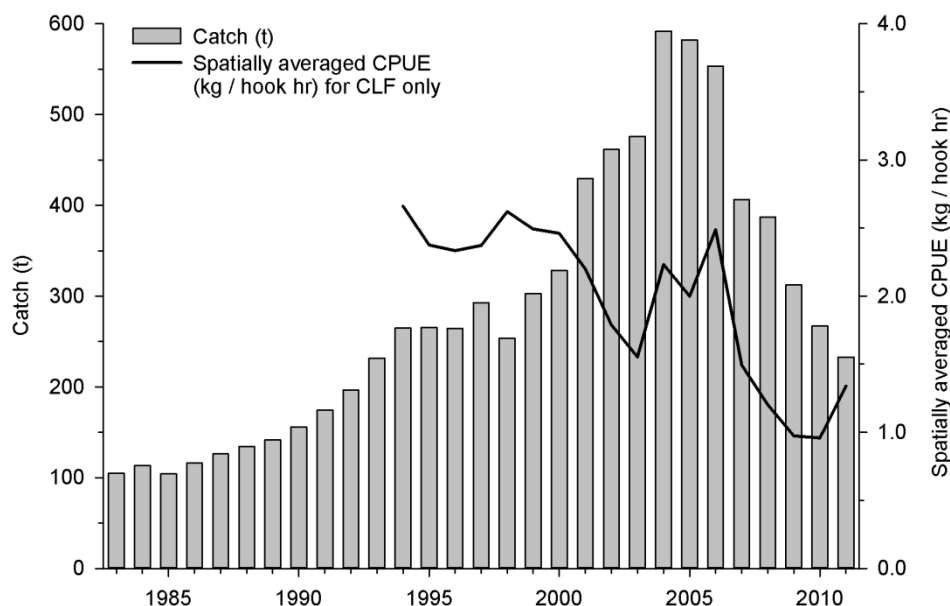


**Figure 9.** Output from the stochastic SRA for the Spot-tail Shark (*Carcharhinus sorrah*). The position of the probability distribution indicates that there is a high degree of certainty (i.e. 95% probability) that the Spot-tail Shark stock is not overfished and also that the current harvest rate is below that necessary to achieve the maximum sustainable yield (i.e. a 96% chance that overfishing is not occurring).

## Black Jewfish

### *Catch reconstruction and spatially averaged CPUE*

The total annual catch of Black Jewfish peaked at almost 600 t in 2004 and 2005 but has since declined to just over 200 t (Figure 10). While the spatially averaged CPUE of Black Jewfish by the commercial CLF has fluctuated over time, the long-term trend has been a decline.



**Figure 10.** Total catch (t) of Black Jewfish (*Protonibea diacanthus*) by all fisheries operating in the NT and spatially averaged CPUE (kg / hook hr) of this species by the Coastal Line Fishery (CLF) only. The incremental increases in annual catches to 1994 are the result of applying a decay function backwards in time using the 1994 catch as a starting point. This was done to simulate the increase in the recreational harvest of Black Jewfish when there was no other way to derive an estimate.

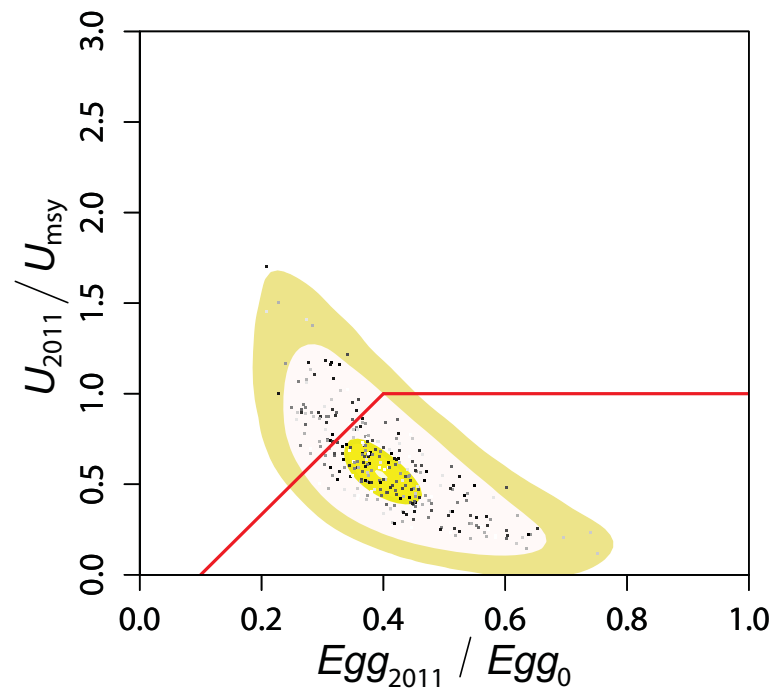
### *Outputs from deterministic and stochastic SRA models*

The deterministic SRA on Black Jewfish indicated that the biomass of the stock is 62% of that prior to any fishing activity. It also suggested that the current harvest rate is around 33% of that required to achieve MSY.

The outputs from the stochastic SRA on this species (Figure 11 and Plate vi, Appendix B) advise of a high probability (i.e. 71%) that the stock is overfished and a moderate (21%) chance that the current harvest rate exceeds that required to achieve MSY (i.e. a 21% chance of overfishing occurring).

We acknowledge that there are some areas along the NT coast where Black Jewfish aggregations are lightly fished or unfished, because their location is not yet known. We stress that the results presented here are indicative of the situation around heavily fished accessible reefs (i.e. within a 100 km radius of major coastal population centres), as opposed to lightly-fished or unfished areas.



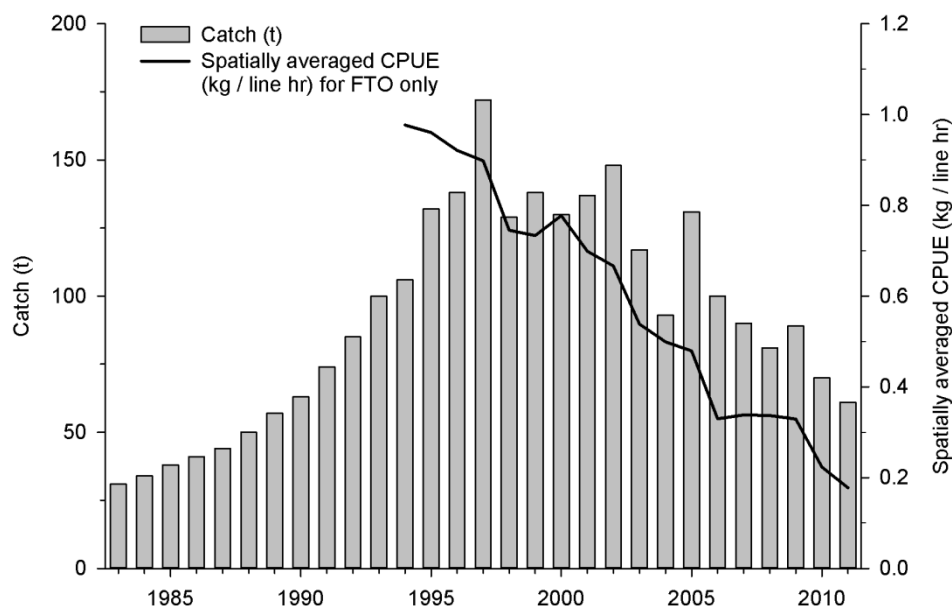


**Figure 11.** Output from the stochastic SRA for Black Jewfish (*Protonibea diacanthus*). The position of the probability distribution indicates reasonable certainty (i.e. 71% probability) that the Black Jewfish stock is overfished around accessible reefs and a moderate (21%) chance that the current harvest rate in these areas exceeds that necessary to achieve recovery (i.e. a 21% chance that overfishing continues to occur and is exacerbating the problem).

## Golden Snapper

### *Catch reconstruction and spatially averaged CPUE*

The catch of Golden Snapper peaked at just over 170 t in 1997 and has steadily declined thereafter (Figure 12). The spatially averaged CPUE of Golden Snapper by FTOs has also decreased since reporting by this sector began in 1994.



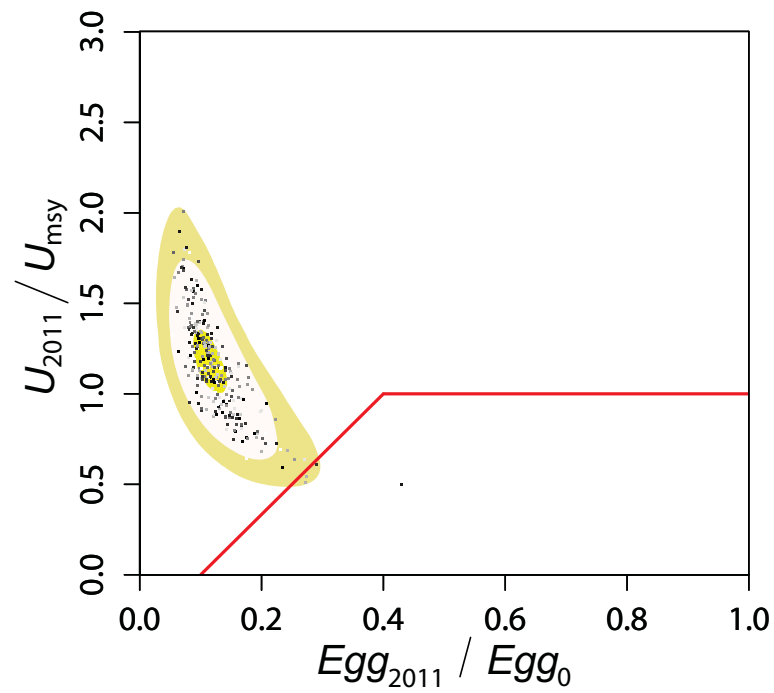
**Figure 12.** Total catch (t) of Golden Snapper (*Lutjanus johnii*) by all fisheries operating in the NT, and the spatially averaged CPUE (kg / line hour) of this species by the fishing tour operator (FTO) sector only. The incremental increases in annual catches to 1994 are the result of applying a decay function backwards in time using the 1994 catch as a starting point. This was done to simulate the increase in the recreational harvest of Golden Snapper when there was no other way to derive an estimate.

### *Outputs from deterministic and stochastic SRA models*

The deterministic SRA on Golden Snapper suggested that the biomass of the stock is now just 25% of that prior to any fishing activity. It also indicated that the current harvest rate is around 77% of that required to achieve MSY.

