A review of the population dynamics of dugongs in southern Queensland: 1830-2012

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Contents

List of acronyms and abbreviations

Cwlth	Commonwealth
DAFF	Department of Agriculture, Fisheries and Forestry (Queensland)
DPA	Dugong Protection Area
NPRSR	Department of National Parks, Recreation, Sport and Racing (Queensland)
EHP	Department of Environment and Heritage Protection (Queensland)
GBRMPA	Great Barrier Reef Marine Park Authority
GSS	Great Sandy Strait
JCU	James Cook University
PBR	Potential Biological Removal
PVA	Population Viability Analysis
MPA	Marine Protected Areas
Qld	Queensland
R_{max}	maximum rate of population increase
SE	Standard Error
QSCP	Queensland Shark Control Program
UQ	University of Queensland

Summary

Historical accounts and survey data for dugong populations in southern Queensland were reviewed. The focus of the review was to determine if there is any evidence that dugong abundance in the Hervey Bay-Great Sandy Strait (GSS) and Moreton Bay regions has changed since European settlement. Historical records, anecdotal reports, government datasets and aerial survey data were examined. Quantitative aerial survey datasets spanned 36 years (1976-2011) for Moreton Bay, and 24 years for Hervey Bay-GSS (1988-2011).

The population structure of dugongs in southern Queensland is uncertain, but there are indications from genetic data and the Queensland Shark Control Program (QSCP) bycatch data to suggest that dugong populations in Hervey Bay-GSS and Moreton Bay are sufficiently connected to be considered a single stock. Quantitative data were therefore examined under two scenarios: (1) Hervey Bay-GSS and Moreton Bay are separate stocks, and (2) Hervey Bay-GSS and Moreton Bay are the same stock. Neither the aerial survey data nor the QSCP bycatch data indicated a change in dugong abundance since the 1980’s under either scenario.

Historical accounts suggested a decline in dugong abundance in southern Queensland in the late 1800’s because of the commercial dugong fishery, leading to the first two-year closure of the fishery in 1888. Dugongs were observed to be abundant in Moreton Bay in 1893, and reported to be scarce again by 1908. By 1935, dugong fisheries were focused on Hervey Bay and few data are available up until the QSCP was established in 1962. The QSCP data indicated a decline in dugong bycatch on the Sunshine Coast (the region between Hervey Bay-GSS and Moreton Bay) from 1963 to 1980, but this was not supported by anecdotal reports that suggested that the Moreton Bay stock was stable or rebuilding.

Population connectivity also has important implications for monitoring anthropogenic threats to dugongs in southern Queensland. Years where comprehensive aerial surveys and records of dugong mortalities were available were analysed using the precautionary Potential Biological Removal (PBR) approach. Under Scenario 1, Hervey Bay-GSS PBR limits were not reached in any of the years that were analysed, but limits may have been reached in Moreton Bay during 2000 and 2005. Under Scenario 2, PBR limits were not reached in years where data were available. These results indicate that the much larger population of Hervey Bay-GSS could act to stabilise the smaller Moreton Bay population from local declines if these regions represent a single stock, but that only very low levels of anthropogenic mortality may be sustainable in the smaller Moreton Bay population if it is a separate stock. This underscores the importance of determining an appropriate spatial level for managing dugong populations in southern Queensland.

Introduction

The marine environment of southern Queensland is characterised by two large subtropical embayments that are sheltered from the Pacific Ocean by large sand islands (Figure 1). Hervey Bay (25º, 152"45'E) is a large embayment (~3940 km^2) adjoining the Great Sandy Strait (GSS), a 70 km passage separating the mainland from Fraser Island. Moreton Bay lies approximately 125 km to the south of the GSS and is flanked by four large sand islands; North Stradbroke and Moreton Islands to the east, Bribie Island to the north, and South Stradbroke Island to the south (Figure 1). Diverse and abundant marine mammal assemblages are found in both embayments, and Moreton Bay occurs in close proximity to a city of more than two million people (Brisbane) (Chilvers *et al.* 2005).

Both Moreton Bay and Hervey Bay-GSS support the most extensive seagrass areas in the region, providing suitable pastures for large herds of dugongs (*Dugong dugon*). It has been estimated that Moreton Bay supports approximately 250 km^2 of seagrass (Hyland *et al.* 1989). Hervey Bay has one of the largest areas of seagrass in eastern Australia, estimated to be around 1000 km^2 in 1988 (Lee Long *et al.* 1993) and in a more detailed study, 2307 ± 279 km^2 of seagrass (McKenzie 2000).

Dugongs in Queensland are protected as a vulnerable species by the *Nature Conservation (Wildlife) Regulation 2006* (Qld) under the *Nature Conservation Act 1992* (Qld), and as a migratory species under the *Environment Protection and Biodiversity Conservation Act 1999* (Cwlth) and the international Convention on Migratory Species (CMS). The *Nature Conservation (Dugong) Plan 1999* (Qld) was implemented under the *Nature Conservation Act 1992* (Qld) to reduce the mortality of dugongs in commercial gill-net fisheries in Queensland waters. Recently, the *Nature Conservation and Other Legislation Amendment and Repeal Regulation (No. 1*.) *2013* amended marine mammal approach distances for vessels for greater consistency with national guidelines, and introduced special management provisions for dugongs. Dugongs are also protected in southern Queensland by the Moreton Bay Marine Park (declared in 1993, zoned in 1997 and rezoned in 2009) and the Great Sandy Marine Park (declared in 2006), under the *Marine Parks Act 2004* (Qld). The area from Hervey Bay to Tin Can Bay was declared a Zone A Dugong Protection Area under the *Fisheries Act 1994* (Qld) by the *Fisheries Amendment Regulation (No. 11) 1997* (Qld), and limitations on commercial netting in the area are in place to reduce the entanglement risk to dugongs from this activity.

Life history of dugongs in southern Queensland

Dugongs are seagrass specialists (Heinsohn and Birch 1972; Marsh *et al.* 1982), and their distribution is therefore largely constrained to shallow, protected waters where seagrass is prevalent. Historically, dugongs ranged across the Indo-west Pacific (Husar 1978). Today, the highest densities of dugongs are in Australia, with year-round resident populations in Australian tropical and subtropical coastal waters between Shark Bay in Western Australia and Moreton Bay in Queensland (Marsh 2002).

On the east coast of Australia, Moreton Bay is likely to represent the southern limit of stable dugong populations because of low winter temperatures and/or because of the distance to suitable seagrass areas south of Moreton Bay (approx. 590 km to Port Stephens in New South Wales). Dugongs are occasionally reported much further south in New South Wales, including records as far south as Sydney (Anon. 1952; Allen *et al.* 2004).

Much of what is known of life-history parameters of dugongs comes from tropical Queensland (reviewed by Marsh *et al.* 2011). Dugongs are long-lived (at least 70 years). Based on adult survival estimates from manatees and empirical reproductive data from dugongs in the Torres Strait, maximum population growth was estimated to be between one and five per cent per annum (Marsh *et al.* 2004).

Age at first pregnancy has been estimated from carcass studies where age is inferred from growth layers in tusks, and ranges from 6 to 17 years (Marsh *et al.* 2011). Gestation lasts 12 to 14 months, the usual litter size is one and the period between calving has been estimated to range between two to seven years (Marsh *et al.* 2011). Age at sexual maturity of males tends to be similar to that of females in the same population, and is from 7 to 15 years (Marsh *et al.* 2011). Age at first breeding and breeding frequency are variable within and between populations, and are thought to be driven by the abundance and quality of food (Marsh and Kwan 2008; Marsh *et al.* 2011).

Little is known of the mating system of dugongs, except that aggressive competition between males has been observed (Anderson 1997). Dugongs are known to reproduce in Moreton Bay (Preen 1989). The presence of calves and year-round high densities of dugongs suggest that this is also likely to be the case in the Hervey Bay-GSS region.

The life history, behaviour and dependency of dugongs on inshore seagrasses makes them susceptible to human impacts such as fisheries entanglement and interactions with vessels, in addition to habitat disturbance (Marsh *et al.* 1999). Little is known of natural levels of mortality of dugongs in Queensland, but reports of dugongs that are dead, injured or in ill health are recorded in the StrandNet database, which is maintained by the Department of Environment and Heritage Protection (EHP). Shark predation is likely to be significant in some areas (Wirsing *et al.* 2007; Biddle *et al.* 2011; Marsh *et al.* 2011).

Dugongs feed almost exclusively on seagrasses from the families Potamogetonaceae and Hydrocharitaceae particularly of pioneer species such as *Halophila* and *Halodule* genera (Preen 1995b; Preen 1995a; reviewed by Marsh *et al.* 2011). The nutritional requirements of dugongs are largely unknown, but in a study of the composition and nutrition of a seagrass meadow used by dugongs in Hervey Bay, *Halodule uninervis* and *Halophila ovalis* dominated the below and above ground seagrass biomass (Sheppard *et al.* 2007). A subsequent study suggested that high nitrogen seagrasses were preferred in Hervey Bay, based on tracked dugongs being located more often over high-nitrogen seagrasses relative to other seagrasses (Sheppard *et al.* 2010). Other items such as sessile macroinvertebrates and algae are consumed, but are thought to be either incidental to seagrass consumption or eaten when the preferred seagrass species are scarce (Preen 1995b; Marsh *et al.* 2011). Intensive cultivation grazing of large dugong herds on preferred seagrass species in Moreton Bay is thought to prevent the expansion of less preferred seagrasses such as *Zostera capricorni* (Preen 1995a), and increase the nitrogen concentration and decrease the fibre concentration of preferred species (Aragones *et al.* 2006).

The dependency of dugongs on seagrass suggests a strong link between seagrass availability and dugong population dynamics, and several studies have attributed local declines in dugong density and reproductive potential to major seagrass loss (e.g. Preen and Marsh 1995; Gales *et al.* 2004; Marsh and Kwan 2008). The seagrass species that are preferred by dugongs have a low tolerance to prolonged low-light conditions (Longstaff *et al.* 1999). This implies that processes that elevate turbidity, such as disturbance of sediments, eutrophication, flooding and severe weather events may impact dugong populations. However, establishing a clear link between weather-related disturbance and dugong abundance is confounded by the fact that dugongs are thought to migrate away from impacted areas.

Understanding the movement patterns of dugongs is fundamental to conservation management. This realisation has provided much of the impetus for several satellite tagging studies, which have established that dugongs are highly mobile at a range of spatio-temporal scales and that movement patterns vary considerably between individuals (reviewed by Marsh 2002; Sheppard *et al.* 2006; Marsh *et al.* 2011). The majority of tracked animals have been localised near seagrass beds (Marsh and Rathbun 1990; Marsh 2002; Marsh *et al.* 2011), although numerous dugongs have made migrations in excess of 500 km (Sheppard *et al.* 2006 and references therein). The reasons for these long-distance migrations are uncertain, and much of what is known of movements and migration of dugongs is correlative, because of the difficulties in conducting manipulative or laboratory experiments with large, free-ranging mammals. Nevertheless, individual heterogeneity in long-distance migration or dispersal is evident in many taxa, and has been linked to traits such as individual phenotype, physiological state and the social environment (Bowler and Benton 2005; Handley and Perrin 2007; Chapman *et al.* 2012; Whitmee and Orme 2012).

At the small-scale, movements over diel cycles appear to be associated with the tidal availability of intertidal and shallow subtidal seagrass beds (reviewed by Marsh *et al.* 2011). At a larger scale, dugongs regularly move between known foraging areas on the eastern banks of Moreton Bay to deeper areas outside the bay during winter (Preen 1992; Sheppard *et al.* 2006). Similar behaviour was recorded in Hervey Bay (Sheppard *et al.* 2006). This has been attributed to thermoregulatory behaviour, because deeper waters are thought to be provide a refuge from cooler waters on the foraging areas (Preen 1992; Sheppard *et al.* 2006). Similar behaviour has been noted in manatees (Deutsch *et al.* 2003; Edwards *et al.* 2007).

