DISCUSSION

The numbers of dugongs caught in shark nets set off the urban coast of Queensland at shark contract areas between the latitudes of 16.5° and 27.5°S declined strongly from the inception of the Queensland Shark Control Program in 1962. The estimated rate of decline for a reduced (balanced) data set averaged 8.7% per year [95% CI = (7.1, 10.6)]. This represents a decline to 3.1% (1.4, 6.1), of initial catch rates over the 38-year sampling period (1962–1999). For the full data set, the overall capture rate declined at 8.2% per year (6.8, 9.7), a rate only marginally lower than for the reduced data set. The rate of decline also increased over time, starting at about 6% in 1962, and increasing to 14% in 1999 (figure 8). There is no statistical evidence that the changes to the Program introduced after the 1992 review (*Review of the operation and maintenance of shark meshing equipment in Queensland waters*, 1992) changed the pattern of declining catches. However, given the low number of dugongs caught post 1992, the power to detect such a change is weak. As explained above, our overall analysis is conservative, especially with respect to dugong mortality in the early years of the Queensland Shark Control Program. Thus it is likely that the actual decline in the number of dugongs caught is greater than that reported here.

The catch rates varied strongly between contract areas, and to a lesser degree between beaches within contract areas (figures 5 and 6). Four of the six contract areas (Cairns, Townsville, Rockhampton (all in the Great Barrier Reef World Heritage Area), and the Sunshine Coast (figure 1) showed large declines over the sampling period. Two areas (Mackay and the Gold Coast, figure 1) showed a modal distribution of catches, with higher catches centred around 1980–1982. There was weak monthly variation in catch rates (figure 4). Dugong catches tended to be higher in the second half of the year than in the first half. A similar seasonal pattern is also reflected in the Queensland Parks and Wildlife Service stranding database for 1996 and 1999 (Limpus et al. 1999). This seasonal effect may reflect changes in dugong activity in the second half of the year in response to a seasonal reduction in above-ground seagrass biomass (Aragones & Marsh 2000) and / or dugong breeding activity (Marsh et al. 1984; Boyd et al. 1999). Catch rates did not appear to be influenced by the number of nets deployed at a netted beach and the number of fishing days per month, although the power to detect these effects was weak because of the confounding effects of beach and year. The catch rates did not change following the annual removal of the nets for periods of 1–2 months.

Explanations for the Decline in Dugong Catches in Shark Nets

This estimated decline in dugong catch could be taken as an estimate of a decline from all causes in dugong numbers averaged over the areas where nets were deployed if there are no confounding factors unrelated to any real change in population numbers. Before reaching the conclusion that dugong numbers have seriously declined, it is important to examine the following underlying assumptions, which are related to possible confounding factors:

1. Practices of shark netting have not changed over the sampling period.
2. Dugongs have not changed their behaviour in the areas fished by the shark nets.
3. Catch rates are dependent on dugong population density.

Changes in the Practice of Shark Meshing?

The Queensland Shark Control Program uses cord nets. These nets are 62 m long, 6.4 m deep and have a mesh size of 50 cm (*Review of the operation and maintenance of shark meshing equipment in Queensland waters*, 1992). In 1992, the Queensland Shark Control Program

introduced measures to reduce the capture of non-target species as detailed by Gribble et al. (1998). These measures included: the replacement of shark nets at Rockhampton and at one beach near Townsville with drumlines; education and training initiatives to increase the chances of non-target species being released alive; and the staged introduction of acoustic alarms on nets at beaches in the Gold Coast (1992–1993); Sunshine Coast (1994 whales / 1998 dolphins) and Cairns contract areas (1994–1995). These alarms were introduced to reduce the possibility of accidental entanglement of cetaceans. Their effect on dugongs is unknown. We conclude that these changes in the practice of shark meshing are unlikely to have a major impact on the long-term declines in dugong catch depicted in figures 5–8, as the major declines occurred before the 1990s. This conclusion is supported by the lack of a significant difference between the pre- and post-1992 capture rates of dugongs in the Shark Control Program as explained above (but note the lack of power in the test).

Changes in the Behaviour of Dugongs in the Areas Fished by the Nets?