The outputs from the stochastic SRA on this species were more worrisome, and indicated that the current harvest rate of Golden Snapper is up to double that required to achieve MSY (Figure 13 and Plate vii, Appendix B) and that the stock is depleted such that egg production is only around 10% of that prior to any fishing activity (from the horizontal position of the “fried egg”). Hence, the NT Golden Snapper stock is both overfished and overfishing is occurring.

Strictly speaking, the “fried egg” probability plot show in Figure 13 is so far to the left that, according to the PPMC 40:10 rule, fishing for Golden Snapper should be stopped. That said there are large areas of the NT coast where Golden Snapper are fished at low levels. We stress that the results presented here are indicative of the situation around heavily fished accessible reefs (i.e. within a day trip of major coastal population centres), as opposed to lightly-fished or unfished areas.

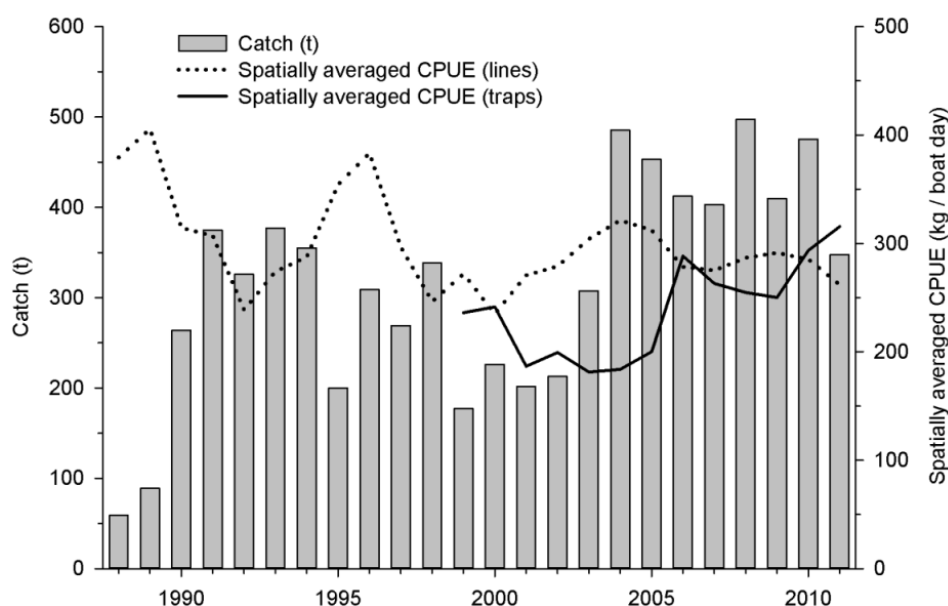


**Figure 13.** Output from the stochastic SRA for Golden Snapper (*Lutjanus johnii*). The position of the distribution indicates a high level of certainty (i.e. 100% probability) that the Golden Snapper stock is overfished around accessible reefs as well as a very high (99%) chance that the current harvest rate in these areas exceeds that necessary to achieve recovery (i.e. a 99% chance that overfishing continues to occur and is exacerbating the problem).

## Goldband Snapper

### Catch reconstruction and spatially averaged CPUE

The catch of Goldband Snapper by the TRF over the last two decades shows a stepped pattern; catches varied between ~200 t and ~380 t from 1990 to 2003, then increased to between ~350 t and ~500 t thereafter. The spatially averaged CPUE for the line component of this fishery has shown a gradual decline since 1989, whereas the CPUE for the trap component (from 1999) has increased.

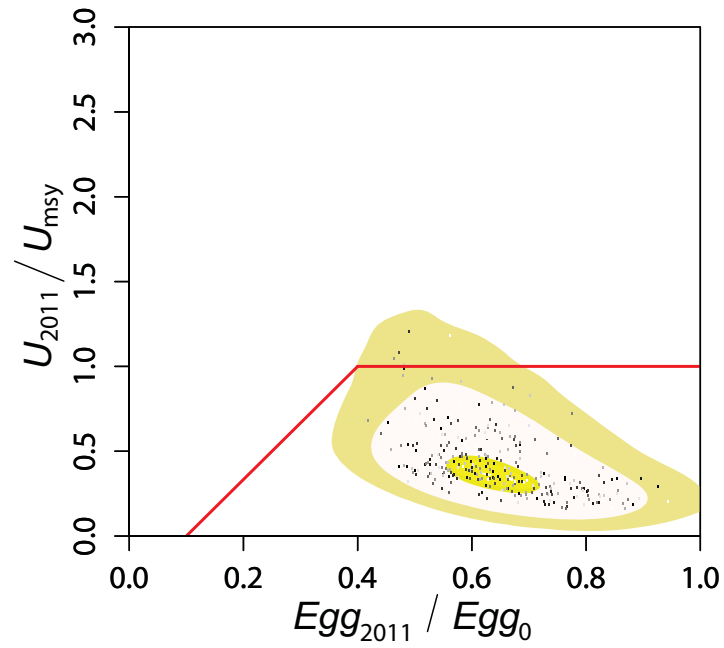


**Figure 14** Catch (t) and spatially averaged CPUE (kg / boat day) of Goldband Snapper (*Pristipomoides multidens*) for the line and trap components of the Timor Reef Fishery. Note that the trap CPUE is shown for comparative purposes only and was not used in either SRA.

### Outputs from deterministic and stochastic SRA models

As mentioned previously, the deterministic SRA for Goldband Snapper was run using two scenarios because of contradictions between total, natural and fishing mortality rates over time. Neither scenario produced outputs that were consistent with existing data, suggesting that the difference sources of mortality (as well as the pattern in vulnerability) must fall somewhere in between. A combination scenario (whereby old fish become less vulnerable to the fishing gear,  $M$  is low [0.16] and  $F$  is moderately high [0.2]) was then employed in the Stochastic SRA.

Using this combination of parameters and the available age data, the stochastic SRA indicated that the Goldband Snapper population in the Timor Sea is not overfished and that egg production is around 70% of that prior to any fishing activity (Figure 15 and Plate viii, Appendix B). The analysis also indicated that there is a high degree of certainty (98% probability) that the current harvest rate is below that required to achieve MSY.

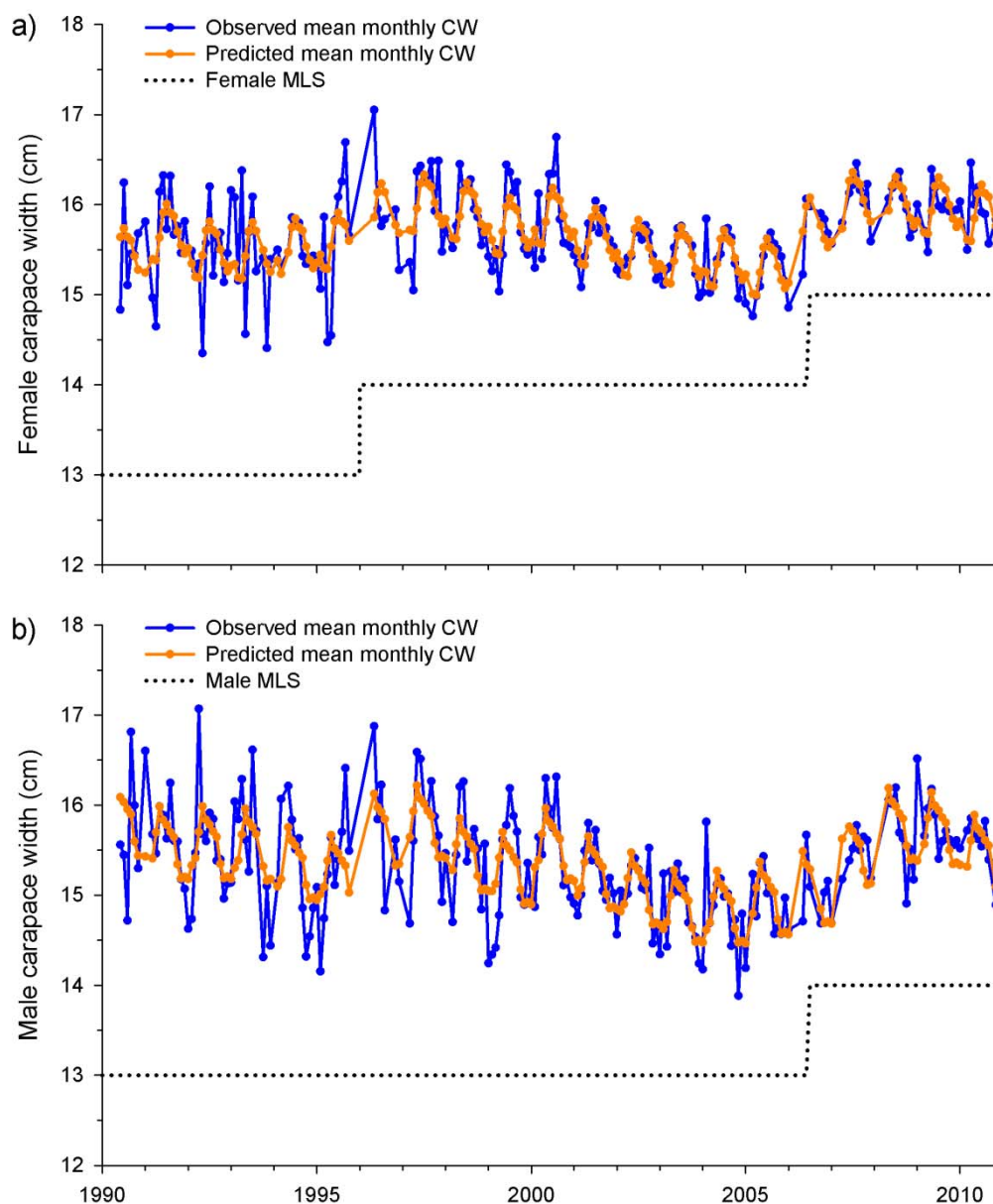


**Figure 15.** Output from the stochastic SRA for Goldband Snapper (*Pristipomoides multidens*). The position of the probability distribution indicates that the Goldband Snapper stock is not overfished and that there is a high degree of certainty (i.e. 98% probability) that the current harvest rate is below that necessary to achieve the maximum sustainable yield (i.e. a 98% chance that overfishing is not occurring).

## Giant Mud Crab

### Harvest reconstruction

The MLS for commercially harvested female Giant Mud Crabs in the NT has been increased twice since the inception of the fishery, once in January 1996 and again in May 2006 (Figure 16a). Over the ten years following the initial increase, the mean monthly CW of females gradually declined from year to year until the MLS was increased a second time. Since then, the seasonal pattern in female CW appears to have stabilised.