On the Eastern Banks of Moreton Bay, where most dugongs are found (Figure 1), temperatures as low as 15°C have been recorded in winter (Read *et al.* 1996). Oceanic waters outside the bay are up to 5°C warmer (Preen 1992; Lanyon 2003). Water temperature measured by sensors on dugongs tracked during winter averaged 17.7°C (standard error, SE = 0.07) inside the Bay compared to 19.4°C (SE = 0.23) outside the Bay (Preen 1992). At a similar latitude to southern Queensland in Western Australia (26°S), seasonal use of foraging grounds is correlated to temperature (Anderson 1982; Anderson 1986;Masini *et al.* 2001; Holley 2006) and dugongs appear to avoid temperatures colder than 18°C (Preen *et al.* 1997).

While the geographic distribution of dugongs is almost certainly limited by cold temperatures at high latitudes (Allen *et al.* 2004), the evidence for a fixed 'critical thermal minimum' (*sensu* Preen 1992) is less clear. This is because animals can tolerate short exposure to cooler temperatures when thermal refuges are available (e.g. Helmuth *et al.* 2006; Chapperon and Seuront 2011), and because of potential population, life-history, state and context-specific differences in thermal tolerances. Mortality may be associated with sustained periods of cold weather, as suggested by recent evidence of cold stress syndrome in dugong carcasses salvaged in Moreton Bay (Owen *et al.* 2013).

Population structure

Little has been published on the genetic structure of dugong populations in eastern Australia. Tikel (1997) used mitochondrial sequence data (198 base pairs of the 5’ control region) to identify two distinct lineages within Australia which overlapped in the Great Barrier Reef Region. A subsequent study featured additional samples and a 492 base pair segment of the same control region and found that haplotypes of the ‘restricted lineage’ were more prevalent in dugongs of southern-central Queensland (south of the Townsville region) than elsewhere across the range of the species in Australia, and that dugongs from the ‘widespread lineage’ were rare in southern-central Queensland compared to other locations across the range (Figure 4.6 in McDonald 2005; see also Blair *et al.* 2013). In the latter study, an analysis using six microsatellite loci developed for the Florida manatee did not find significant structuring other than isolation-by-distance at the Australian scale. Samples from Hervey Bay, Moreton Bay and Shoalwater Bay were grouped into the same ‘southern Queensland’ region in this analysis.

Nevertheless, while the presence of differences at neutral loci indicates population divergence, the opposite, namely an absence of detectable differences at neutral loci, does not necessary imply genetic homogeneity (Ryman *et al.* 1995; Nordeide *et al.* 2011). This is because the loci examined represent a very restricted fraction of the genome (Ryman *et al.* 1995) and because the power of statistical tests for detecting geographic differences depends on the sample size, and the rates of migration, mutation and recombination (Hudson *et al.* 1992). Other factors that can obscure the genetic signature of different populations include population size and isolation time (Palumbi 2003; Knutsen *et al.* 2011). Subsequent research has developed 26 microsatellite loci in dugongs (Broderick *et al.* 2007), but these markers have not yet been used to examine population structure**.** Ongoing research based at James Cook University (JCU) is using 10 microsatellite markers to investigate population structure in Queensland at a finer spatial scale, and preliminary data suggest a marked genetic break between Shoalwater and Townsville (Blair 2012).

Populations can also be connected by demographic processes, which may act independently of genetic processes, because gene flow depends on the reproductive success of immigrants but animals may also move into an area temporarily without breeding (Lowe and Allendorf 2010). Demographic connectivity is a function of the relative contribution of net immigration and has important implications for the viability of local populations (Lowe and Allendorf 2010). Quantifying demographic connectivity depends on mark-recapture and tracking studies. Modern multistate capture-mark-recapture models allow estimation of survival rates and movements between populations (e.g. Kendall *et al.* 2006; Kendall *et al.* 2011).

To date, there have been no documented records of tagged dugongs moving between Moreton and Hervey Bay-GSS (C.J. Limpus, unpublished data), but the results of tagging studies by the University of Queensland (UQ) have not yet been published. No dugongs tracked with satellite tags have been reported to have moved between these regions, although comparatively few dugongs have been tracked to date in southern Queensland (Preen 1992; Sheppard *et al.* 2006; C.J. Limpus, unpublished data). However, incidental catches of dugongs (i.e. bycatch) in the Queensland Shark Control Program (QSCP) between Moreton and Hervey Bay-GSS (Rainbow Beach and on the Sunshine Coast) suggest that movement between these areas is likely to occur (Table 3, Table 4).

Dugongs have been caught in the QSCP over the entire extent of the Sunshine Coast, including locations up to 70 km from the nearest known dugong habitat, such as Noosa and Coolum. The ~150 km stretch between Hervey Bay-GSS and Moreton Bay (Rainbow Beach-Sunshine Coast) is ocean-exposed and does not have large areas of shallow seagrass beds or resident dugong populations. It is possible that some feeding occurs along this stretch, because dugongs have been observed to feed on algal covered reefs elsewhere (Whiting 2002) and it is not known whether seagrass is present in deeper waters offshore. It is also possible that dugongs caught closer to Hervey Bay-GSS (Rainbow Beach) or the southern end of the Sunshine Coast are moving temporarily to and from core habitat areas. Nevertheless, the most plausible explanation for dugong bycatch along the entire stretch of the Sunshine Coast is migration between Hervey Bay-GSS and Moreton Bay.

The extent and consequences of movements of dugongs between major foraging areas in southern Queensland should be tested with comprehensive mark-recapture, genetics and tracking studies, but there is sufficient data available to suggest that movements of dugongs between Hervey Bay-GSS and Moreton Bay are likely. On this basis, the data in this review are analysed under two scenarios: (1) Hervey Bay-GSS and Moreton Bay are separate populations and hence separate management units, and (2) Hervey Bay-GSS and Moreton Bay have sufficient genetic and demographic connectivity to be considered the same population for the purposes of management.

Perspectives on monitoring dugong population dynamics

The main limitations to quantitative stock assessment of dugong populations are that:

- dugongs undergo substantial large-scale movements (Holley 2006; Holley *et al.* 2006; Sheppard *et al.* 2006; Whiting 2008) and cannot be considered to be closed populations at local scales.
- dugongs are shy of vessels (Anderson and Birtles 1978; Hodgson 2004; Hodgson and Marsh 2007) and are mostly found in coastal waters with reduced or variable water clarity. Where the seafloor cannot be seen or where dugongs avoid the survey vessel, uncorrected counts of dugongs will always be underestimates of actual abundance.

In order to address these limitations, aerial surveys and, to a much lesser extent, mark-recapture studies (Lanyon *et al.* 2002) have been the main approaches to quantify the density of dugongs.

A major issue with dugong aerial surveys is that animals below the surface are often less likely to be detected by observers than animals at or near the surface. This issue of imperfect detection is termed the ‘availability bias’ and has been the topic of several studies aimed at improving the accuracy of estimates from aerial surveys (Marsh and Sinclair 1989b; Pollock *et al.* 2006). Briefly, the availability bias has been corrected by estimating the proportion of dugongs on the surface in clear water (where all dugongs are observable) and applying this to areas with lower water clarity (Marsh and Sinclair 1989b). A further source of bias is observer error, known as the ‘perception bias’ and occurs when dugongs are visible but are not detected, and is corrected using a mark-recapture approach based on two independent observers on each side of the survey aircraft (Marsh and Sinclair 1989b). Dugongs are ‘marked’ when recorded by one observer and are ‘re-captured’ when recorded again by an independent observer.

Despite considerable effort to address this problem, the availability bias is still a considerable source of error. Pollock *et al.* (2006) used a fibreglass dugong model and the dive profiles of 15 dugongs to improve this method. However, it is likely that dive behaviour of dugongs is influenced by water clarity, tidal conditions and water depth, and that the dive behaviour of individual dugongs within a herd is not independent. Dive behaviour in dugongs is also modified by perceived predator risk (Wirsing *et al.* 2011).

It has recently been argued that systematic variation in dive profiles could lead to biased aerial survey estimates in areas with heterogeneous bathymetry (Hagihara *et al.* 2013). Based on the dive profiles of nine satellite tracked dugongs (five in Hervey Bay and four in Moreton Bay), Hagihara *et al* (2013) found that dugongs were less likely to be in a surface ‘detection zone’ when they were in areas of intermediate depth (5-25 m depth) than when they were in shallower or deeper areas.

An important consequence of the variability and inaccuracy in density estimates from aerial surveys is that only a large change in abundance can be detected, and that small declines (or increases) over time are likely to be missed (Taylor *et al.* 2007). Based on a sampling precision of 11 per cent, Marsh and Saalfeld (1989) estimated that ten annual surveys would be required to detect a decline of five per cent per annum in the northern Great Barrier Reef with a 95 per cent confidence. On this basis, it was recommended that surveys be conducted at large spatial scales and at a minimum of five-year intervals, to minimise spatial and temporal errors, respectively (Marsh and Saalfeld 1989).

Where the accuracy of quantitative estimates for marine mammals is limited, an alternative approach to management involves a conservative estimate of the mortality rate expected to lead to a decline, rather than detecting the decline itself (Wade 1998). This approach, known as Potential Biological Removal (PBR), relies on an estimate of the abundance of dugongs, an estimate of the variability in abundance and an estimate of the maximum rate of population increase (R_{max}). It is a precautionary approach that (1) incorporates uncertainties in marine mammal survey data, (2) is based on parameters that can be estimated, and (3) facilitates prompt management decisions (Taylor *et al.* 2000).

Another approach is to model the risk that a dugong population falls under a critical value in a specified time period using various management scenarios (Heinsohn *et al.* 2004). This approach is known as Population Viability Analysis (PVA) and uses estimates of variation in demographic parameters to simulate stochastic processes and to predict the probability of demographic extinctions (Boyce 1992). Correspondence between model predictions and reality can be poor (e.g. Lindenmayer *et al.* 2000), although some authors argue that PVAs might still be useful in comparing relative risks associated with different management actions (Brook *et al.* 2000; McCarthy *et al.* 2000). PVA is known to be very sensitive to minor errors in demographic parameters, such as observational errors, and is based on the premise that environmental conditions and the distribution of demographic parameters are constant throughout the simulated time period (Coulson *et al.* 2001; Sinclair *et al.* 2006).

Currently the most serious limitation to modelling dugong population dynamics is the lack of empirical data on dugong survival (Marsh *et al.* 2011). This is an issue that can only be realistically addressed with long-term Capture-Mark-Recapture (CMR) studies. Until these data are obtained, approaches such as PVA and PBR should be considered tentative (Marsh *et al.* 2011). Nevertheless, because PBR has been the main tool used to estimate the risks posed to dugongs from anthropogenic mortality to date (Lanyon 2003; Marsh *et al.* 2004), it is calculated for the purposes for this review.

Although not based on population dynamics, another approach to monitoring dugongs is based on the relative density of dugongs as a proxy for habitat utilisation (Grech 2009). Aerial survey datasets are used to generate maps of the relative density of dugongs, by spatial interpolation to a 2 x 2 km grid (Grech 2007). This approach has the advantage of being directly amenable to spatial risk assessment (Grech and Marsh 2008) and in informing spatial conservation management (Grech *et al.* 2011), but does not support quantitative assessments of population trends or sustainable mortality rates.

History of dugong population estimates in southern Queensland

The first written accounts of dugongs in Moreton Bay were recorded by Flinders in 1799 (Flinders 1814), although he thought at the time that he was describing sea lions. Many of the earlier written accounts of dugongs in southern

Queensland were in relation to the commercial dugong fishery (Thorne 1876; Welsby and Thomson 1967; Lergessner 2007). Dugongs in Queensland were commercially hunted between 1847 and 1969, primarily to support an industry for medicinal dugong oil (Cilento *et al.* 1959; Daley *et al.* 2008). The commercial dugong industry in southern Queensland has been reviewed in detail by a number of authors (Thorne 1876; Welsby and Thomson 1967; Peterken 1994; Lergessner 2007; Daley *et al.* 2008). Historical accounts of traditional Indigenous hunting in southern Queensland were reviewed by Lergessner (2007), although the magnitude of this hunting before European settlement is unknown.

Historical records of landings and exported oil from the commercial dugong fishery in Queensland have been analysed for population trends by Peterken (1994) and Daley *et al.* (2008). It is important to note that even when records of reported landings or exported product are accurate and complete, they are not necessarily directly representative of abundance because they are also a function of catchability and effort. The relationship between abundance, catchability and effort for this fishery is unknown, and there are numerous examples from fisheries indicating substantial non-linearity in the relationship between these variables (e.g. Rose and Kulka 1999; Zhou *et al.* 2007). Nevertheless, at a more course analytical scale, low catches with high fisheries effort are indicative of low dugong abundance, and high catches with low effort are indicative of high dugong abundance. In general, effort for dugong fisheries in southern Queensland has increased at times when there has been a market for dugong oil (Thorne 1876; Welsby and Thomson 1967; Peterken 1994; Lergessner 2007; Daley *et al.* 2008).