A possible explanation for the decline in the by-catch of dugongs in the Queensland Shark Control Program is that dugongs learn to avoid the nets, which have been left in place for long periods. We have no data to support this assumption and limited data to reject it. As outlined below, most captures have been of single dugongs and the only long-term social unit identified for dugongs is the cow-calf pair, suggesting a limited opportunity for dugongs to learn about the nets from the experience of others. The confirmed proportion of animals released alive from the nets is low (2%, *Review of the operation and maintenance of shark meshing equipment in Queensland waters*, 1992). However, this percentage probably underestimates the actual percentage released alive as the status of most dugongs in the nets was not recorded. Dugongs of all ages and both sexes are caught, and when the distributions of sizes, sexes and estimated ages are considered there are no major gaps (Marsh 1980). If dugongs learned to avoid nets we might expect a preponderance of young animals in the nets and a rise in dugong catch rates when the nets were reintroduced each year after their annual removal. However, the removal time may have been too short for dugongs to unlearn any avoidance behaviour. We conclude that, at our current state of knowledge, the decline in dugong catches cannot be explained by dugongs learning to avoid the nets.

A more plausible explanation for the decline in dugong by-catch is that dugongs have been alienated from the beaches where shark nets have been located by increased human use. Although boat traffic is banned from the immediate vicinity of nets, the presence of a net is an inducement to bathers. There is no evidence to reject or support this displacement hypothesis.

Catch Rates do not Reflect Dugong Population Density?

Heinsohn (1972) analysed the pattern of dugong mortality in Townsville shark nets from their introduction in 1964 through July 1971. His data were obtained directly from the local contractor and are more detailed than the official QDPI data analysed in this study. In addition, Heinsohn's data include catches that were not included here because of discrepancies among the QDPI database and the QDPI logbooks. Heinsohn (1972) reports that 22% of 119 nettings comprised multiple captures of up to five dugongs (a netting was defined as an instance in which one or more dugongs were found in a single shark net at the time it was checked every second day). Eleven of the 18 pairs of dugongs caught were netted in the first year. All the aggregations of more than two dugongs were caught in the first year of netting. Heinsohn & Spain (1974) compared the shark netting statistics for 1972,

the year after cyclone Althea caused extensive damage to seagrass beds in the Townsville region. The annual catches of dugongs increased from an average of 12.7 before the cyclone to 41 in 1972. Heinsohn & Spain (1974) attributed this change to increased dugong movements in search of food following extensive cyclone damage to the seagrass beds. In 1972, 18% of nettings were multiple captures of up to three dugongs (three occasions). After 1972, at least 98.5% of dugong nettings in Townsville have been of single individuals. Over all contract areas, at least 97.3 % of dugong nettings have been of single individuals, suggesting no substantive change in the relationship between the pattern of dugong catches and population density since at least the early 1970s.

Is the Decline Plausible?

If dugong catches in shark nets are a reliable index of dugong numbers, and if the depletions occurred at regional rather than at local scales, the dugong population in the Great Barrier Reef region would have been of the order of 50 000 animals in the early 1960s based on the 1986–1987 population estimate for the region (Marsh & Saalfeld 1990). Is this plausible? Unfortunately, it is impossible to estimate the dugong carrying capacity of the region in the 1960s for two reasons: (1) we do not know the carrying capacity of any seagrass meadow, and (2) we do not know the area of seagrass along the Queensland coast in the 1960s. Thus we cannot use an estimate of carrying capacity to check the plausibility of the decline suggested by the shark netting data. Preen (1992) estimated a dugong density of 7.4 km^2 of seagrass in Moreton Bay in the early 1990s. Whether dugongs were at carrying capacity at this density and whether this result is applicable to other seagrass communities is unknown.

Additional Evidence for a Decline in Dugong Numbers Along the Urban Coast of Queensland

Analysis of dugong catches in shark nets (figures 5 and 6) indicate strong declines between the early 1960s and 1999 in four of the six areas (Cairns, Townsville, Rockhampton (all in Great Barrier Reef World Heritage Area), and the Sunshine Coast, figure 1). The data suggest that the number of dugongs remaining in the contract areas should be higher in Townsville and Rockhampton than in Cairns and variable in Mackay. These patterns are reasonably consistent with the results of dedicated aerial surveys for dugongs conducted in 1986–1987, 1992 and 1994 (Marsh & Saalfeld 1990; Marsh et al. 1994, 1996). The difference between the aerial survey population estimates for dugongs in the Great Barrier Reef World Heritage Area in 1986–1987 (3479 $\pm$ s.e. 459) and 1994 (1682 $\pm$s.e. 236) (Marsh et al. 1996) accords with the decline predicted from these data (8.7% p.a decline for seven years = 47%). The large decline in the Cairns area (figures 5 and 6) is supported by both: (1) the aerial survey results (too few dugongs were sighted in 1987 and 1992 to estimate the dugong population in the area), and (2) the anecdotal information of Bertram & Bertram (1973) who reported that 200 dugongs per year were being taken by Aboriginal people from nearby Yarrabah in 1965. Aboriginal elders also consider that dugong numbers in the southern Great Barrier Reef World Heritage Area have been declining for at least 20 years (Ross Williams pers comm. 1996).