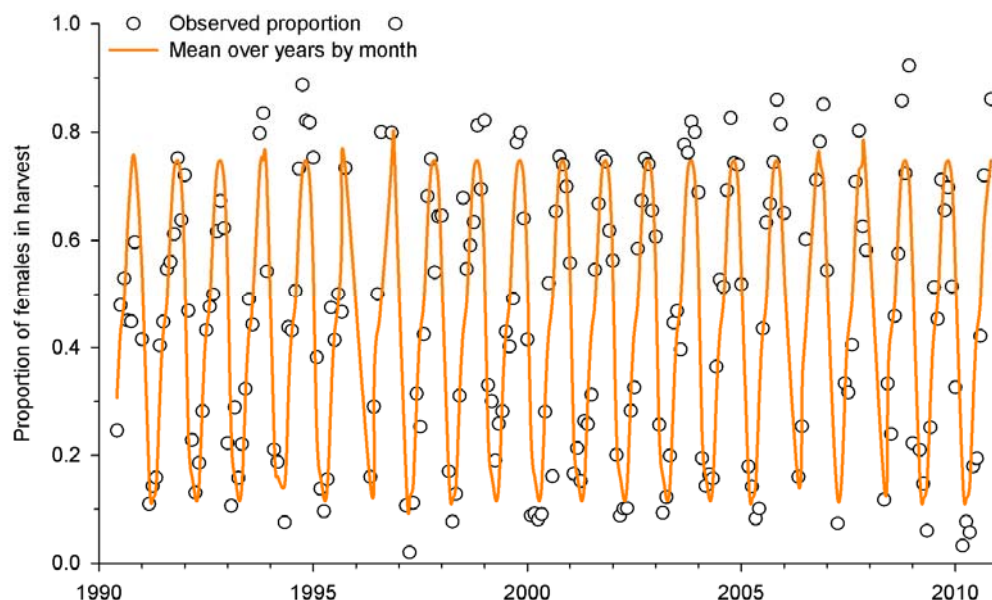
**Figure 16.** Observed (blue lines) and predicted (orange lines) mean monthly carapace width (CW) for (a) female and (b) male Giant Mud Crab (*Scylla serrata*) harvested by the NT Mud Crab Fishery from May 1990 to October 2010. Dotted lines represent the Minimum Legal Size (MLS) for each sex over time.

The MLS for commercially harvested male giant mud crabs has been increased once, in May 2006. Prior to this, mean monthly CW of males (Figure 16b) followed a similar trajectory to that of females, including an upward shift in mean CW in 1996, the year that the MLS for females was first increased. The seasonal pattern in mean monthly CW of males since the 2006 MLS increase has been more variable (between years) than that exhibited by females.

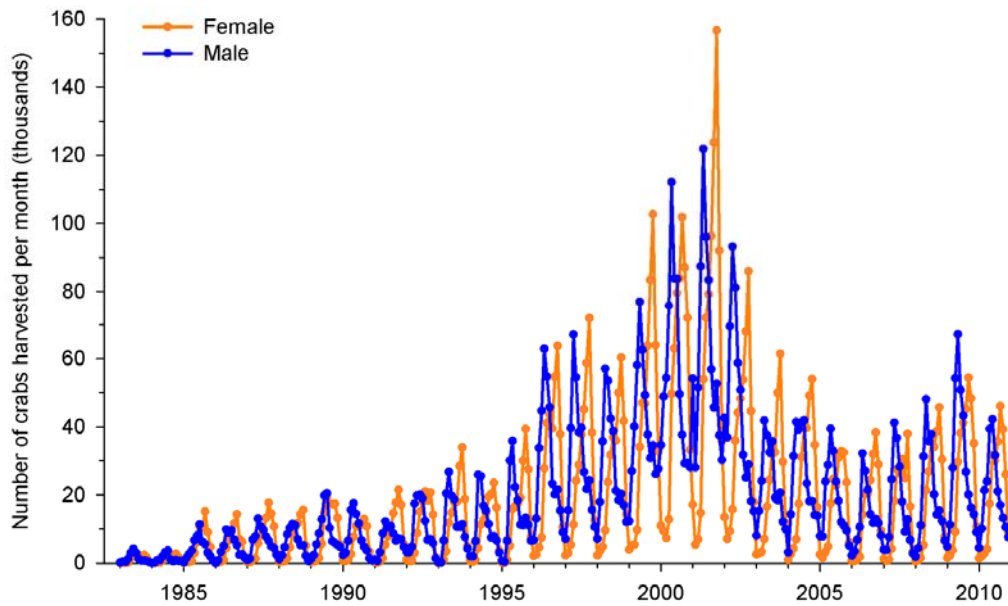
The linear (crab width) models (orange lines in Figure 16; see catch/harvest reconstruction section of the materials and methods) are certainly an adequate representation of changes in mean CW for more recent years, whereas sampled mean CW varied more than predicted by the models in some earlier years (1990-1998) for which monthly sample sizes were generally smaller. For four years in particular, (1993, 1994, 1999, and 2004), observed mean sizes of males dropped more near the end of the year (months September to December) than expected, approaching the MLS. Such low mean CWs might be interpreted as indicating that almost all legal males had been harvested just before those months. However, good numbers of larger males appear in the harvest in months immediately following these low periods, suggesting that larger males must have been present in the population but were just not vulnerable to capture for some reason.

The monthly monitoring data show a dramatic seasonal pattern in sex ratio that is remarkably consistent from year to year despite considerable changes in fishing effort (Northern Territory Government 2012), average CW, and MLSs (Figure 17). The average over years of sex ratio by month ( $Pfem_t$ ), is a very good predictor of observed sex ratio for most (monthly) sampling times (t) over the sampling period.

Using the overall mean monthly WW (derived from  $Pfem_t$ , the predicted mean monthly CW of both sexes and the sex-specific width-weight relationships) and corresponding monthly yield (by weight) we were then able to estimate total harvest by number for each month across the market monitoring time series. The model was also applied backwards in time to the initiation of the commercial fishery. The estimated number of male and female Giant Mud Crab harvested per month by the NT MCF is shown in Figure 18.



**Figure 17.** Observed proportion (open circles) and mean proportion (orange line) of female Giant Mud Crab (*Scylla serrata*) harvested by the NT Mud Crab Fishery from May 1990 to October 2010



**Figure 18.** Estimated number of female (orange line) and male (blue line) Giant Mud Crab (*Scylla serrata*) harvested per month by the NT Mud Crab Fishery from January 1983 to December 2010

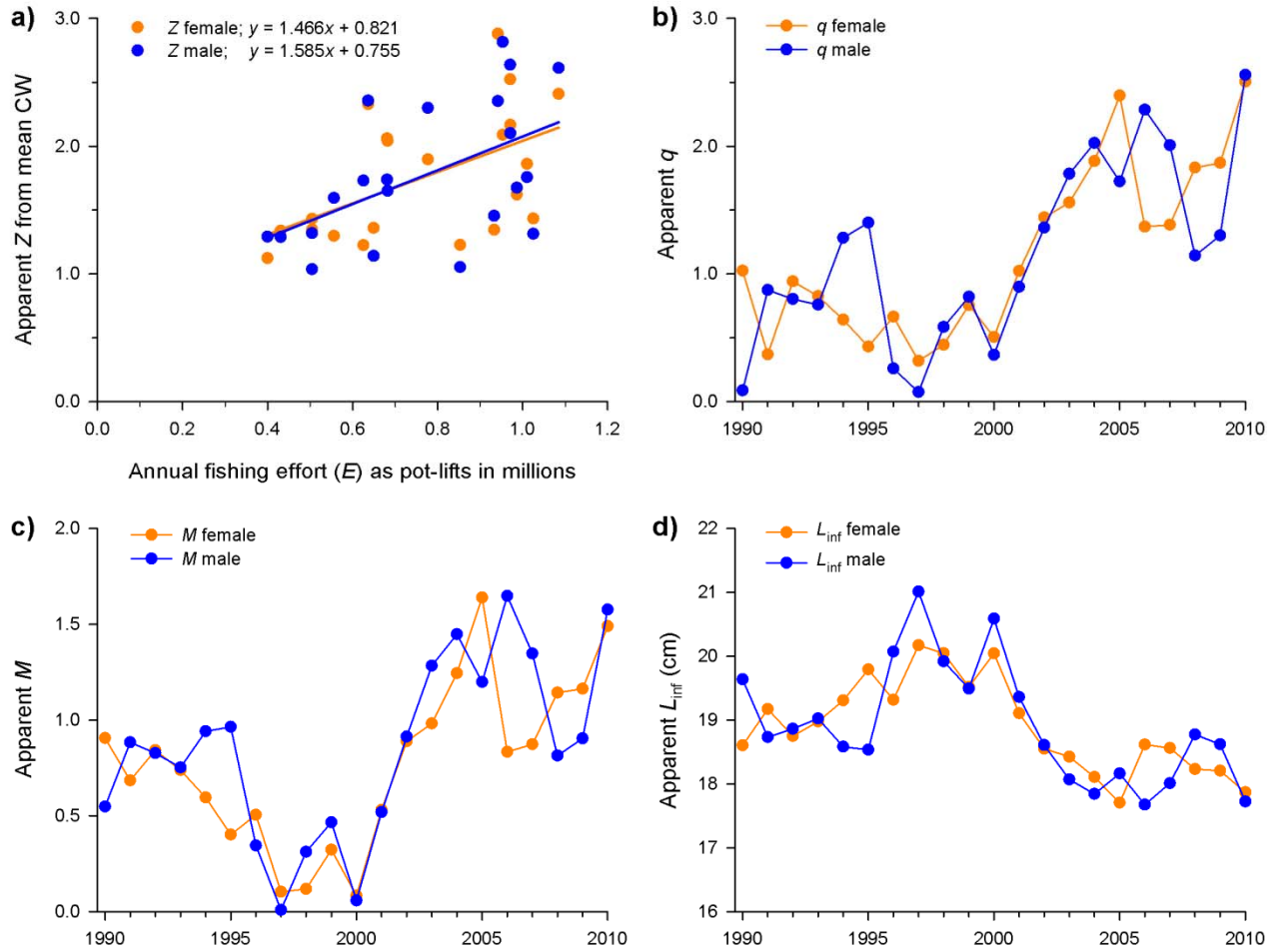
The harvest numbers in Figure 18 are likely overestimates (by as much as 20%) for the first few years of the fishery; for years before 1990 the average CW by sex in 1990 were used in the numbers calculation. There was likely some decline in mean WW from 1983 to 1989, as fishing effort and mortality increased. The main effect of this overestimation of harvest numbers on the assessment is likely to be modest overestimation of annual recruitments for the 1983 to 1989 period, not a major management issue since there is no clear evidence of decline in recruitment since the start of the fishery (the overestimation would make such a decline appear more severe).