The first attempts at quantifying the abundance of dugongs in southern Queensland using aerial surveys took place in Moreton Bay in the 1970's (Heinsohn *et al.* 1978) and in Hervey Bay in the 1980's (Preen and Marsh 1995) .

Timeline of dugong abundance estimates in southern Queensland

- **1830-1860:** dugongs were one of the earliest marine species to be exploited by the Europeans after their arrival in Moreton Bay in the 1820's (Peterken 1994). By the 1830's a small non-indigenous dugong fishery commenced at Amity on North Stradbroke Island. In the 1840's land was cleared at St Helena Island, near the mouth of the Brisbane River for a dugong fishery station. The first official mention of the industry occurred in 1847 (Lergessner 2007). The St Helena fishery was reported to have caught around two dugongs per night in nets placed across channels leading to foraging areas around the Island between September to March (Lergessner 2007). This first commercial enterprise closed in 1859 because of the "intemperance of the men employed" (Thorne 1876) and because the dugong oil was adulterated with shark livers and other animal fats (Lergessner 2007). The dugong oil industry in the Hervey Bay-GSS area was established at Tin Can Bay in 1850.

- **1860-1880:** The St Helena Island dugong oil fishery was re-opened in 1862 and closed 1869, again because of adulteration of the oil (Lergessner 2007). Small-scale dugong fisheries continued throughout the period. The other main fisheries were the government sponsored indigenous fishery on Bribie Island (1877-79) and Amity, on North Stradbroke (Lergessner 2007). By 1876, three dugong fishing stations were established in the Hervey Bay region. Thorne (1876) discussed the story of fishermen in Hervey Bay observing dugongs passing their boat, which were presumably on their way to tidal foraging areas. Over a period of 3 to 4 hours the fishermen observed what Thorne estimated to be a herd of several thousand dugongs, based on the fact that it was '0.5 miles wide and 3-4 miles long' (~3.9 to 5.2 km^2). Thorne (1876), in his exhortations of the value of the dugong industry, described the dugongs as "vast herds of dugong that came in and went out with the tide". Peterken (1994) analysed Queensland dugong oil export records between 1859 and 1909, and estimated that the peak harvesting rate occurred between 1870-79 when oil equivalent to approximately 125 dugongs was exported. In 1878, concerns over the scarcity of dugongs for the dugong oil industry in Hervey Bay-GSS were voiced the in the *Maryborough Chronicle* (Peterken 1994), to the Harbours and Marine Department (Lergessner 2007).

- **1880-1900:** dugong fishermen in 1884 reported low catch rates in Moreton Bay, which was attributed at the time to seagrass loss from oyster dredging (Lergessner 2007). In 1887 the *Queensland Fisheries Act 1887* (Qld) gave the government the powers to prohibit or restrict dugong fisheries. A two-year closure of the dugong fishery in Moreton Bay and between Cape Conway and Palmerston was introduced in September 1888, because of concerns about sustainability of the industry (Peterken 1994). Floods occurred in the Mary and Brisbane Rivers in March 1890 (Peterken 1994). After the ban was lifted only three dugongs were reported to have been caught in 1891, but it was observed that there was a herd of between 300 and 400 on the Eastern Banks near Mud Island (Lergessner 2007). Gear restrictions and license fees were introduced in 1891-92 (Lergessner 2007). By 1892, 46 dugongs were reported to have been caught in Moreton Bay (Lergessner 2007). Major floods occurred in the Brisbane River (draining into Moreton Bay) and the Mary River (draining into Hervey Bay) in February 1893. In July 1893, the dugong fishermen Fred Campbell observed a herd of dugong covering an area of approximately 1.3 km^2 (300 yards wide and 3 miles long) at the western entrance of the Rous Channel in Moreton Bay. This story was later recorded by Welsby (Welsby and Thomson 1967). Fred thought that the herd included several hundred foraging dugong with around 20-30 breathing at the surface at any given time. A second two-year closure was introduced on October 1893 (lifted in April 1894).

Towards the end of the 1800’s a dugong fishery at Burrum Heads commenced and lasted until the 1960’s (Peterken 1994).

- **1900-1930:** intermittent landings in the dugong fishery of Moreton Bay between 1900 and 1920s were attributed to a collapse in the market, because of contamination of dugong oil (1902), bad weather (1908) and the scarcity of dugongs (1909) (Daley *et al.* 2008). It has also been speculated that there may have been seagrass loss following a major flood in the Brisbane River in March, 1908 (Peterken 1994). Harbours and Marine Department reported a decline in the dugong fishery between 1908 and 1912 because of a scarcity of dugongs (Peterken 1994). Catches of dugongs were not included in the annual Queensland fisheries reports between 1912 to 1929. Welsby (Welsby and Thomson 1967) noted a herd of around >80 dugongs near the Rainbow Chanel in Moreton Bay during 1928. An analysis of anecdotal accounts indicated that a small revival in the fishery took place during World War I, prompted by shortages of cod liver oil, and that only limited fishing continued during the 1920’s (Daley *et al.* 2008).

- **1930-1960**: By 1935, Hervey Bay was the focus of the southern Queensland dugong fishery (Anon. 1936; Daley *et al.* 2008). In the 1930’s elevated catches were attributed to increased effort (Daley *et al.* 2008) and to the take in the fishery further north at Burrum Heads in Wide Bay (Lergessner 2007). The Bilsborough fishery at Burrum Heads was reported to have taken large annual catches from the 1930’s to the 1960’s, although officially reported landings and anecdotal reports from dugongers are conflicting (Peterken 1994; Lergessner 2007). Few data are available for Moreton Bay between 1940 and 1960. Lergessner (2007) reported that between 1940-50, Harbours and Marine deliberated over providing protection for dugongs, but that there appeared to be “such an abundance that plans were shelved”. Anecdotal observations by a former fisheries biologist suggested that the abundance of dugongs in Moreton Bay between 1948 and 1960 was similar to contemporary levels (Ern Grant, *in litteris*, 5 September 2012).

- **1960-1970:** the dugong fishery continued in the Hervey Bay region to 1965 (Peterken 1994) and to 1969 at Burrum Heads (Lergessner 2007). Commercial dugong fisheries were prohibited on March 20, 1969 by a Queensland *Order of Council* which amended the *Fisheries Act 1957-1962*. The basis of this was strong and growing public opposition to the killing of dugongs (Ern Grant, *in litteris*, 5 September 2012), rather than any biological concerns about the status of the stock(s). Few records of abundance were available for this period, but an account of a herd of between 40-80 dugongs feeding in central Moreton Bay in 1965 was reported (Bertram and Bertram 1973).

- **1970-1980**: In the early 1970’s, Bertram and Bertram (1973) wrote that dugong populations in southern Queensland were rebuilding, although no data were presented. For Moreton Bay, they stated that “there is an impression of increasing numbers again” (Page 311, Bertram and Bertram 1973), for Hervey Bay they reported “fair numbers, perhaps increasing” and for Maryborough (GSS), they reported “fair numbers from here northwards and possibly increasing” (Page 312, Bertram and Bertram 1973). Widespread, major flooding occurred throughout southern Queensland in January 1974. The mid 1970’s marked the beginning of aerial surveys of dugong abundance. It was estimated from 16 monthly aerial surveys between 1976 and 1977 that at least 300 dugongs occurred in Moreton Bay (Heinsohn *et al.* 1978) (Table 2). This was reported at the time as a re-discovery of a large dugong population that had been considered to be depleted (Heinsohn *et al.* 1978). Most dugongs were sighted on the sandbanks to the west of the South Passage (Marsh 2002), but one dugong was seen within 3.5 km of the western shore of Moreton Bay and others were seen in the centre of Moreton Bay (Heinsohn *et al.* 1978).

- **1980-1990**: the first quantitative aerial survey of the whole of Moreton Bay was conducted in August 1988 (Marsh *et al.* 1990), and resulted in an estimate of 458 ± 78 SE (Standard Error) dugongs. Between July 1988 and February 1990, 28 standardised aerial surveys were conducted and suggested that the area supported a year-round population of between 500 and 569 individuals (Preen 1992; Marsh 2002). 1988 also marked the first quantitative aerial survey of dugongs in the Hervey Bay-GSS region, when the population was estimated to be 2206 ± 420 SE (Preen and Marsh 1995) (Table 1).

- **1990-2000**: in 1992, two floods and a cyclone resulted in the loss of approximately 1000 km^2 of seagrass from Hervey Bay (Preen and Marsh 1995; Preen *et al.* 1995). A total of 99 dugong carcasses were subsequently recovered and the prevalence of silt, algae and dead seagrass rhizomes in stomachs of dead dugongs suggested a shortage of preferred food items (Preen and Marsh 1995; Marsh *et al.* 2011). Elevated numbers of stranded dugongs were also later reported along the northern and central New South Wales coasts (Preen and Marsh 1995). An aerial survey conducted approximately eight months after this extreme weather event, in November 1992, suggested that most dugongs in southern Hervey Bay had moved into the GSS (Preen and Marsh 1995). Preen and Marsh(1995) also suggested that dugongs may have migrated further to Moreton Bay in response to the seagrass loss because an aerial survey in April 1993 counted 664 dugongs in Moreton Bay (uncorrected data, Preen and Marsh 1995), which represented an increase from earlier surveys (Table 1, Figure 5).

In December 1993, 21 months after the floods, the regional dugong population in Hervey Bay-GSS was estimated to be between 579 and 629 (Table 1). The number of dugongs in the subsequent aerial survey of Hervey Bay-GSS in 1999 (Table 1) suggested an increase in population size that could not be explained by population growth in a closed population, which further supported the interpretation that dugongs had migrated away from Hervey Bay-GSS and had subsequently returned. The results of aerial surveys also suggested that the events of 1992 may have impacted on the reproductive dynamics of the population. Prior to the floods and the cyclone, it was estimated that approximately 22 per cent of the dugongs in the Hervey Bay-GSS region were calves, compared to approximately 2.2 per cent afterwards (in 1993).

Aerial surveys undertaken in 1995 by Lanyon (2003) suggested that the population in Moreton Bay may have been even larger than that suggested by Preen (1995). The 1995 surveys were conducted at two-month intervals throughout the year, with population estimates from 503 to 1019. This study featured much higher sampling intensity than the early studies, especially in areas known to be frequented by dugongs. Lanyon (2003) compared her survey design with that used by Preen (1992) by conducting one survey with each method on the same day. She counted 239 dugongs with the Preen (1992) survey design compared to 630 with the new survey design, suggesting that the earlier surveys may have underestimated dugong abundance in Moreton Bay.

In May 1996, much of the catchment of Moreton Bay experienced an approximately one-in-twenty year rainfall event, which deposited a large load of sediment and dissolved organic material into the bay (Moss 1998). No aerial surveys were conducted at the time. Approximately 15 km^2 of seagrass meadows were lost in the area of Deception Bay (north west side of Moreton Bay). Major seagrass loss occurred in the GSS and in intertidal and shallow subtidal areas of Hervey Bay following flooding of the Mary River in February 1999 (McKenzie 2000).

- **2000-2005**: an outbreak in the filamentous cyanobacteria *Lyngbya majuscule* on the Eastern Banks of Moreton Bay in March 2001 prompted aerial surveys in Hervey Bay-GSS and Moreton Bay in April and November 2001 (Lawler 2002). The apparent decline in the estimated number of dugongs between the mid 1990's and early in the 2000's in Moreton Bay (Figure 6) may have been related to slightly different survey designs, reduced dugong abundance or emigration. Substantially more dugong were also counted in the November surveys of 2001 than in the April surveys in both Hervey Bay-GSS and Moreton Bay (Figures 5 and 6), highlighting how seasonal variation can influence aerial survey results. Seagrass surveys in 2002 indicated that most seagrass lost in the Hervey Bay-GSS region had recovered from losses in the 1999 floods (McKenzie and Campbell 2002; Campbell and McKenzie 2004).