#### *Simple equilibrium model*

The results of the different approaches to solving the simple-equilibrium model (**Equation 1**) are presented in Figure 19. The y-intercepts for the regressions of total mortality ( $Z$ ) versus Fishing Effort ( $E$ ) (Figure 19a) suggest that natural mortality ( $M$ ) is around 0.8 for both sexes. Estimates of catchability ( $q$ ) obtained from the slopes of these regression lines were in the order of 1.5 to 1.6. At the highest observed fishing efforts, the regressions indicate  $F$  for both sexes peaked at around 1.0-1.5, at  $Z$  averaging about 2.0.

The second approach to solving the model (which examines possible changes in catchability over time, Figure 19b) suggests that  $q$  has apparently doubled since 2000, which is quite possible, though not well in line with assessments of the change in areas fished. The latter would suggest an earlier catchability increase than indicated in Figure 19b. However, when annual  $Z$  values predicted from  $E$  (i.e. from regression lines in Figure 19a), and the model is then used to predict changes in mean CW ( $\bar{l}$ ) from year to year, the fit of the model to changes in mean annual CW by sex (Figure 20) is not impressive. The model under-predicts mean female size for years before 2001, and male sizes for the 1996-2001 period.

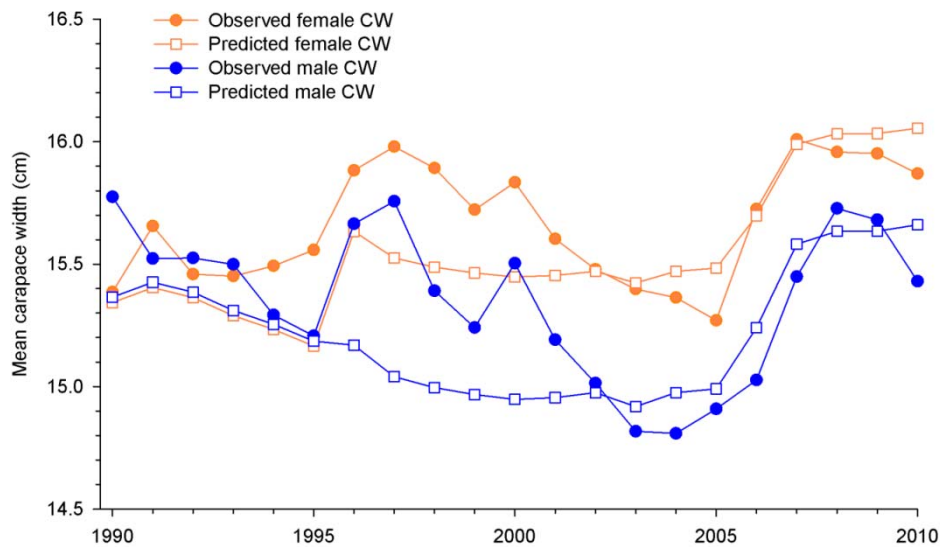




**Figure 19.** Results of different approaches to solving the Beverton-Holt (1956) size-mortality rate equilibrium relationship applied to mean carapace width (CW) of the Giant Mud Crab (*Scylla serrata*) and size limit average annual data from the NT Mud Crab Fishery. Apparent changes in: **a)** total mortality rate (Z) with annual fishing effort (E); **b)** catchability (q) over time if Z has been correctly predicted from CW changes (noting  $F = Z - M$  and  $q = F \div E$ ); **c)** natural mortality rate (M) over time if the values of F have been correctly predicted from E and **d)** maximum theoretical carapace width ( $L_{inf}$ ; cm) over time if Z has been correctly predicted from E.

The third approach to solving the equilibrium model (which examines changes in apparent natural mortality over time; Figure 19c) produced estimates of M much larger than seem reasonable, unless the higher abundances associated with high recruitments in the late 1990s (inferred from Figure 18) caused some change in competitive conditions. However, the highest values of apparent M are for more recent years, since recruitment has declined from the 1990s peak. It is possible that these changes in apparent M are an artefact of changes in q and/or  $L_{\infty}$ .

Finally, the fourth approach to solving the model (which describes changes in apparent maximum CW over time; Figure 19d) suggests that  $L_{\infty}$  of both sexes has declined over the last 10-15 years. This result is consistent with the theory of growth and the Von Bertalanffy model, where K should be stable over time (since it represents metabolic loss rate) whereas  $L_{\infty}$  should vary over time with feeding conditions and/or effects of fishery selection on growth.

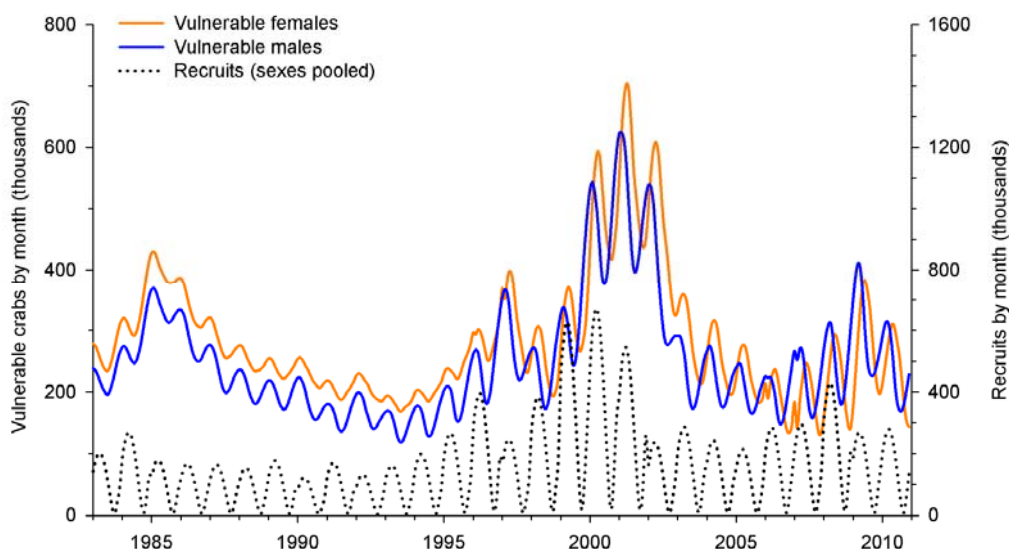


**Figure 20.** Comparison of observed mean carapace width (CW) of the Giant Mud Crab (*Scylla serrata*) to predictions from the equilibrium model ( $\bar{I}$ ), using regression predictions of annual  $Z$  from  $E$ , historical MLSs and an  $L_{\infty}$  of 18.4 cm for both sexes. Note that the  $L_{\infty}$  values used give the best overall fit to the time series.

#### *Size-age-sex monthly stock synthesis model*

Initial parameter estimates presented to the Solver analysis tool (in MS Excel) were varied across trials to represent various hypotheses about catchability and seasonal variation, as a “multiple shooting” approach to ensure that the search procedure would not converge to different local minima in the parameter space for different starting estimates (a high risk for models with periodic dynamics); no such minima were found. The resulting (apparently unique) parameter estimates gave excellent fits to the monthly catch estimates by sex, but not such good fits to the mean length data (not shown).

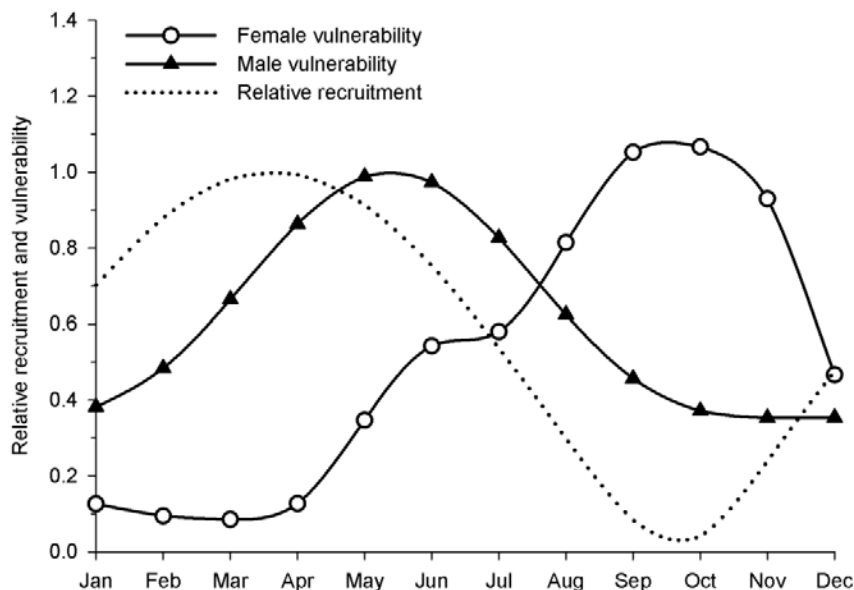
Average annual fishing mortality rates after 2000 were estimated to be around 1.17 for females and 1.22 for males, similar to the fishing rates estimated with the simpler equilibrium analysis. The model systematically under-predicted mean CW for the 1996-2000 period, and predicted the wrong timing of peak CW for females in recent years (after the 2006 change to a 15 cm MLS for this sex). The under-prediction of mean CW during the late 1990s is due to relatively high apparent recruitment during that period, needed to explain increases in the numbers of crabs caught (Figure 21). The discrepancy in timing of peak female CW after 2006 was apparently due to underestimation of female growth rates, leading to later recruitment to the MLS.



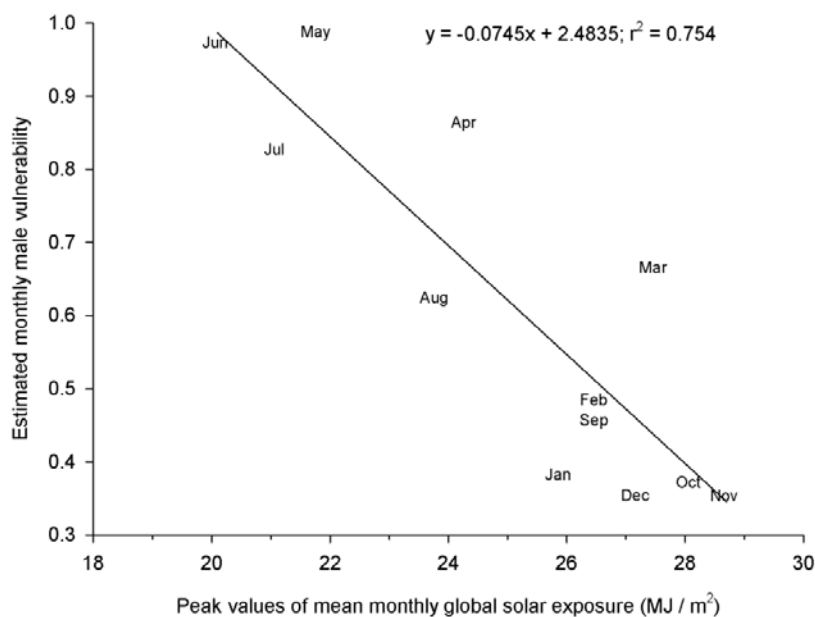
**Figure 21.** Dynamic model predictions of recruitment (sexes pooled) and vulnerable numbers of male and female Giant Mud Crab (*Scylla serrata*) from January 1983 to December 2010. Monthly recruitment (right axis) is deliberately scaled below monthly vulnerable numbers (left axis) to emphasise the chronology of events (i.e. recruits give rise to vulnerable crabs).

Seasonal patterns of estimated recruitment and vulnerability for the initial fitting trials are consistent with observations on the fishery (Figure 22). Recruitment to age 12 months was estimated to peak in March, a bit later than expected if spawning is mainly in December but not unreasonable if larval and juvenile growth does not follow the von Bertalanffy model. The seasonal spread in apparent time of recruitment was realistic given likely variation in individual growth rates, and is about the spread expected if the coefficient of variation in CW is around 0.08-0.10.

Calculated female vulnerability peaked in September-October, with a sharp drop afterward as expected from the offshore female spawning migration. Seasonal changes in calculated male vulnerability were surprisingly high, with vulnerability peaking near the start of the dry season then dropping to around 40% of its peak by the start of the wet season in October. This seasonal pattern in male vulnerability is most likely the result of a behavioural change by males towards the end of the dry season that continues into the wet season and reverts to “normal” as the next dry season approaches. Possible behavioural changes by males during this period include: moving into habitats inshore of the mangrove zone (where fishers typically do not go) or remaining in their burrows to limit their exposure to either low salinity (caused by freshwater run-off) or extreme heat (up to 44°C in shallow waters in the afternoon; Mounsey 1989). Support for “heat exposure” hypothesis comes from plotting monthly values of male vulnerability estimated here against peak values (across all years) of mean monthly global solar exposure (Figure 23).



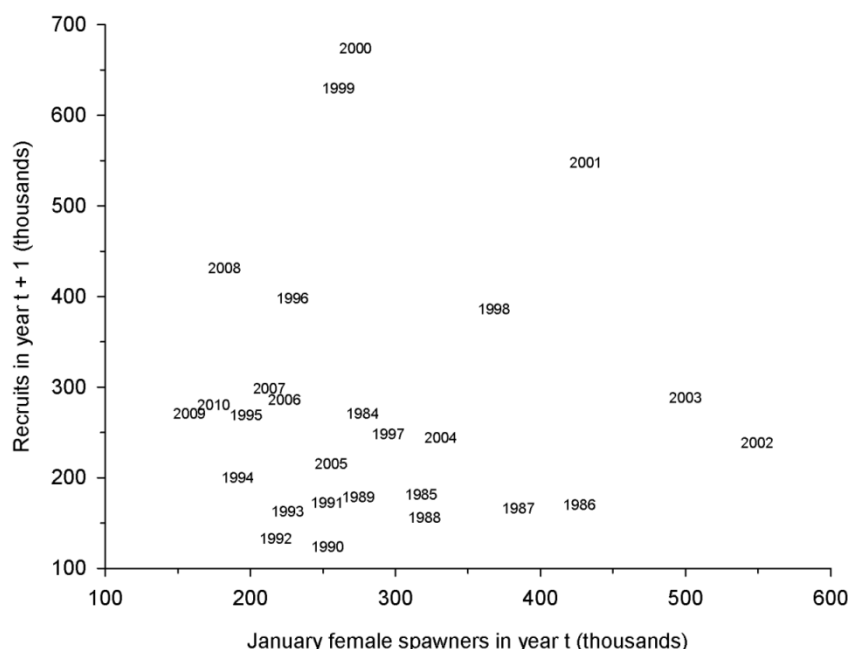
**Figure 22.** Estimates from the monthly sex-age model of monthly variation in relative recruitment and vulnerability to fishing of both sexes of Giant Mud Crab (*Scylla serrata*)



**Figure 23.** Apparent relationship between estimated monthly vulnerability of male Giant Mud Crab (*Scylla serrata*) and peak values of mean monthly global solar exposure ( $\text{MJ} / \text{m}^2$ ) recorded at the Borrooloola weather station (Bureau of Meteorology station number 014723) Northern Territory, from 1990 to 2011

In this case we have used data from the Borrooloola weather station (available at the Australian Government Bureau of Meteorology website <http://www.bom.gov.au/climate/data/>, station number 014723, years 1990 to 2011) because of its proximity to an important mud crab fishing area (the McArthur and Wearyan rivers and surrounds). Whilst there appears to be a reasonable correlation between monthly male vulnerability and solar exposure, we are mindful that this example comes from a single location and that other factors may also be at play.

Plots of estimated annual recruitment against estimated female vulnerable abundance in January one year earlier (Figure 24) showed no indication of reduced average recruitment at low spawning stock sizes, that is no evidence of recruitment overfishing. The very high recruitments of 1999-2001 (which drove historical peak catches for the fishery) were apparently produced at relatively low spawning stock sizes, and there was apparently no substantial response of recruitment to the 2006 increase in female MLS.



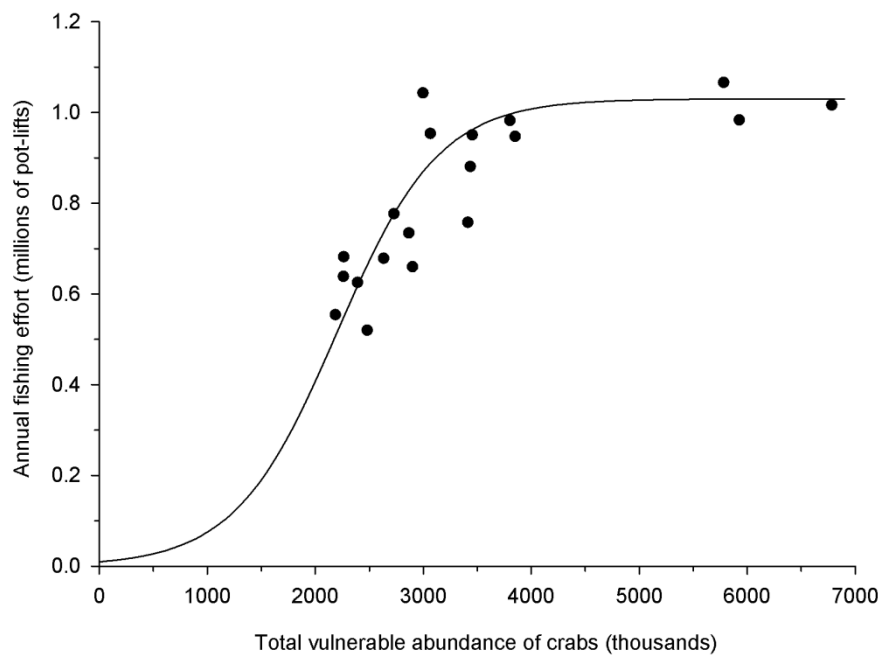
**Figure 24.** Estimates of seasonal maximum recruitment rates of Giant Mud Crab (*Scylla serrata*) versus January female abundance in the previous year

Additional estimation scenarios were carried out with various restrictions on the parameters, to see if nearly as good fits to the data could be obtained under various alternative hypotheses about recruitment and vulnerability. In particular, we first forced a higher  $L_{\infty}$  value (20.0 cm) as estimated by Haddon et al. (2005) for the best fitting value (19.03 cm); this was expected to result in higher estimates of  $F$  (so as to keep CW near observed values). This scenario did indeed result in higher values of  $F$  (2.01 for females, 1.78 for males) and demonstrates extreme sensitivity of the model to assumptions about growth parameters. That is, we cannot rule out the possibility that the “best” estimates represent underestimates of  $F$ .

As a second scenario for the possibility of underestimation of  $F$ , we forced the overall  $q$  to be three times the initial fitted estimate, while allowing the Solver procedure (hereafter referred to as “Solver”) to vary  $L_{\infty}$ . This high- $q$  scenario did result in high estimated  $F$  for males (2.78), but Solver adjusted the seasonal vulnerability schedule to give a much lower  $F$  value for females (1.12), and  $L_{\infty}$  around 19.1 as in the original fits. Furthermore, fits to the male CW data were very poor for this scenario, with the model predicting mean CW substantially below the data (by 0.5-2.0 cm for most years and seasons). Other test scenarios involved forcing recruitment to peak in different months and with more or less seasonal spread; generally these scenarios resulted in poor fits to the length data, often with less inter-annual variation (less decline over 1998-2000) than observed. However, better fits to recent (post 2004) seasonal CW data for females, at least in terms of predicted timing of CW decrease due to recruitment, were obtained by shifting the timing of maximum recruitment back from March to January.

A key sustainability mechanism for the commercial sector of the NT MCF in future may be the numerical response of fishing effort to changes in crab abundance associated with recruitment variation. Since the early 1990s, total fishing effort has apparently responded strongly to changes in total abundance (Figure 25) and there is every reason to expect a basic logistic pattern with further effort decline should lower recruitments occur in future (since in such cases it will become unprofitable to fish even earlier each year).

Reduced effort at lower abundances has apparently occurred mainly through reductions in both maximum seasonal effort and earlier decline in effort during the build-up and wet season (October to February). In future, such responses will be particularly helpful in providing extra protection for female crabs, especially if the current (commercial) MLS is maintained. In contrast, reduction in the (commercial) female MLS could result in higher fishing efforts in the October-November period, leading to more severe impacts on females.



**Figure 25.** Annual fishing effort (pot-lifts in millions) plotted as a function of the monthly sex-age model estimates of total annual abundance of Giant Mud Crab (*Scylla serrata*) summed over months and sexes, 1992 to 2010. Solid line is the fitted logistic response model.