- **2005-2011:** by 2005, aerial survey estimates of dugongs in both regions were similar to those made in 1988 (Hervey Bay) and the Preen surveys in the 1990's for Moreton Bay (Table 1, Table 2). A sharp rise in the southern oscillation index (SOI) late in 2009 heralded major floods in southern Queensland in the summer of 2010-11. Eight months after these floods it was estimated that 17 per cent of dugongs were in poor condition (Lanyon *et al.* 2011, as cited by Sobtzick *et al.* 2012) and a record number of stranded dugongs were reported both in Moreton Bay and on the east coast of Queensland (Meager and Limpus 2012). In November 2011, the estimated number of dugongs in Moreton Bay was 883 ± 68 which represented nearly twice that of 2005 (454 ± 41 SE) (Sobtzick *et al.* 2012). An increase of this magnitude is unlikely to be explained by population growth in a closed population, implying that dugongs migrated into Moreton Bay. Proportionally fewer dugongs were sighted in the north western side of Moreton Bay in the aerial surveys of 2011 than in the aerial surveys of 2005 (Sobtzick *et al.* 2012), suggesting that some dugongs also migrated to the Eastern Banks (Figure 1) from other areas of Moreton Bay. The proportion of dugongs sighted with calves in Moreton Bay (8.5 per cent) and Hervey Bay (9.7 per cent) in the November 2011 was within the normal range (Sobtzick et al. 2012).

  Seagrass meadows of the Eastern Banks of Moreton Bay were not as strongly impacted by the 2010-11 floods as in other areas on the east coast of Queensland. The Eastern Banks received an 'A-' rating eight months after the floods from the Healthy Waterways ecosystem health monitoring program, compared to an 'A' ranking before the floods (data from www.health-e-waterways.org). The eastern side of Moreton Bay has a predominantly oceanic influence, whereas three major river systems, the Pine, Brisbane and Logan-Albert Rivers discharge turbid water into the western and southern sides of the Bay (Abal and Dennison 1996; Davie and Hooper 1998). The western side of Moreton Bay also has relatively weak currents compared to the eastern side, resulting in an east-west gradient in water clarity (Abal and Dennison 1996 and references therein). This suggests that the eastern side of Moreton Bay may be an important refuge for dugongs in southern Queensland during floods.

  Inshore seagrass sites adjacent to Hervey Bay were assessed as being in fair to poor condition following the 2011 floods (Data from Seagrass Watch, http://seagrasswatch.org/hervey_bay.html; accessed 20 March 2013).

At a monitoring site at Burrum Heads, where dugong feeding trails are frequently seen, seagrass cover was at levels similar to 2000. Seagrass meadows throughout the GSS region were assessed as fair in abundance in 2010, and have been variable since 1999 (Data from Seagrass Watch, http://seagrasswatch.org/GreatSandyStrait.html; accessed 20 March 2013).

Analyses of historical population trends

Marsh and colleagues (2005) discussed how historical anecdotal reports of the densities of dugongs extrapolated over a larger region can result in gross over-estimates of dugong abundance. One striking example is when anecdotal reports from the late 1800's (1876 in Hervey Bay and 1893 in Moreton Bay) were used in conjunction with a measure of density from a single aerial photo of a dugong herd to estimate the historical abundance of dugongs in Eastern Australia and Moreton Bay (Jackson *et al.* 2001). On this basis, Jackson and colleagues (2001) then went on to estimate a >208 fold decline of dugongs in Moreton Bay, based on an estimate of >104,000 dugongs in the late 1800's. They estimated the Hervey Bay population comprised of 357,000 individuals, and an 74 per cent decline of the population between Brisbane and Torres Strait, based on an estimate of between 1×10^6 and 3.6×10^6 in the 1800s compared to the aerial survey estimates of the 1990's. The historical estimate of dugong abundance in Moreton Bay in 1893 should be placed in an historical and ecological context, because it (1) occurred five months after a major flood in southern Queensland, and (2) the estimate was from a commercial dugong fisherman during a time period when there was presumably debate about whether the fishery should be closed (during a time period following the first closure of the dugong fisheries and months prior to the second closure of the dugong fishery).

An alternative approach has been to hindcast aerial-survey estimates based on the temporal trend of QSCP bycatch (Marsh *et al.* 2001; Marsh *et al.* 2005). The QSCP targets large sharks which are considered to be potential dangerous to humans using baited drumlines and large-mesh nets. Dugongs are occasionally incidentally caught as bycatch in nets and very occasionally caught on drumlines. In southern Queensland, nets have been used on the Sunshine Coast and Gold Coast since 1962, at Rainbow Beach since 1974, between 1974 and 1976 at Bundaberg and between 1974 and 1979 on North Stradbroke Island (Paterson 1990). Marsh *et al.* (2001, 2005) fitted a log-linear model to the 1962-1999 dataset. Based on the assumption that there has been a constant relationship between QSCP bycatch and the abundance of dugongs, they then used a composite aerial survey estimate of dugongs from the mid 1990's (4220, 95 per cent confidence intervals from 2360 to 8360) to estimate that there were 72,000 dugongs in the region between Cairns and the New South Wales border in 1962, with 95 per cent confidence intervals from 31,000 to 165,000. The 1962 hindcast estimate was based on a number of assumptions, such as (1) the likelihood of dugong entanglement is directly correlated to dugong density across the region, (2) the catchability coefficient is constant across the time period (i.e. the extent to which dugongs are vulnerable to entanglement) and (3) the composite aerial survey estimate in the 1990's was accurate. In southern Queensland, the long-term data for the Sunshine and Gold Coasts were included in this analysis (Figure 2). No clear trend was evident on the Gold Coast (Figure 2). The peak of dugong bycatch in the early 1980's was attributed to possible movements of dugongs in or through the area in response to extreme weather events of 1980 and 1982 (Marsh *et al.* 2005). On the Sunshine Coast, a decline was evident (Figure 2).

For the current review, the Department of Agriculture, Fisheries and Forestry (DAFF) QSCP data were re-analysed using an additional 13 years of subsequent data (1962-2012, Figures 3 and 4). In the present analysis, bycatch was standardised by nominal fishing effort, because of numerous changes in the number of nets deployed per beach and region prior to the 1990's. Nominal fishing effort represented the total number of nets deployed per region and month, averaged over each year. Dugongs caught or entangled on drumlines were not analysed because these events were rare. Because the data were sparse over beaches and months (i.e. dugongs were not caught on all beaches in all months of the year), the total annual catch over each region was aggregated. The first year (1962) was not included in the analysis because bottom-set monofilament nets were initially used before being replaced by surface-set nets (Gribble *et al.* 1998) and there was likely to have been considerable experimentation with gear placement in the initial phase of the program. Only data on the Sunshine Coast were modelled because dugong bycatch was low and variable on the Gold Coast (Figure 3c). The overall trend of catches for the entire region of southern Queensland is given by Figure 3a, but this dataset was not analysed separately because there have been numerous major changes in gear deployment in regions such as Rainbow Beach, North Stradbroke Island and Bundaberg.

A generalised additive model fitted to the annual, standardised bycatch on the Sunshine Coast indicated a decline in bycatch prior to ca. 1980 and stable bycatch rates between 1980 and 2012 (Figure 4). There are, however, several caveats to the long-term population trends implied from the QSCP bycatch. Firstly, as discussed earlier, dugongs caught on the Sunshine Coast are likely to be migrating between major habitat areas because shark nets are not set close to dugong habitats in this region. To this end, the high rate of net entanglement in the QSCP on the Sunshine Coast recorded in the early years of the QSCP could be explained by a number of factors that are not necessarily mutually exclusive, such as (1) higher rates of movements between Moreton Bay and Hervey Bay-GSS prior to 1980 than after 1980, (2) decreased catchability of dugongs since 1980 (i.e. dugongs are equally abundant but less likely to be caught because of changes to net configuration or net placement), or (3) higher densities of dugongs in southern Queensland in the early 1960's.

Ultimately, it is the productivity of preferred seagrasses that determines the number of dugongs that a given area can sustain. Dugongs consume significant quantities of seagrass each day (Preen 1992; Aragones 1994) and knowledge of the biomass, productivity and recovery times of seagrass can be used to estimate the maximum carrying capacity of an area (Marsh *et al.* 2005). Using this approach, Marsh *et al.* (2005) concluded that contemporary dugong habitat between 16.5°S and 28°S was unlikely to have been able to support the number of dugongs in their hindcast estimate, which suggested that they either overestimated the number of dugongs in 1962 or that the carrying capacity of the region has reduced since.

More realistic estimates of carrying capacity should incorporate competition and other density-dependent processes, which act both within and between species. Other species utilising the same resources include green turtles, fish and invertebrates (O'Brien 1994; Lanyon *et al.* 1989; Limpus 2009). Aside from competition for resources (which reduces carrying capacity), positive feedbacks have also been observed where intense grazing by dugongs may act to increase the abundance of preferred seagrass species at the expense of less preferred species (Preen 1992), or modify the nutritional quality of preferred species (Aragones *et al.* 2006). Such ecosystem dynamics could be addressed by a mass-balance trophic approach (Pauly *et al.* 2000; Castelblanco-Martínez *et al.* 2011) or an ecosystem model.

Evidence for a decline in dugong abundance in southern Queensland?

In Moreton Bay, the overall trend in the aerial survey data (Figure 5) suggests a possible increase in the dugong population since the first surveys in 1976 and the first quantitative surveys in the 1980's, but this cannot be rigorously tested statistically because of changes in survey methods throughout the period. In particular, surveys in the 1970's were likely to have underestimated dugong abundance because they were not as comprehensive as later surveys (as discussed in Lanyon 2003). This suggests a downwards bias in the aerial surveys prior to 1988. Similarly, the Preen (1992) and Preen and Marsh (1995) surveys in the late 1980's and early 1990's did not use the Marsh and Sinclair (1989b) bias correction nor had the same coverage as later surveys, and were therefore also likely to be downwards biased. This is likely to be the reason for the apparent increase in dugong abundance between 1976 and 1995 evident from the aerial survey data (Figure 5). The net result is that there is no evidence of a systematic change in the dugong population in Moreton Bay since 1976 based on the aerial survey data**.** Based on the dataset of comparable quantitative aerial surveys between 1995 and 2011, the estimated number of dugongs has varied markedly around an average of 653 with estimates between 344 (in 2000) to 1019 (in 1995) (Table 1). An ordinary least squares (OLS) linear regression fitted to this dataset indicated no significant population trend (b=-0.004 ± 0.035 SE; r^2 = 0.0015, df=10; p = 0.91). The QSCP data also suggest that the Moreton Bay population has been stable since 1980 (Figure 4).

Prior to 1980, evidence is more scarce and inconsistent. The decline between 1963 and 1980 suggested by the QSCP on the Sunshine Coast (Figure 4) is at odds with the anecdotal report by Bertram and Bertram (1973) which suggested that dugong numbers in Hervey Bay and Moreton Bay were increasing. Published transcripts in study of the oral history of commercial fishing in south-east Queensland were also reviewed (Anon. 2002). One Moreton Bay fisherman (1953/4-1997) said that he thought dugong populations had rebuilt since the 1960's.

Fewer data or anecdotal observations are available for the Hervey Bay-GSS region, but again, there is no evidence of a systemic change in dugong abundance since aerial surveys commenced in the 1980's (Figure 6). Estimates of dugong abundance from aerial surveys have varied over the time period, with an average of 1495 dugongs and estimates between 579 and 2547 (Figure 5). No significant trend was evident from an OLS regression (b=48.3±31.8 SE; r^2 = 0.22; df= 8; p = 0.167). The regression slope was influenced by the trend of population increase between 1993 and 2005 (Figure 6), but the analysis had very low power because of the high variability in population estimates within and between years. The dugong population estimate in 1988 was within the range of the dugong population estimate made in 2005 (Figure 6).