All of the results above are based on data collected from the commercial sector of the MCF, which has limited spatial overlap with the recreational sector. A fishing effort induced decline in maximum CW in areas popular with recreational fishers (e.g. Darwin and Bynoe harbours) is expected to occur in future (if it is not already happening) given current and predicted population growth in Darwin, Palmerston and the rural area. Likewise, this population growth will increase the harvest rate of females, potentially impacting on the viability of the stock. Any significant growth in the number of interstate or overseas visitors targeting mud crabs in these and other areas will have similar impacts.

## DISCUSSION

The results presented here provide a mixed picture of the health of particular fish stocks in NT waters; there are examples of stocks that have recovered from industrial scale fishing in the 1970s and 1980s (e.g. the three shark species, Spanish Mackerel and the western stock of Grey Mackerel); others which have only recently been targeted and are being fished sustainably (e.g. the GoC stock of Grey Mackerel); as well as those which are either on the verge of becoming or have now become overfished where accessible (i.e. Black Jewfish and Golden Snapper, respectively).

It is important to recognise that there are two sources of mortality that we are concerned about when discussing strategies to arrest the decline of Black Jewfish and Golden Snapper stocks in the NT. These are harvest mortality and incidental mortality. There are several elements to incidental mortality but the most pertinent in this instance is barotrauma (or more correctly fatal barotrauma) and it is this that we refer to here. Harvest mortality can be limited through regulatory controls such as a personal possession limit, a MLS or a TAC. Incidental mortality (of the *target species*) is almost impossible to limit in isolation through regulatory controls and requires behavioural changes by fishers.

There is virtually no incidental mortality (through catch and release fishing) of either Black Jewfish or Golden Snapper by commercial operators as they invariably harvest everything they catch. By contrast, recreational fishers in the NT release around 30% of the Black Jewfish and 50% of the Golden Snapper that they catch (West et al. 2012). The relative impact of all sectors (including FTOs) on the Black Jewfish and Golden Snapper has changed significantly over the last 20 years and all stakeholder groups must now assist in the recovery of these species.

There are a number of strategies available to combat the problem facing Black Jewfish and Golden Snapper stocks in the NT. Some are common to both species, whilst others are different because of differences in vulnerability to capture, size/age at maturity and growth rates between the two species. The first strategy common to both species is to educate recreational fishers of the ways in which they impact each stock and the need to modify their behaviour to limit such impacts. Cessation of catch and release fishing of these species (when the possession limit is reached), and moving elsewhere to target other (preferably pelagic) species is considered the single most effective means of solving the problem.

In addition to changes in fisher behaviour, more restrictive harvest controls such as a reduction in the personal possession limit and/or the application of a MLS may aid in the recovery of these species. Decreases in possession limits are generally considered the best option providing that behavioural changes are made (otherwise incidental mortality will remain high). We also recognise that the application of a MLS that protects juveniles in shallow waters (where they can be effectively released) would limit harvest mortality of younger fish.

NT Fisheries has recommended that personal and vessel possession limits for recreational fishers targeting Black Jewfish and Golden Snapper be reduced. These measures are expected to decrease the harvest mortality of Golden Snapper by around 19% and stop that of Black Jewfish climbing even higher (based on data in West et al., 2012). Even if these harvest controls are adopted and there is behavioural change over time (that reduces incidental mortality), it may be three or more years before overall mortality of these species return to sustainable levels. Given this time lag, area closures are also being considered to effect immediate and substantial reductions in harvest and incidental mortality of these species.

The task of limiting the impacts of the commercial sector and FTOs is more straightforward as their catch/harvest can be capped through a variety of mechanisms (noting the issue of incidental mortality of fishes caught by FTO clients will still stand). NT Fisheries has released discussion papers for public

comment on the future management of these sectors also. Proposed changes are similar for both groups and include limiting access and/or catch within a zone around Darwin.

Whilst the effectiveness of harvest controls applied to commercial fishers and FTOs can be readily monitored through logbook systems, no routine data collection systems have been implemented for the NT recreational sector. At present, the only sources of reliable and consistent information are the recreational fishing surveys conducted in 1994-1996 (Coleman 1998), 2000-2001 (which formed part of a national survey; Coleman 2004) and 2009-2010 (West et al. 2012).

The problem of irregular collection of recreational fishing data is not unique to the NT and is shared with many other jurisdictions both in Australia and abroad. Indeed, a recent parliamentary inquiry into the role of science for the future of fisheries and aquaculture recommended that “the (Federal) Minister for Agriculture, Fisheries and Forestry work with State and Territory counterparts to commission a regular estimate of recreational fishing activity and impacts in Australia, with data and results published in a yearly consolidated report, using a nationally agreed data collection model” (Commonwealth of Australia 2012). The cost of these surveys is the primary reason for their irregularity. However, partial automation of this work through the use of small tablet computers, “smart” phones and online angler reporting (through a secure website), should streamline this process and make it possible for future surveys to be conducted more frequently at reduced cost.

Given the current declines of Black Jewfish and Golden Snapper, much can be learnt from the history of overfishing of the red snapper (*L. campechanus* – the northern hemisphere “cousin” of the Golden Snapper) in the Gulf of Mexico and southern Atlantic coast of the United States (US). The fishery for this species is over a century old, has several orders of magnitude more participants, and is managed by several US jurisdictions as well as their Federal Government. Recruitment of this stock was also (until fairly recently) compromised through the bycatch of juveniles in shrimp trawlers operating in nursery areas.

In 1998, the first (US) red snapper assessment indicated that the stock was overfished and undergoing overfishing, much the same as the NT Golden Snapper situation a quarter of a century later. At that time stock assessment scientists suggested a 75% reduction in fishing mortality (i.e. from direct harvest and bycatch) was needed in order to allow the stock to recover by the year 2000 (Hood et al. 2007). In hindsight, the recovery timeframe may appear over-ambitious given the life-history of the species and complex nature of the fishery, but a target was necessary nonetheless.

The body responsible for implementing changes to the management of fishery, the Gulf of Mexico Fisheries Management Council (GMFMC) believed that such a cut would be too severe, instead opting for a 20% reduction. This of course only delayed the inevitable need for additional restrictions in subsequent years and meant that the likelihood of a timely stock recovery was much reduced (Hood et al. 2007). Because of the lack of appropriate action at the outset, the recreational catch of red snapper in the Gulf of Mexico is now controlled through a combination of a two fish personal possession limit and an open season of around 40 days, the exact timing of which varies slightly from year to year. Clearly, we must ensure that this sequence of events is not repeated in the NT and that appropriate management action on Black Jewfish and Golden Snapper is taken quickly.

A common argument against the need for more stringent harvest controls (particularly in the case of slower growing fishes) is that there are still plenty of small fish around and so the stock cannot be in trouble. This line of argument fails to consider the impacts of the removal of larger fish, especially larger females. These more aggressive individuals are invariably the first to be removed by fishing and so the task of maintaining the stock is left to the remaining smaller fish. The importance of large females in maintaining a healthy stock is illustrated particularly well on the Florida Fish and Wildlife Conservation Commission's website (<http://www.myfwc.com/fishing/saltwater/recreational/snappers/gulf-red-snapper/>) where they show that one



24 inch (or 61 cm) female red snapper produces the same number of eggs as 217 females that are just 7 inches shorter (i.e. 17 inches or 41 cm). It is likely that the Golden Snapper exhibits a similar relationship between length and fecundity (egg production) given that it belongs to the same genus as the red snapper. The lack of published information on the size-fecundity relationship for Golden Snapper, as well as other basic biological information (e.g. stock structure etc.) is of concern. Projects that fill such knowledge gaps should be undertaken as a matter of urgency.

The shark and mackerel assessments described here were similar insofar as all stocks (except Grey Mackerel in the GoC) were subject to heavy exploitation by Taiwanese commercial fishing during the 1970s and 1980s as well as IUU fishing. These factors complicated the assessments because of uncertainties surrounding the accuracy of Taiwanese fishing information, the extent of IUU fishing and the reliability of shark identification before 2000. Despite these issues, assumptions (which we believe are appropriate) were made to adjust catches where they were not known. The model outputs only diverged when the annual catch totals were artificially increased by several orders of magnitude (a common method used to check the reliability of a fisheries model).

The current status of our local shark and mackerel stocks demonstrate that overfishing can be arrested and recovery achieved. However, the major difference between these examples and issues surrounding Black Jewfish and Golden Snapper is that commercial fishing was solely responsible for the decline of the shark and mackerel stocks and a reduction in harvest mortality was achieved by removing the foreign operators that were responsible. As indicated above, a solution to the current situation is more challenging because the recreational sector (including FTO clients) have contributed to the stock declines of Black Jewfish and Golden Snapper.

The model outputs for the deep water Goldband Snapper indicate that it is being fished within sustainable limits. However, the wide spread of data points on the stochastic SRA plot (Figure 15) suggest a high level of uncertainty around the estimates of Goldband Snapper stock status. Much of this uncertainty stems from the use of highly variable CPUE data and size at age curves derived from small sample sizes. Hence, more accurate estimates of both the harvest rate and growth rate of Goldband Snapper are required to provide a greater level of confidence in the model outputs.

Unfortunately, the high rate of incidental mortality experienced by Goldband Snapper caught from the deep waters they inhabit (i.e. 40 m to 200 m; Lloyd et al. 1999) precludes the use of conventional tag-recapture techniques to estimate the harvest rate of this species. Genetic tagging is a potential tool but is expensive and complex. One quick and effective means to evaluate the harvest rate would be a biomass survey over a known distance (i.e. the swept area method). A survey of this nature would provide a fishery-independent estimate of relative biomass (to replace fishery-dependent CPUE data) and allow the collection of larger number of samples for ageing.

The market monitoring program for the NT MCF represents one of the longest and most comprehensive time series on *Scylla serrata* size and sex ratio anywhere in the world. This data set, in conjunction with monthly catch and effort records, has enabled us to use both simple and complex modelling approaches to describe patterns in mortality rates, catchability, vulnerability (to capture), and the maximum theoretical CW of this species over the past 20 years.

The simple equilibrium model proposed by Beverton and Holt (1956) provided estimates of the long term trend in total mortality rate from changes in mean CW. The model indicated that annual fishing mortality  $F$  is most likely around 1.0, similar to previous estimates (see Knuckey 1999) and near the natural mortality rate ( $M$ ) estimated by the total mortality versus effort regression. This model also suggested that there has been a decline in maximum CW in recent times, perhaps due to selection by the fishery.

Declines in body size have been observed in several other animals subject to fishing and hunting (Darimont et al. 2009). This should not cause alarm in the case of the Giant Mud Crab, given it is a fast growing, highly fecund species, but it does highlight the need to continue the mud crab market monitoring program to detect any further decline in maximum CW.