Based on the assumption that Hervey Bay-GSS and Moreton Bay constitute a single stock (i.e. Scenario 2), aerial surveys that were undertaken at both locations within a four-month period were combined to estimate the overall trend in the putative southern Queensland population over time (Figure 7). Overall, a decline was not evident across this time series because abundance estimates in 1988 were similar to those of 2005-2011 (i.e. 95 per cent confidence intervals overlapped, Figure 7). No significant linear trend was evident from an OLS regression (b=26.1±40.5 SE; r^2 = 0.094; df= 4; p = 0.55), but there was again high variability within and between years, and few data points. There were insufficient years of data to fit a non-linear model, but estimates appeared to decline between the mid 1990's and 2001, followed by a steep increase between 2001 and 2005 (Figure 7). This apparent increase in dugong abundance between 2001 and 2005 exceeds predictions based on maximum natural population growth (i.e. five per cent, Marsh *et al.* 2004), indicating either (i) uncertainty in the aerial survey estimates, or (ii) immigration into the southern Queensland region from elsewhere. In regards to (ii), it is possible that the southern Queensland dugong stock is connected to dugong populations further north, or that dugongs temporarily migrate out of the region. In support of this argument, a dugong tagged in Hervey Bay was later relocated 485 km north at Clairview near Shoalwater Bay (Sheppard *et al.* 2006) and two dugongs tagged in Shoalwater Bay were relocated at Hervey Bay (Preen 1999, as cited by Marsh 2002), suggesting potential connectivity with dugongs in central Queensland. Compared to southern Queensland relatively few quantitative data are available for dugong abundance in central Queensland, but a substantial population is found in the Shoalwater Bay region (Bertram and Bertram 1973; Anderson and Birtles 1978; Sobtzick *et al.* 2012). A study of population genetic differentiation in east Queensland is currently ongoing (Blair 2012), and will hopefully shed light on connectivity between dugong populations throughout the region.

Has the distribution of dugongs in southern Queensland changed?

Although there were no systematic surveys of dugongs in Moreton Bay prior to the 1970's, several authors have noted that historical observations indicate that dugongs were once more common on the western and southern sides of Moreton Bay early in 1900's than is presently the case (Preen 1992; Lanyon 2003; Chilvers *et al.* 2005). This is probably because of historical losses of seagrass from the western and southern sides of Moreton Bay (Abal *et al.* 1998). It was estimated in 1998 that approximately 20 per cent of seagrass had been lost from Moreton Bay since European settlement (Kirkman 1978; Abal *et al.* 1998). Most urbanisation has occurred on the western shore of Moreton Bay (Pressland *et al.* 1998), and the western and southern sides of Moreton Bay are also under much stronger estuarine influence than the predominantly oceanic eastern side (Abal and Dennison 1996; Davie and Hooper 1998). Proportionally fewer dugongs were sighted in the north western side of Moreton Bay in the post-flood aerial surveys of 2011 than in the aerial surveys of 2005 (Sobtzick *et al.* 2012), suggesting that the eastern side of the Bay may be utilised more frequently by dugongs after floods.

Few data on historical changes in seagrass (or dugongs) since European settlement are available for Hervey Bay-GSS. The seagrass distribution was first mapped in the GSS region in 1973 and 1988 in Hervey Bay, but it is difficult to identify changes in seagrass cover over time because of the different mapping techniques and extent of ground truthing prior to 1998 (McKenzie 2000).

Has anthropogenic mortality exceeded Potential Biological Removal (PBR) limits in southern Queensland?

PBR limits were calculated from corrected aerial survey data and were compared with records of human-induced mortalities in southern Queensland in years where comprehensive data were available (after 1996). Records of dugong mortalities in southern Queensland were obtained from StrandNet (https://www.derm.qld.gov.au/strandnet/application), which is a database of sick, injured, debilitated or dead marine wildlife managed by EHP in collaboration with the Department of National Parks, Recreation, Sport and Racing (NPRSR) and the Great Barrier Reef Marine Park Authority (GBRMPA). StrandNet receives reports from the Queensland Shark Control Program (QSCP) from the Department of Agriculture, Fisheries and Forestry (DAFF). It is acknowledged that most indigenous hunting of dugongs is not reported to StrandNet. Dugong hunting by Aboriginal or Torres Strait Islander people is allowed in Queensland under various state and Commonwealth laws and is reported voluntarily. Illegal hunting is generally only reported when it is encountered by NPRSR and GBRMPA staff. It is also acknowledged that not all carcasses can be recovered and that the cause of death cannot always be determined, especially when carcasses are too decomposed and/ or when they occur in remote locations and cannot be recovered for necropsy. Further, human-related mortalities such as net entanglements can be difficult to identify without detailed necropsies. Nevertheless, it is unlikely that a large number of dugong carcasses in southern Queensland have not been reported, due to the proximity of dugong habitats to urbanised areas and the amount of vessel traffic in this region.

As discussed earlier, there is also considerable uncertainty in aerial survey estimates. In light of this uncertainty and the aforementioned potential for underestimating anthropogenic mortality, a recovery factor of 0.5 was used in PBR calculations (following the recommendations of Wade 1998 and Taylor *et al.* 2000). A precautionary range of R_{max} from 2 to 4 per cent was also used because R_{max} has not been explicitly estimated for Moreton Bay. This analysis indicated that PBR limits were not reached in either Moreton Bay or Hervey Bay-GSS during 2011 (Figure 8). Under Scenario 1 (i.e. discrete populations), anthropogenic mortality levels in Moreton Bay reached PBR trigger limits in 2000 and exceeded the lower PBR limits in 2005 (Figure 8a). In both of these years, three dugongs were reported to have been killed by human-related activities, which included interactions with vessels (two), entanglement in a fisheries net (one), hunting (one) and entanglement in nets used in the QSCP (two) (Table 4). PBR limits in Hervey Bay-GSS were not reached in the four years for which both StrandNet data and aerial survey data were available (Figure 8b).

Under Scenario 2 (i.e. the Moreton Bay and Hervey Bay-GSS region represents a single stock), PBR limits were not reached in the three years for which aerial survey and StrandNet data were available for both regions (Figure 8c). This was because of the larger population estimates and lower rates of mortality in the Hervey Bay-GSS region (Figure 8b).

Dugong mortalities associated with human activities in southern Queensland are generally low, given the size of human populations in these areas and the intensity of activities such as recreational boating. In the 16 year period between 1996 to 2011, the main source of anthropogenic mortality was from vessels (vessel collisions and propeller cuts), with a total of eight vessel-related mortalities in the Hervey Bay-GSS region and 21 vessel-related mortalities in the Moreton Bay region (Table 3, Table 4). Within the same 16 year time period, only two mortalities in the Moreton Bay region and three in the Hervey Bay region were reported to have been associated with fisheries-related activities (Table 3, Table 4). The QSCP and indigenous hunting were the other main sources of anthropogenic mortality in southern Queensland, although hunting is likely to have been under-reported. The highest levels of annual anthropogenic mortality occurred in 2002 for the Moreton Bay region (seven), and during 1997 and 2001 for the Hervey Bay-GSS region (three). Analysing the effectiveness of existing conservation management for dugongs in southern Queensland was not the objective of the current review. A detailed analysis of the impacts of vessel traffic on dugongs should take into account the sub-lethal impacts of behavioural disturbance and vessel noise, and requires an integrative approach that considers aspects such as how often dugongs are disturbed and how they might compensate for disturbance (Ellison *et al.* 2012; New *et al.* 2013).

Conclusion

Southern Queensland supports a large population of dugongs of considerable conservation importance (Marsh 2002). The proximity of these dugongs to large human populations necessitates continued management to reduce the risks of anthropogenic mortalities, but there is no evidence to suggest that the dugong population in Hervey Bay-GSS or Moreton Bay has declined since 1980. Both aerial survey datasets and QSCP bycatch suggested that the population in Hervey Bay-GSS and Moreton Bay has been stable since 1980.

Historical accounts (i.e. comments from dugong fishermen and closures of the fishery) provided some support for the contention that the abundance of dugongs in southern Queensland was reduced by the commercial dugong fisheries which peaked in the 1870's. Evidence for population trends between 1900 and 1960 is more circumstantial, but suggests periodic fluctuations in the number of dugongs, possibly related to climatic events and/or variation in seagrass density (Marsh *et al.* 2011). QSCP bycatch on the Sunshine Coast suggested a decline in dugong abundance between 1963 and 1980, but this is not supported by anecdotal reports from fishermen and marine scientists for the same time period.

It is important to recognise that even if accurate estimates of pre-European dugong abundance in southern Queensland were available, it is unlikely that contemporary seagrasses would have the same carrying capacity, given the decline of seagrass cover in areas such as western Moreton Bay. In order to address this issue, detailed estimates of the biomass of preferred seagrass species in Hervey and Moreton Bay would be required, particularly for deeper areas. Ideally, this approach would be combined with dynamic ecosystem modelling to estimate a realistic carrying capacity and maximum sustainable population for a given time frame.

At present, there are two major limitations to informed population management of dugongs in southern Queensland:

1) **Population structure.** Populations should be delineated at an appropriate spatial scale, both genetically and demographically. Without this understanding, local declines in the density of dugongs may be interpreted erroneously as losses from mortality or reduced recruitment rather than emigration. This is particularly salient to southern Queensland because Hervey Bay-GSS has the largest population in East Australia south of Cape York (Marsh 2002). If this population is connected demographically and genetically to Moreton Bay, it would act to 'buffer' losses from the smaller population, or from the perspective of meta-population dynamics, may act as a 'source' for the smaller 'sink' subpopulation. Limits for anthropogenic mortality (such as PBR) designed to trigger management responses would therefore be overly conservative. On the other hand, if movements of dugongs between these areas are limited, immigration may not be sufficient to counter local population declines and populations would be largely controlled by internal demographic processes. In this case, populations would be best managed as separate units.

2) **Quantitative abundance estimates:** Aerial survey data remain inaccurate in areas with heterogeneous bathymetry/ low water clarity. Further refinement of the aerial survey approach, particularly with regards to the availability bias correction factor is required. Continual refinement of the availability correction factor emphasizes the need for raw survey data to also be provided. Under the assumption that counts are accurate (e.g. dugongs are not counted more than once), raw aerial survey data provide a true minimum population size.

In conclusion, dugongs are listed as vulnerable in Queensland and there are no separate listings on a population-by-population basis. Even so, there is no evidence to suggest that dugong populations in southern Queensland fulfil any of the criteria for more stringent protection under the *Nature Conservation Act 1992.*

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Table 1. Summary of quantitative and semi-quantitative surveys of dugong abundance in Moreton Bay, Queensland. Aerial survey heights are provided for comparison, although Marsh and Sinclair (1989a) found no significant difference between estimates from 137 and 274 m. *, standard errors were estimated from raw aerial survey data. ?, unknown.

Year and month	Estimate (±SE)	Method	Bias corrections	Source
1976, May	283	Aerial survey, western edge of Moreton Is and North Stradbroke Is, plus transects of the Eastern Banks. Included the area east of South Passage.	No	Lear 1976; as cited by Preen 1992
1976, September	184	As above	No	Lear 1976; as cited by Preen 1992
1976, October	148	As above	No	Lear 1976; as cited by Preen 1992
1976, December	118	As above	No	Lear 1976; as cited by Preen 1992
1977, January	268	As above	No	Lear 1976; as cited by Preen 1992
1977, May	210	24 aerial transects traversing the Bay between Peel and Bribie Islands.	No	Heinsohn 1977, as cited by Preen 1992
1979, August	307	Perimeter survey with some transects of eastern banks.	No	Heinsohn & Marsh 1980; as cited by Preen 1992
1988, July	168	Strip-transect of entire Bay, plus area east of South Passage.	?	Marsh *et al.* 1990, as cited by Preen 1992
1988, ?	458±78	Quantitative aerial survey from 137 m.	Marsh and Sinclair 1989b	Marsh *et al.* 1990; as cited by Chilvers *et al.* 2005
1988, July-December*	369±13	Standardised aerial survey from 274 m. Perimeter survey.	No	Preen 1992
1989, January-November*	359±29	Perimeter survey and standardised aerial survey from 274 m.	No	Preen 1992
1990, January-February*	299±15	Standardised aerial survey from 274 m.	No	Preen 1992
1993, April	664	Quantitative aerial survey from 274 m (following Preen 1992).	No	Preen and Marsh 1995
1995, January	1019±166	Quantitative aerial survey from 274 m	Marsh and Sinclair 1989b	Lanyon 2003
1995, March	605±27	Quantitative aerial survey from 274 m	Marsh and Sinclair 1989b	Lanyon 2003
1995, May	598±88	Quantitative aerial survey from 274 m	Marsh and Sinclair 1989b	Lanyon 2003
1995, July	503±64	Quantitative aerial survey from 274 m	Marsh and Sinclair 1989b	Lanyon 2003
1995, September	946±23	Quantitative aerial survey from 274 m	Marsh and Sinclair 1989b	Lanyon 2003
1995, December	977±46	Quantitative aerial survey from 274 m	Marsh and Sinclair 1989b	Lanyon 2003
2000, December	344±88	Quantitative aerial survey from 137 m	Marsh and Sinclair 1989b	Lawler 2002
2001, April	366±41	Quantitative aerial survey from 137 m	Marsh and Sinclair 1989b	Lawler 2002
2001, November	493±45	Quantitative aerial survey from 137 m	Marsh and Sinclair 1989b	Lawler 2002
2005, November	454±41	Quantitative aerial survey from 137 m	Marsh and Sinclair 1989b	Sobtzick *et al.* 2012
2011, November	883±68	Quantitative aerial survey from 137 m	Marsh and Sinclair 1989b	Sobtzick *et al.* 2012

Table 2. Summary of quantitative and semi-quantitative surveys of dugong abundance in the Hervey Bay-Great Sandy Strait (GSS) region, Queensland. Aerial survey heights are provided for comparison, although Marsh and Sinclair (1989a) found no significant difference between estimates from 137 and 274 m. ?, unknown. *, as reported in Preen and Marsh (1995).

Year and month	Estimate (±SE)	Method	Bias corrections	Source
1988, August	2206±420	Aerial survey. 137 m. Hervey Bay-GSS	Marsh and Sinclair 1989b	Preen and Marsh 1995
1992, November	1109±383	As above	Marsh and Sinclair 1989b	Preen and Marsh 1995
1993, December	579-629 (±126)*	As above	Marsh and Sinclair 1989b	Preen and Marsh 1995
1994, November	807±151	As above	Marsh and Sinclair 1989b	Marsh *et al.* 1996, cited by Marsh 2002
1999, November	1654±248	As above	Marsh and Sinclair 1989b	Marsh and Lawler 2001, cited by Marsh 2002
2001, April	919±146	As above	Marsh and Sinclair 1989b	Lawler 2002
2001, November	1708±392	As above	Marsh and Sinclair 1989b	Lawler 2002
2005, November	2547±410	As above	Marsh and Sinclair 1989b	Sobtzick *et al.* 2012
2011, November	2116±108	As above	Marsh and Sinclair 1989b	Sobtzick *et al.* 2012

Table 3. Summary of dugong strandings and mortality by year and identified sources of mortality for Hervey Bay-Great Sandy Strait (GSS) and adjacent coastal areas, 1996–2011 (Baffle Creek, 24.5°S to northern Sunshine Coast, 27.35°S). Causes of death are either suspected or confirmed. QSCP, Queensland Shark Control Program. Data source: Environment and Heritage Protection, StrandNet (https://www.derm.qld.gov.au/strandnet/application [accessed: March 2012]).

Cause of stranding and mortality	**Year**															
	1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Natural Causes																
Disease and ill health			2	2	2		2					1			1	4
Shark predation											1					
Cause undetermined		1				1									1	
Rescued or natural escape				2	1											
Human Related																
Boat strike/fractures	1	1			1	3		1			1					
Entanglement in floatlines and ropes									1							
Netting		1						1								
Entanglement (other)																
QSCP		1					1			1			1	1		
Ingestion of fishing line/hooks																
Hunting				1					1							
Undetermined																
Undetermined Cause	8	3	9	16	13	10	7	7		5	3	3	7	14	9	20
Total	10	7	12	21	17	14	10	9	4	6	5	4	8	15	11	24

Table 4. Summary of dugong strandings and mortality by year and identified sources of mortality for Moreton Bay and adjacent coastal areas, 1996–2011 (northern Sunshine Coast, 26.35°S, to Coolangatta, 28.2°S). Causes of death are either suspected or confirmed. QSCP, Queensland Shark Control Program. Data source: Environment and Heritage Protection, StrandNet (https://www.derm.qld.gov.au/strandnet/application [accessed: March 2012]).

Cause of stranding and mortality	**Year**															
	1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Natural Causes																
Disease and ill health		2	1	1	2		1	3	1	1		1	3	2	8	3
Shark		1														
Cause undetermined					1											
Rescued or natural escape		1								1						
Human Related																
Boat strike/fractures		1	2		1		5	2	2	1	1	2		3	1	
Entanglement in floatlines and ropes											1					
Netting										1						
Entanglement (other)																
QSCP	3			1	2				1				1			1
Ingestion of fishing line/hooks																
Hunting	3	2					2		3	1						
Undetermined			1													
Undetermined Cause	1	4	2		16	7	12	5	11	4	13	9	10	4	9	18
Total	7	11	6	2	22	7	20	10	18	9	15	12	14	9	18	22

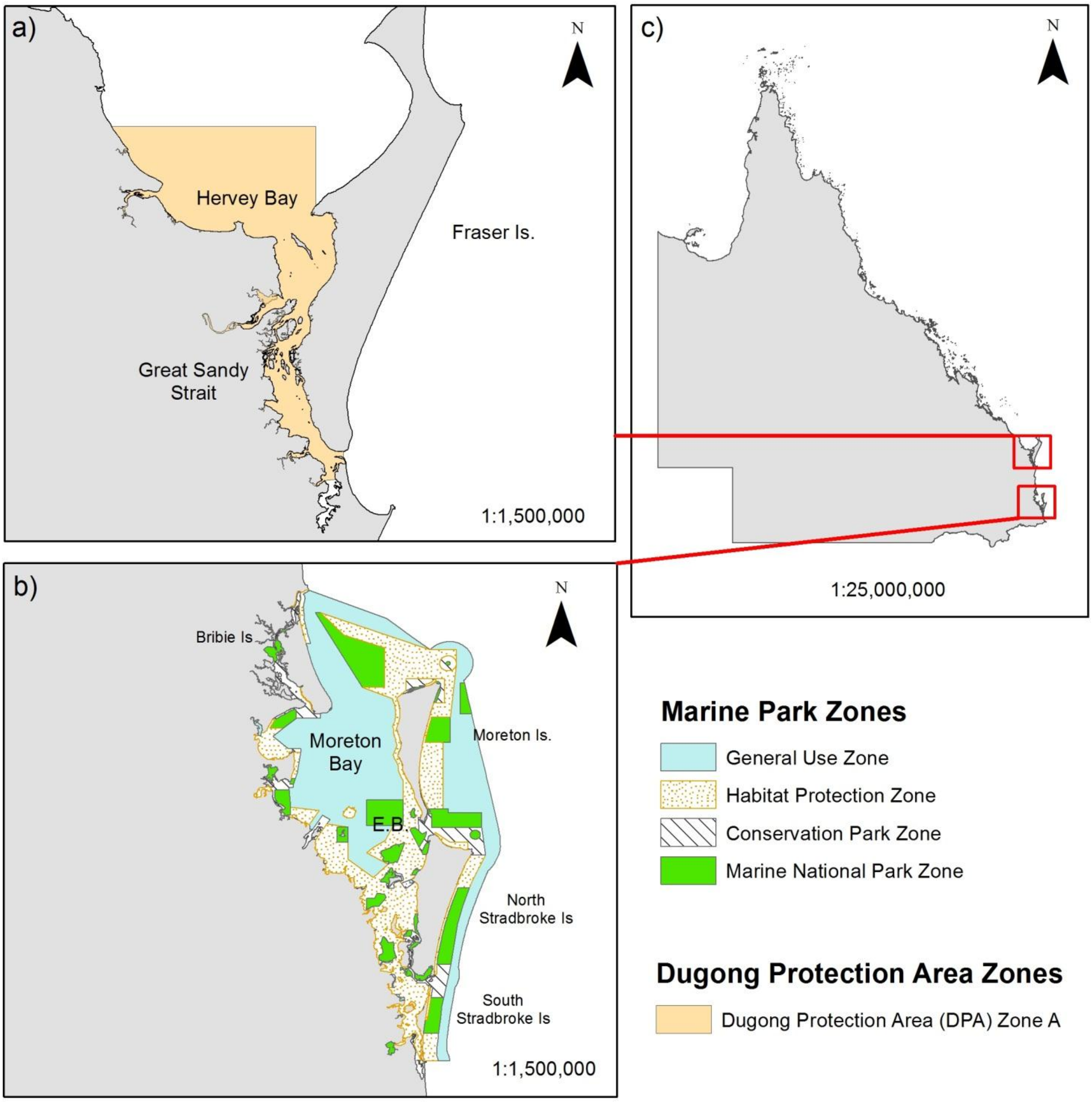

Figure 1. Location of the Hervey Bay-Great Sandy Strait (GSS) region (a) and Moreton Bay (b) within South-East Queensland**,** Australia (c). Also shown are Dugong Protection Areas (Hervey Bay-GSS) and Marine Parks (Moreton Bay). The Great Sandy Strait Marine Park is not shown on (a) but overlaps with much of the DPA and also extends to adjacent regions of Tin Can Bay, Rainbow Beach and Fraser Island. In Moreton Bay, the Eastern Banks are a shallow seagrass area where most dugongs are found.

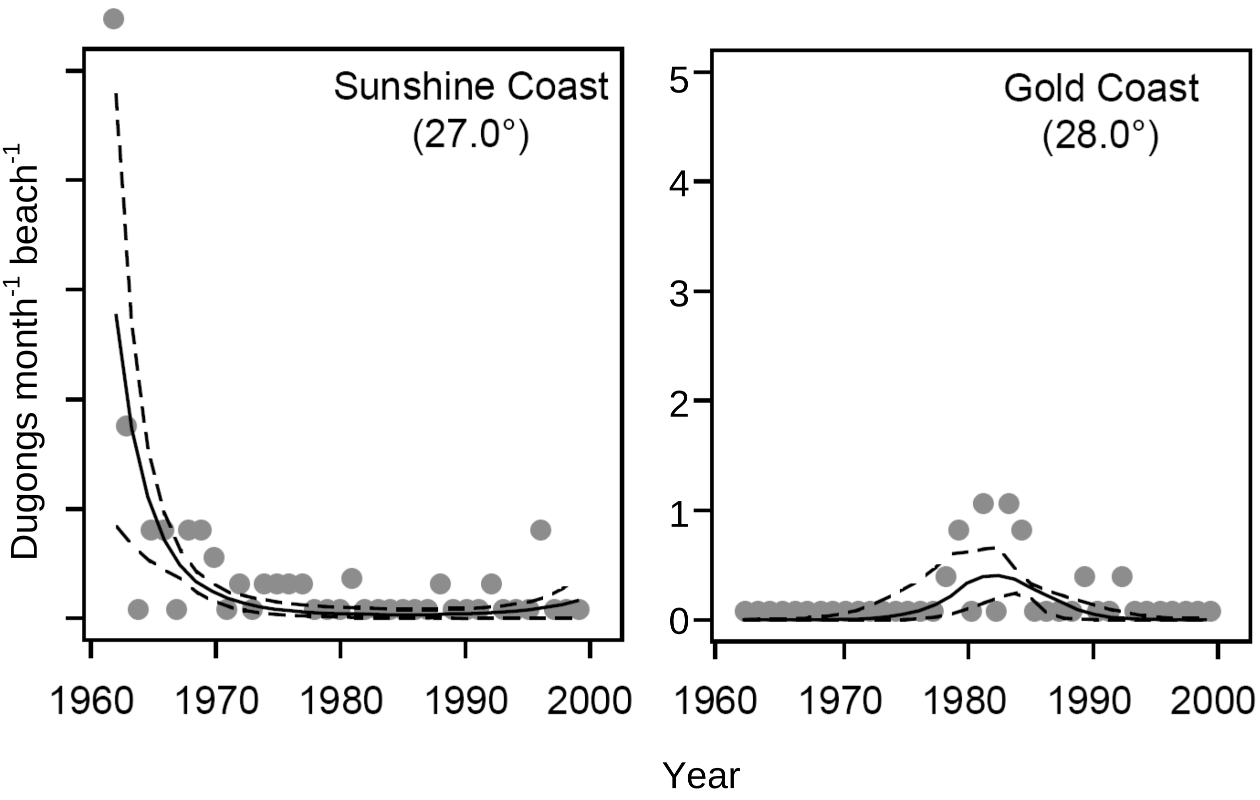

Figure 2. Analysis of incidental catch of dugongs in the Queensland Shark Control Program (QSCP) by Marsh et al. (Marsh *et al.* 2001; Marsh *et al.* 2005), 1962-1999. The data represent a subset of beaches in the QSCP where (i) more than two dugongs were caught and (ii) where >7 years of data were present. Rainbow beach was excluded. Details of the statistical approach were provided by Marsh *et al.* (2005). Briefly, the solid lines represent the fit of generalised linear models and the dotted lines are bootstrapped 95 per cent confidence intervals. Source: Marsh *et al.* (2005), with permission from ESA publications.