The detailed size-age-sex monthly stock synthesis model showed that seasonal and long term patterns in the catch and size data have most likely involved a regular seasonal recruitment pattern interacting with complex seasonal changes in sex- and size-specific vulnerabilities to fishing. The detailed model also fits the data best with an annual  $F$  around 1.0, but estimates as high as 2.0 give almost equally good fits to the data when alternative assumptions are made about the mean growth curve.

A disturbing feature of both the simple equilibrium model and the complex monthly sex-age model, and in all past (Giant Mud Crab) assessment models for that matter, is the extreme sensitivity of their estimates of fishing mortality rate to quite small changes in estimates of growth rate, particularly  $L_{\infty}$ . Changes of even 1 cm in these estimates can lead to doubling or halving of the estimated  $F$ . If uncertainty about growth parameters makes it impossible to use CW sampling to assess past fishing mortality rates ( $F$ ) any more accurately than this, and if trends in  $F$  are masked by changes in growth rate over time, then there clearly remains a need for alternative methods to estimate and monitor changes in fishing mortality.

There are two suggestions regarding alternatives, these are the development and use of 1) a refined “swept area” method and 2) a high-reward or self-reporting tag system. The first method combines estimates of area swept per pot lift (around 100 m<sup>2</sup>) with total effort to give total swept area, then divides this estimate by the total “usable” area of the fishery. The second method would provide very short term estimates of the proportion of tagged crabs caught per unit time (day, month etc.). Such studies could also help in the estimation of  $M$  and improve our understanding of the cause (or causes) of the large seasonal changes in apparent vulnerability.

## CONCLUSIONS/RECOMMENDATIONS

For most of the species assessed current harvest rates are well within those required to ensure sustainable fishing. However, both Black Jewfish and Golden Snapper have been overfished and there was some uncertainty in the outputs for Goldband Snapper and Giant Mud Crab. Based on these results Professor Walters recommended a number of research and management strategies be adopted to address these current issues as well as those that may arise in the future. Professor Walters suggested that there could be tightly controlled development for all of the shark and mackerel species assessed in line with the principles of ecologically sustainable development. However, for the overfished species there would need to be reductions in harvest rates through introducing commercial catch limits and reductions in recreational personal possession limits. In addition, there needs to be further research into the biology of these species, particularly looking at population structure and vulnerability to barotrauma. Professor Walters also recommended that it was critical to continue/commence research programs (e.g. tagging programs, abundance surveys) to provide a further estimate of harvest rate that will provide more surety to assessments of stock status for all species.

The management and research recommendations for each species (or group of species) are tabulated overleaf for quick reference (Table 5).

**Table 5.** Management and research recommendations for selected species (or groups thereof) based on advice from Professor Carl Walters and also outputs from the 2012 stock assessments.

Species	Management recommendations	Research recommendations
Spanish Mackerel and Grey Mackerel	<p>The catch of both mackerels can be increased in line with the principles of ecologically sustainable development</p> <p>The above must be accompanied by rigorous monitoring and regulatory mechanisms that quickly limit catches if and when necessary</p> <p>Pay close attention to any changes in fishing practises that lead to large improvements in fishing efficiency</p>	<p>Undertake more tagging to assess mortality rates, stock structure, movement etc.</p> <p>Recreational catch statistics are desirable</p>
Common Blacktip Shark, Australian Blacktip Shark, and Spot-tail Shark	<p>The catch of all three sharks can be increased in line with the principles of ecologically sustainable development</p> <p>The above must be accompanied by rigorous monitoring and regulatory mechanisms that quickly limit catches if and when necessary</p> <p>Pay close attention to any changes in fishing practises that lead to large improvements in fishing efficiency</p>	<p>Undertake more tagging to assess mortality rates, stock structure, movement etc.</p> <p>Develop a reliable means of distinguishing between the Common and Australian Blacktip Sharks</p> <p>Recreational catch statistics are desirable</p>
Black Jewfish	<p>All sources of mortality on Black Jewfish must be effectively reduced by 15-20%</p> <p>Review the appropriateness of current management arrangements for all sectors taking into account the required reduction in mortality of Black Jewfish</p> <p>Educate recreational fishers and FTO crew members on the need to reduce incidental mortality imposed by catch and release fishing</p>	<p>Recreational catch statistics are essential</p> <p>Undertake more tagging to assess mortality rates, stock structure, movement etc.</p> <p>Conduct more work on reproductive biology, particularly fecundity</p> <p>Collect otoliths for ageing and microchemistry studies, and tissue samples for genetic analysis of stock structure</p>
Golden Snapper	<p>All sources of mortality on Golden Snapper must be effectively reduced by 30-50%</p> <p>Review the appropriateness of current management arrangements for all sectors taking into account the required reduction in mortality of Golden Snapper</p> <p>Educate recreational fishers and FTO crew members on the need to reduce incidental mortality imposed by catch and release fishing</p>	<p>Recreational catch statistics are essential</p> <p>Undertake more tagging to assess mortality rates, stock structure, movement etc.</p> <p>Describe the reproductive biology of this species in northern Australia and</p> <p>Collect otoliths for ageing and microchemistry studies, and tissue samples for genetic analysis of stock structure</p> <p>Determine the incidental mortality relative to depth of capture</p>

Species	Management recommendations	Research recommendations
Goldband Snapper	<p>Review the appropriateness of current management trigger points as improved knowledge of stock structure, growth and biomass responses to fishing become available</p> <p>Continue to collaborate with QLD, WA and Indonesia in the management of shared stocks</p>	<p>Obtain regular fishery-independent indices of biomass using “swept area” surveys</p> <p>Determine spatial variation in growth parameters and stock structure</p> <p>Recreational catch statistics are desirable and offshore FTO catch statistics essential</p> <p>Request spatial catch and effort data for vessels targeting this species in Indonesian waters</p>
Giant Mud Crab	<p>Review management arrangements taking into account improved knowledge of trends in the fishery as well as the future development of all sectors</p>	<p>Recreational catch statistics are essential</p> <p>Continue the mud crab market monitoring program</p> <p>Undertake more tagging to determine mortality rates and movement</p> <p>Develop a refined “swept area” method to estimate fishing mortality</p>

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## APPENDIX A: GLOSSARY OF ABBREVIATIONS AND TERMS

alw	Length weight relationship
CLF	Coastal Line Fishery
cm	Centimetre
CPUE	Catch per Unit Effort
CW	Carapace Width
<i>E</i>	Fishing effort
<i>Egg</i>	Total egg production in a given year (as subscript)
<i>F</i>	Fishing mortality rate
FTF	Finfish Trawl Fishery
FTO	Fishing Tour Operator
GoC	Gulf of Carpentaria
GTG	Growth Type Group (model)
IUU	Illegal, Unreported and Unregulated (fishing)
<i>K</i> or <i>vbK</i>	von Bertalanffy growth coefficient
kg	Kilogram
$L_{inf}$ or $L_{\infty}$	Maximum theoretical length
m	Metre
<i>M</i>	Natural mortality rate
MCF	Mud Crab Fishery
MLS	Minimum Legal Size
MJ	Megajoule
MS	Microsoft
MSY	Maximum Sustainable Yield
nm	Nautical mile
NSW	New South Wales
NT	Northern Territory
ONLF	Offshore Net and Line Fishery
PFMC	Pacific Fisheries Management Council
<i>q</i>	Catchability
QLD	Queensland
$R_0$	Unfished natural recruitment rate
reck	Recruitment compensation ratio
SMF	Spanish Mackerel Fishery
SRA	Stock Reduction Analysis
Surv	Survival rate
t	tonne
$t_0$	Hypothetical age at fish length zero
TAC	Total Allowable Catch
TEP	Threatened, Endangered and Protected (species)
<i>U</i>	Harvest rate
VBA	Visual Basic for Applications
WA	Western Australia
$W_{mat}$	Weight at maturity
WW	Wet Weight
<i>Z</i>	Total mortality rate

## APPENDIX B: SCREEN CAPTURES OF STOCHASTIC SRA OUTPUTS

The following pages contain screen captures of Stochastic SRA outputs for the various fish species/stocks examined here (order as below). The images are rotated counter-clockwise 90° to maximise their size and are identified in the page headers. Note that the plots showing the probability distribution of the two status measures referred to in this report (i.e. relative egg production and harvest rate) are shown in the bottom right hand corner of the *images*. There are also differences in the colour scheme of the plots between the following screen captures and the figures presented in the results section of this report. The latter are based on the same model estimates but use fewer colours to simplify their interpretation.

- i. Spanish Mackerel
- ii. Grey Mackerel - western stock
- iii. Grey Mackerel - Gulf of Carpentaria stock
- iv. Common Blacktip Shark and Australian Blacktip Shark
- v. Spot-tail Shark
- vi. Black Jewfish
- vii. Golden Snapper
- viii. Goldband Snapper

**Stochastic SRA, parfile=spanish mackerel.par, datafile=spanish mackerel time series.csv**

Files

Run Priors Stop

Show Posterior (SIR) Sample

N trials to run: 5000

Years to simulate (100 max): 50

Run MCMC sampling

Par Step: 2

Anom Step: 1

Number of trials: 100000

Trials: 141067 100000

Mean NPV: .4

Prop. crashed: 0.00

Discount rate: 0.97

839.7

Vol. B

B scaler: 0.3

Catch

Rec Anoms

U (C/N)