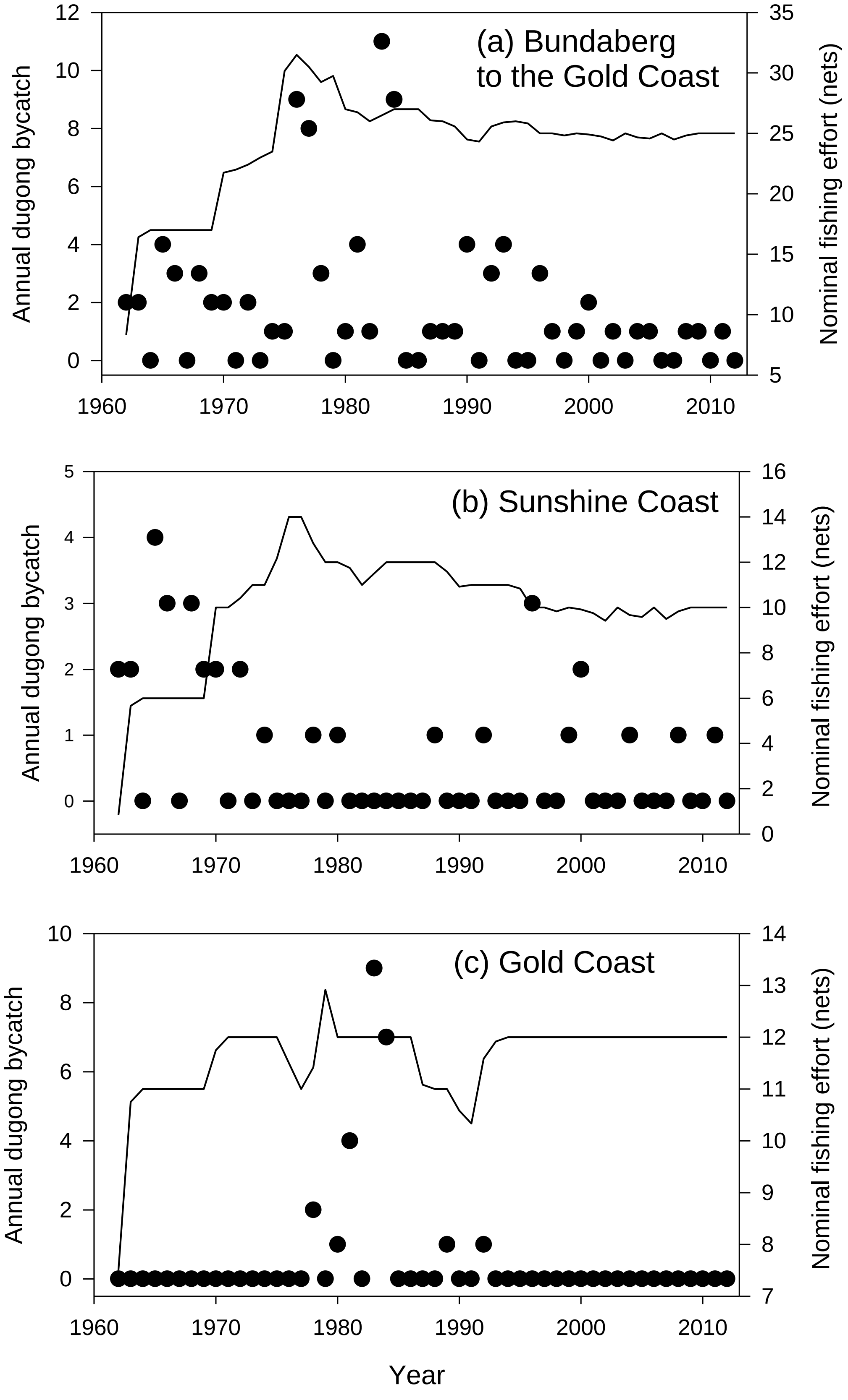

Figure 3. Annual dugong bycatch (incidental catch, circles) in the Queensland Shark Control Program nets, compared to nominal netting effort (number of nets per month averaged over each year, solid line), (a) Bundaberg to the Queensland-New South Wales border, (b) the Sunshine Coast and (c) the Gold Coast. Dugongs known to have been caught in drumlines were not included in this figure.

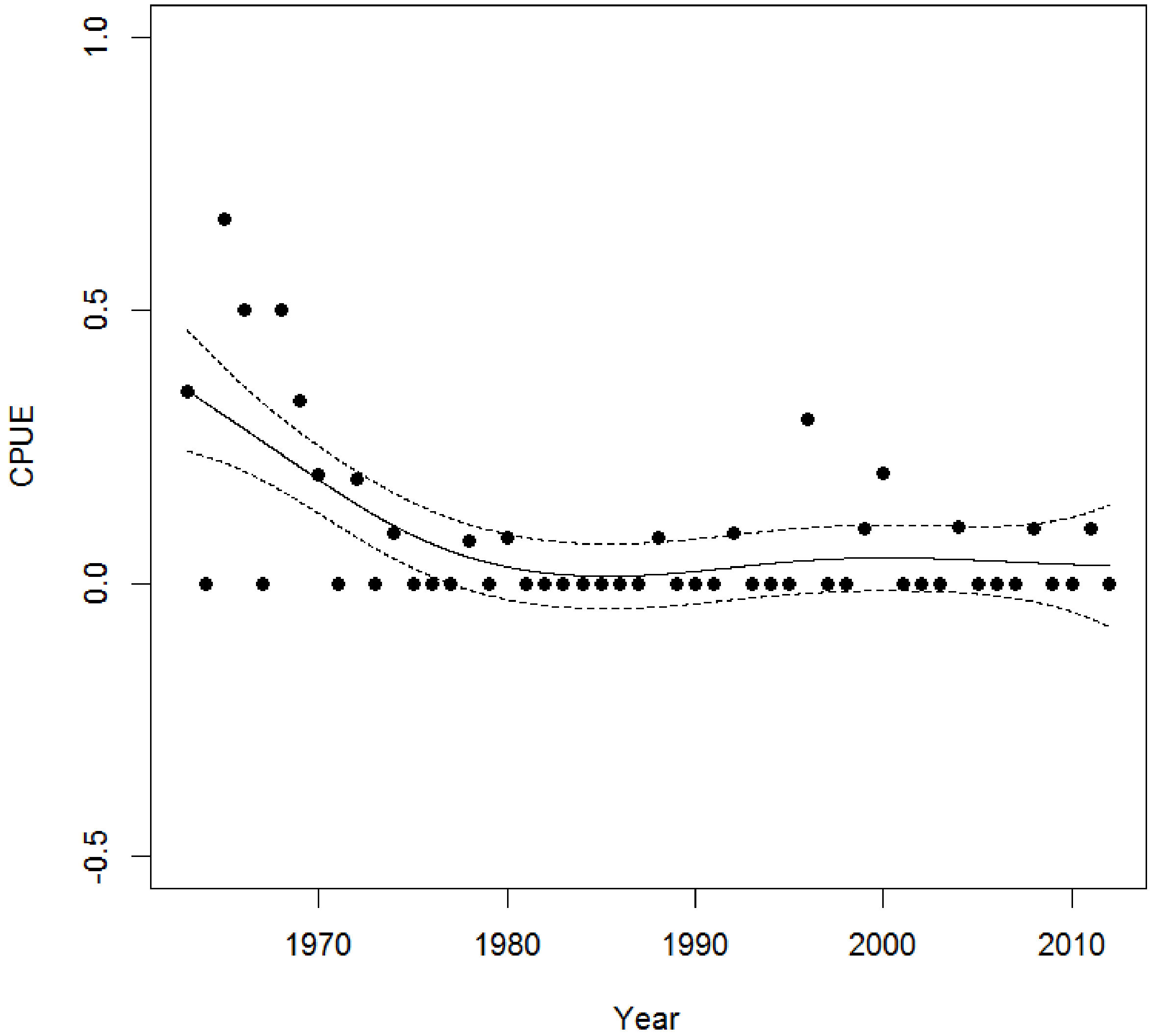

Figure 4. Fit of a generalised additive model (GAM, solid line) and 95 per cent confidence intervals (dotted lines) for the annual bycatch (incidental take of dugongs) on the Sunshine Coast between 1962 and 2012 in the Queensland Shark Control Program. No significant autocorrelation was evident in the residuals. The total catch of dugongs was standardised to Catch Per Unit Effort (CPUE) by dividing the annual number caught by nominal fishing effort (nets, see definition in Figure 3 caption). Data for 1962 were not included in the GAM because there was significant experimentation with gear in the first year of the program, but are provided for comparison. In total, most dugongs have been caught at Noosa (*n* = 10), followed by Maroochydore (7), Caloundra (6) and Mooloolaba (3). Less than three dugongs have been caught on the other beaches.

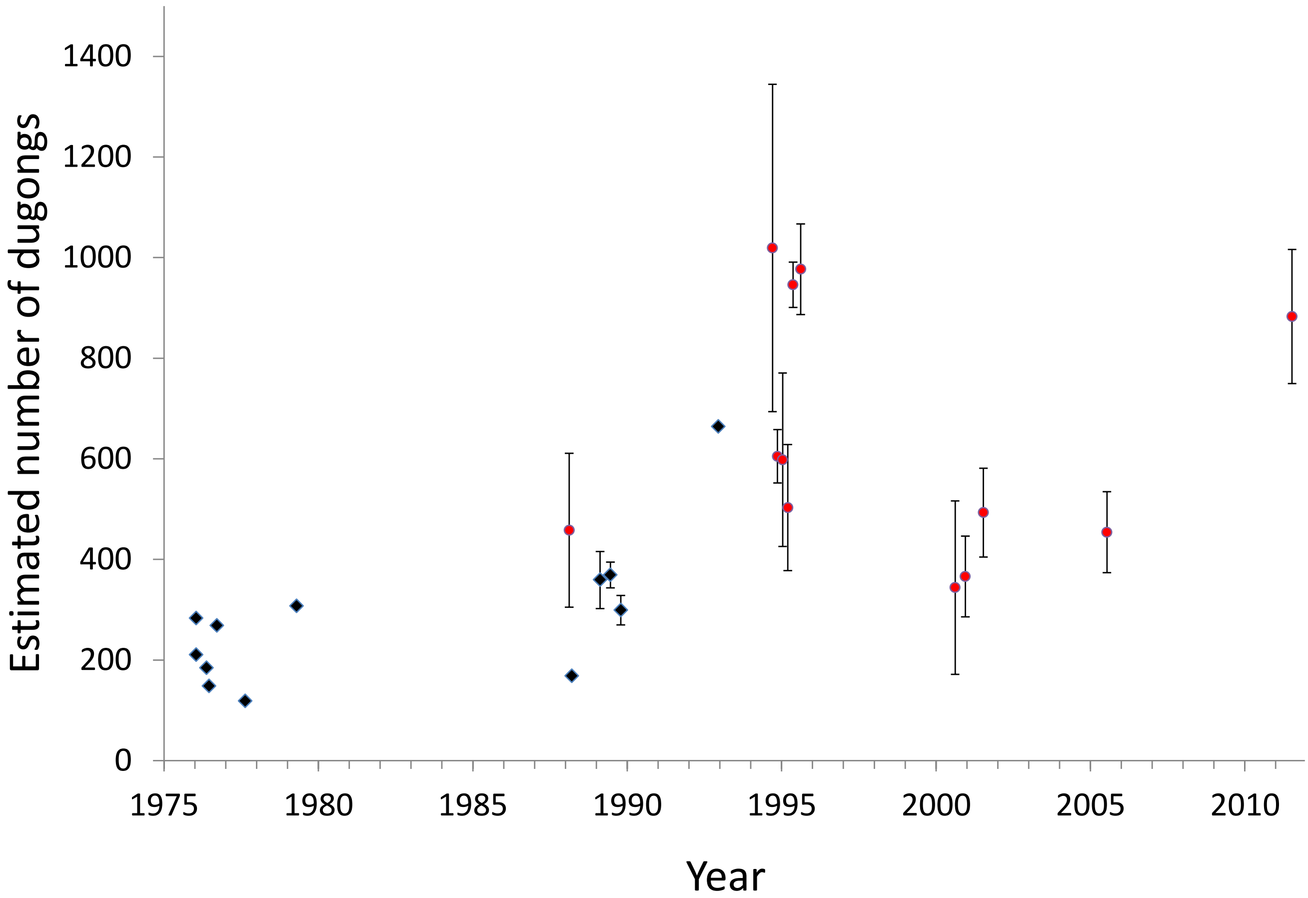

Figure 5. Overall trend in aerial survey estimates of dugong abundance in Moreton Bay. Black diamonds, raw data; red circles, data were corrected following Marsh and Sinclair (1989a). Error bars are 95 per cent confidence intervals, estimated as 1.96 x standard error.