1970 Assume flat U for yrs: 0 to 0

Ubar 2003-2005

Parameters

Bhat 2011: 50 SD Bhat: 1E+20

Uhat 2011: 0.1 SD Uhat: .05

growth von B K: 0.21

growth infinity (cm): 141

CV length age: 0.09

length maturity (cm): 75

wt (kg) at 100 cm: 9.92

growth tzero: 0

Legal length: 0

Age at maturity (for SSB): 3

Recruitment autocorrelation rho: 0

Future TAC (kg): 100000 or Ufuture: 0.2

Sample individual survival for Nac: 1000

Age at maturity survival

Representation of parameter uncertainty

MSY min: 10 MSY max: 20

Umsy min: 0.1 Umsy max: 0.5

S min: 0.55 S max: 0.7

Size distn weight: .000000001

Age distn weight: .000000001

Use historical anomaly estimates Var of abundance index: .04

Bycatch params

bycatch before compensation: 0

future bycatch U: 0.02

Szero

Prop of fisher sample

0 cm Fish length cm

Sample distribution of Umsy and MSY values

MSY

Umsy

Compensation ratio

0 100

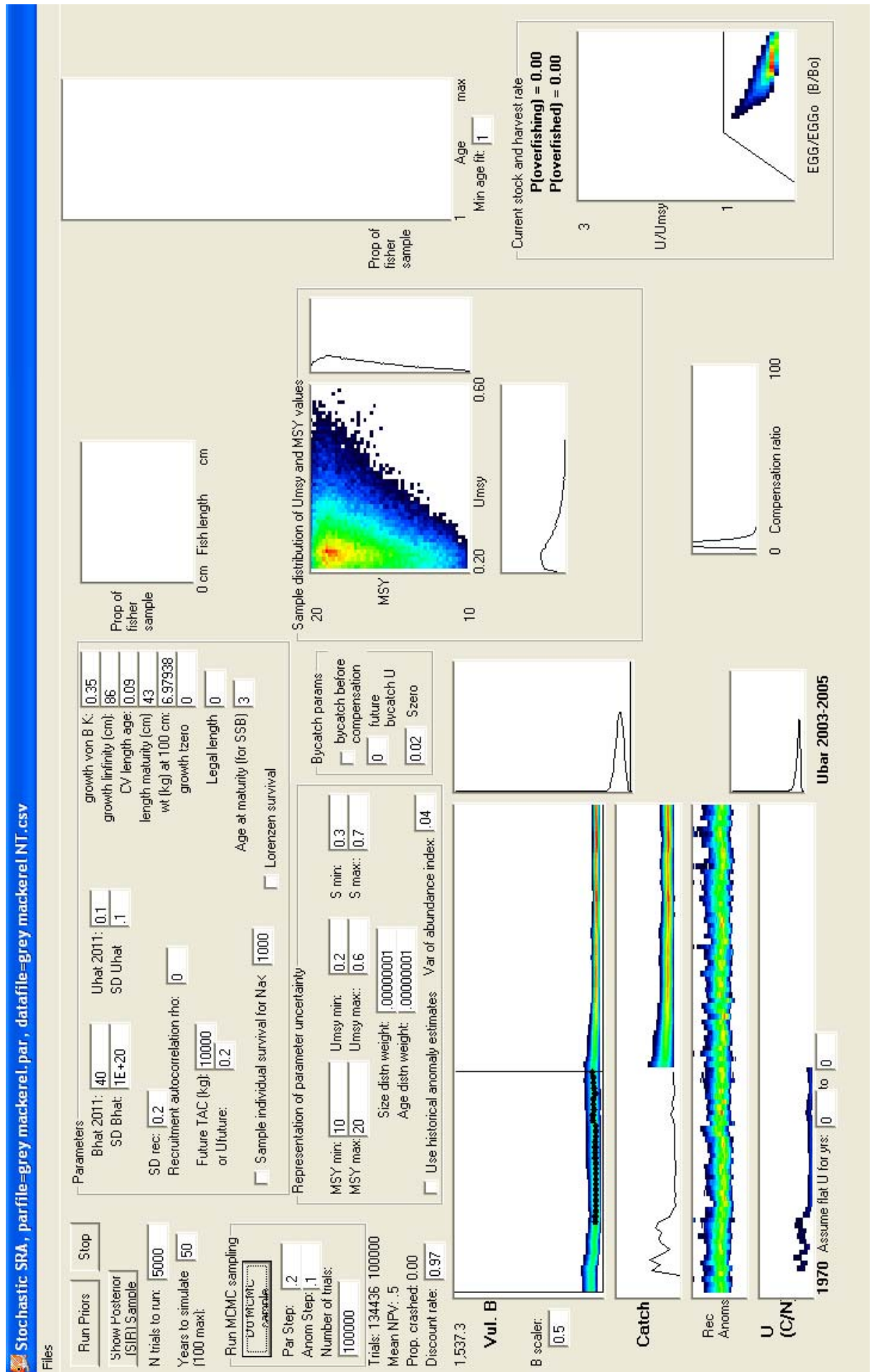
Current stock and harvest rate

$P(\text{overfishing}) = 0.00$

$P(\text{overfished}) = 0.01$

U/Umsy

EGG/EGG<sub>0</sub> (B/B<sub>0</sub>)



iii. Grey Mackerel - Gulf of Carpentaria stock

Stochastic SRA, parfile=grey mackerel.par, datafile=grey mackerel Gulf.csv

Files

Run Priors Stop

Show Posterior (SJR) Sample

N trials to run: 5000

Years to simulate (100 max): 50

Run MCMC sampling

Uo MCMC sample

Par Step: 2

Anom Step: 1

Number of trials: 100000

Trials: 124390 100000

Mean NPV: .3

Prop. crashed: 0.00

Discount rate: 0.97

1,233.5

Vul. B

B scaler: 0.3

Catch

Rec Anoms

U (C/N)

1970 Assume flat U for yrs: 0 to 0

Ubar 2003-2005

Parameters

Bhat 2011: 40

SD Bhat: 1E+20

Uhat 2011: 0.4

SD Uhat: 1

growth von B K: 0.35

growth infinity (cm): 86

CV length age: 0.09

length maturity (cm): 43

wt (kg) at 100 cm: 6.97938

growth zero: 0

Legal length: 0

Age at maturity (for SSB): 3

Recruitment autocorrelation rho: 0

Future TAC (kg): 10000

or Ufuture: 0.2

☐ Sample individual survival for Nac: 1000

☐ Lorenzen survival

Representation of parameter uncertainty

MSY min: 10

MSY max: 30

Umsy min: 0.1

Umsy max: 0.6

S min: 0.3

S max: 0.7

Size distn weight: .000000001

Age distn weight: .000000001

☐ Use historical anomaly estimates

Var of abundance index: .04

Bycatch params

☐ bycatch before compensation

☐ future bycatch U

Szero: 0.02

Sample distribution of Umsy and MSY values

Prop of fisher sample

0 cm Fish length cm

Prop of fisher sample

0 cm

Sample distribution of Umsy and MSY values

MSY

Umsy

0 0.10 0.60

10 30

Current stock and harvest rate

$P(\text{overfishing}) = 0.00$

$P(\text{overfished}) = 0.00$

U/Umsy

EGG/EGGo (B/Bo)

0 100

Compensation ratio



Stochastic SRA, parfile=Tilstoni.par, datafile=Tilstoni.csv

Files

Run Priors Stop

Show Posterior (SIRI Sample)

N trials to run: 5000

Years to simulate (100 max): 50

Run MCMC sampling

Par Step: 12

Anom Step: 1

Number of trials: 100000

Trials: 117067 100000

Mean NPV: .6

Prop. crashed: 0.00

Discount rate: 0.97

Parameters

Bhat 2010: 50 Uhat 2010: 0.05 SD Bhat: 1E+20 SD Uhat: 0.05

growth von B K: 0.14

growth infinity (cm): 199

CV length age: 0.09

length maturity (cm): 122

wt (kg) at 100 cm: 9.957

growth tzero: -1.8

Legal length: 0

Age at maturity (for SSB): 4

Recruitment autocorrelation rho: 0

Future TAC (kg): 10000 or Ufuture: 0.2

☐ Sample individual survival for Nac: 1000

☐ Lorenzen survival

Representation of parameter uncertainty

MSY min: 10 Umsy min: 0.05 S min: 0.5

MSY max: 20 Umsy max: 0.1 S max: 0.7

Size distn weight: .00000001

Age distn weight: .00000001

☐ Use historical anomaly estimates Var of abundance index: .04

Bycatch params

☐ bycatch before compensation

☐ future bycatch U

Szero: 0.02

Prop of fisher sample

0 cm Fish length cm

Sample distribution of Umsy and MSY values

MSY

Umsy

Prop of fisher sample

1 Age max

Min age fit: 1

Current stock and harvest rate

$P(\text{overfishing}) = 0.00$

$P(\text{overfished}) = 0.01$

U/Umsy

EGG/EGGo (B/Bo)

Compensation ratio

0 100

Ubar 2003-2005

1970 Assume flat U for yrs: 0 to 0

Vul. B

B scaler: 0.3

Catch

Rec Anoms

U (C/N)

Run Priors

Stop

Show Posterior  
(SIR) SampleN trials to run: 5000  
Years to simulate  
(100 max): 50

Run MCMC sampling

MCMC sample

Par Step: 2

Anom Step: 1

Number of trials:

100000

Trials: 125867 100000

Mean NPV: .3

Prop. crashed: 0.00

Discount rate: 0.97

546.6

Vol. B

B scaler:

0.3

Catch

Rec  
AnomsU  
(C/N)

1970 Assume flat U for yrs: 0 to 0

Ubar 2003-2005

Parameters

Bhat 2011: 20 Uhat 2011: 0.1  
SD Bhat: 1E+20 SD Uhat: .1

growth von B K: 0.34  
growth infinity (cm): 123  
CV length age: 0.09  
length maturity (cm): 106  
wt (kg) at 100 cm: 10.02  
growth tzero: -1.9

Legal length: 0  
Age at maturity (for SSB): 4

SD rec: 0.2  
Recruitment autocorrelation rho: 0  
Future TAC (kg): 10000  
or Ufuture: 0.2

☐ Sample individual survival for Nac: 1000 ☐ Lorenzen survival

Representation of parameter uncertainty

Representation of parameter uncertainty

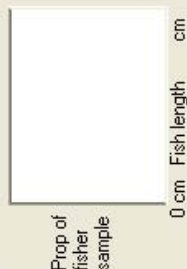
MSY min: 3 MSY max: 10 Umsy min: 0.05 Umsy max: 0.2 S min: 0.5 S max: 0.7

Size distn weight: .000000001  
Age distn weight: .000000001

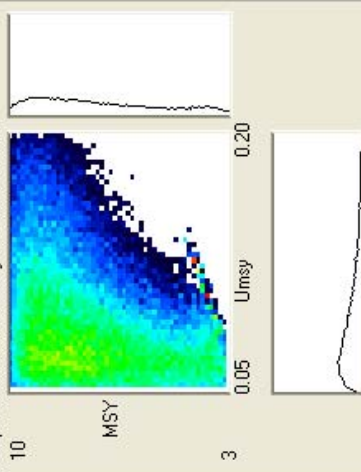
☐ Use historical anomaly estimates Var of abundance index: .04

Bycatch params

☐ bycatch before compensation  
☐ future bycatch U  
Szero: 0.02



Sample distribution of Umsy and MSY values



Prop of fisher sample

Age  
Min age fit: 1 max

Current stock and harvest rate

 $P(\text{overfishing}) = 0.04$   
 $P(\text{overfished}) = 0.05$ 