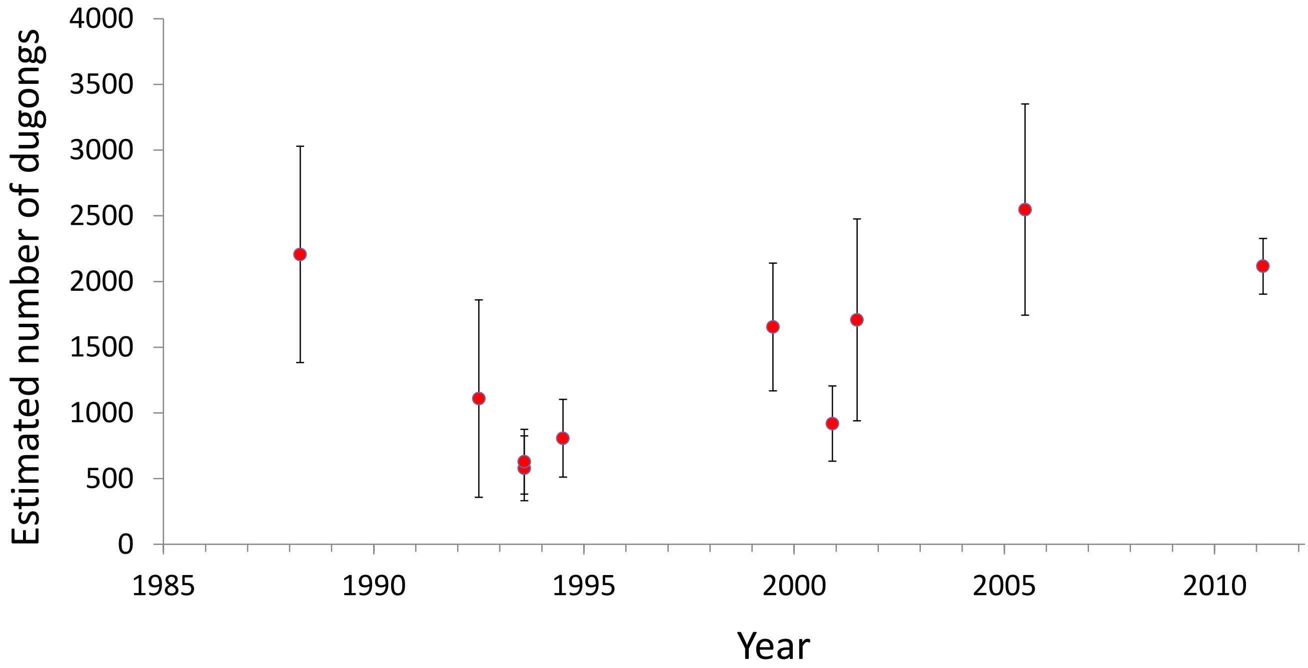

Figure 6. Overall trend in aerial survey estimates of dugong abundance in the Hervey Bay-Great Sandy Strait (GSS) region. Red circles, data were corrected following Marsh and Sinclair (1989b). Error bars are 95 per cent confidence intervals, estimated as 1.96 x standard error.

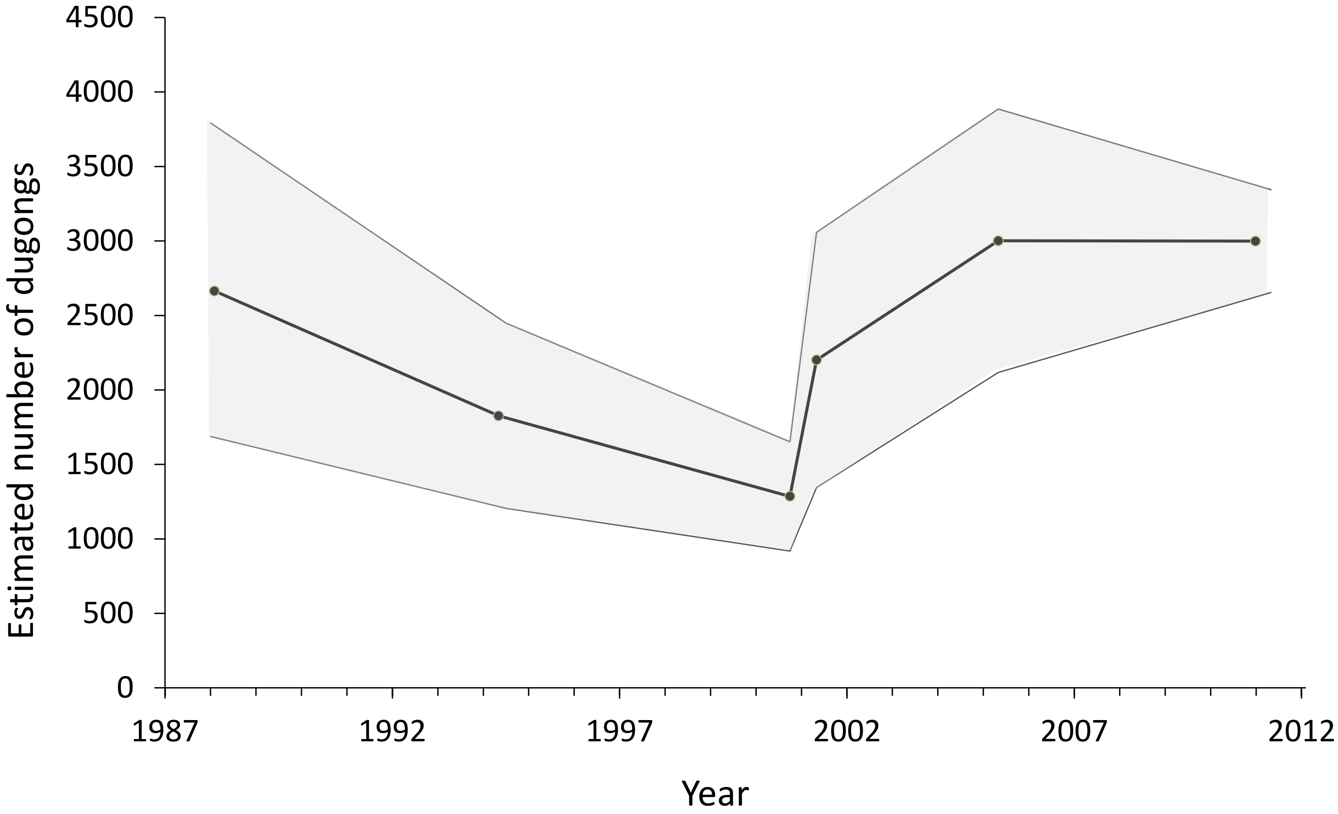

Figure 7. Overall trend in aerial survey data for the putative southern Queensland stock (sum of Hervey Bay-Great Sandy Strait and Moreton Bay population estimates) between 1988 and 2011. The shaded area represents the 95 per cent confidence intervals. Only datasets where surveys of Hervey Bay-GSS and Moreton Bay were undertaken within a four-month period area were included, data were corrected following Marsh and Sinclair (1989b).

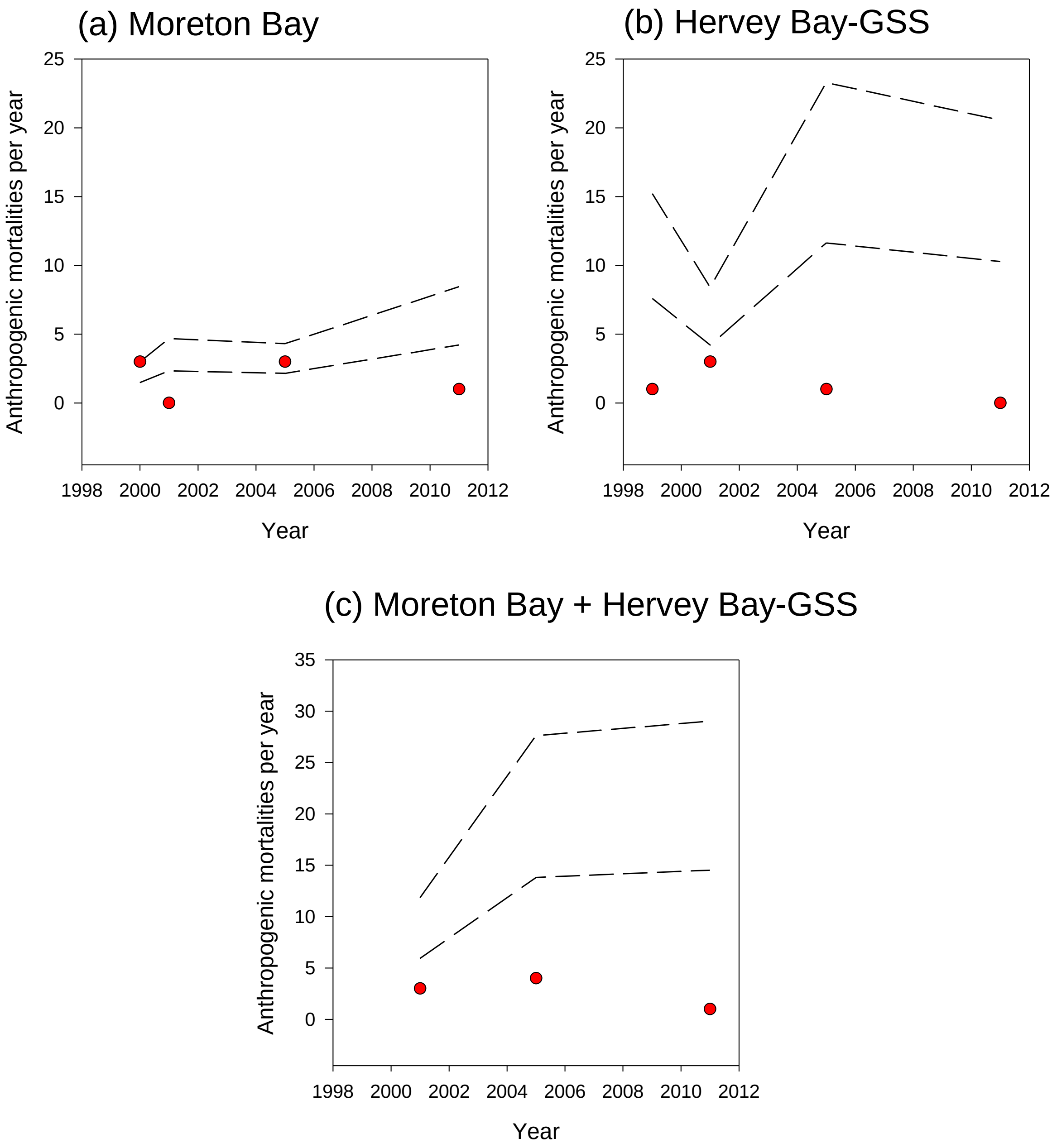

Figure 8. Anthropogenic mortalities of dugongs recorded in StrandNet (red dots) compared to estimates of Potential Biological Removal (PBR) (F_R = 0.5; upper dotted line: R_{max} = 0.04; lower dotted line, R_{max} = 0.02), for (a) the Moreton Bay region, (b) the Hervey Bay-Great Sandy Strait (GSS) region and (c) both regions combined. Note that although aerial surveys were also in undertaken in both regions in April 2001, only the November 2001 surveys are included in this figure for consistency with other years.