Marsh and Lawler (2001) conducted another standardised aerial survey in the time series in 1999, five years after the last survey, to assess again the status of the dugong in the southern Great Barrier Reef region. This is the first estimate of dugong abundance in the region since the establishment of the Dugong Protection Areas (Marsh 2000) and the ban on Indigenous hunting of dugongs south of Cooktown. The results of the 1999 survey indicate that dugong numbers in both the southern Great Barrier Reef and Hervey Bay regions in

October–December 1999 were significantly higher than the corresponding estimate in 1994, and not significantly different from that obtained in 1986–1987. Most of the increase was in the northern part of the survey region (the Central Section of the Great Barrier Reef Marine Park). It is not possible for the differences between the 1994 and 1999 surveys to be the result of natural increase in the absence of immigration. The dugong is a long-lived species with an estimated maximum rate of increase of the order of 5% p.a. or 27.6% over five years (Marsh 1995; Boyd et al. 1999). The rate of increase required to produce the effect recorded in this survey would need to be much greater than this because the controls on major sources of anthropogenic mortality, Indigenous hunting and commercial net fishing, were not introduced until 1997. Marsh and Lawler (2001) considered that the most plausible explanation for the increase observed is movement of substantial numbers of dugongs into the survey area, probably from the northern Great Barrier Reef region. While there is no direct evidence for this occurring, there is increasing evidence that seagrass abundance fluctuates over spatial scales on hundreds of kilometres in response to extreme weather events (Preen et al. 1995; Poiner & Peterken 1996). Satellite tracking of dugongs has also proven that dugongs commonly move over large distances (Marsh & Rathbun 1990; Marsh et al. 1999; Preen 2000).

Two of the shark-meshing contract areas (Mackay and the Gold Coast, figure 1) showed a modal distribution of catches, with higher catches centred around 1980–1982. This pattern also accords with the hypothesis of changes in seagrass distribution in response to extreme weather events. A plausible but unproven explanation for the observed increase in dugong catches in these contract areas in the 1980s is that dugongs moved into the Mackay and Gold Coast contract areas in response to seagrass loss elsewhere (see Marsh et al. 1999).

Nonetheless, none of these results is inconsistent with the hypothesis that there has been a long-term decline in dugong numbers on the urban coast of Queensland. These results are consistent with the hypothesis that the overall pattern decline has been complicated by large-scale movements of dugongs, possibly in response to changes in seagrass distribution.

Implications for Management of the Dugong in Queensland

The results of this analysis of the dugong catch in shark nets set for bather protection along the Queensland coast reinforce the assertion that the dugong numbers recorded in the dedicated aerial surveys reflect population numbers far below those in the early 1960s (Marsh et al. 1996). We cannot quantify the spatial scale over which this decline has occurred, i.e. whether it represents local or regional scale depletions. However, our current understanding of dugong movements (Marsh et al. 1999; Preen 2000) suggest that the depletion is likely to have occurred over a regional scale. More than 50% of dugongs tracked using satellite transmitters in the Great Barrier Reef World Heritage Area have moved more than 80 km in a few months (unpublished data) with maximum movement up to 800 km in a few days (Marsh et al. 1999; Preen 2000). In addition, we cannot quantify the relative importance of the various causes of this long-term decline in dugong numbers. They probably differ in different areas (Marsh et al. 1996). However, shark meshing *per se* was estimated to cause an average mortality of about 0.5% of the estimated 1986–1987 population in the southern Great Barrier Reef (Gribble et al. 1998). This is about 6% of the overall decline in shark net captures for the whole region (8.7% per year).

The relationship between dugong numbers in the early 1960s and those at the time of European settlement along the east Queensland coast during the 19th century is unknown. However, we consider it unlikely that dugong numbers were higher in 1960 than at the

time of European settlement, given that a cottage commercial industry for dugong oil was widespread along the Queensland coast from the latter half of the 18th century until dugongs were protected in 1967 (Nishiwaki & Marsh 1985). This conclusion is supported by anecdotal information, e.g. Bertram & Bertram (1973). Thus the most salient questions to be determined by management agencies and stakeholders is the target level of recovery for dugong populations in this region and the time frame to achieve this target. As discussed above, population models suggest that dugong populations are unlikely to increase at more than 5% p.a. (Marsh 1995; Boyd et al. 1999). On this basis the dugong populations on the urban coast of Queensland would take at least 70+ years to recover to 1960 levels in the absence of immigration from more remote areas further north. As explained above, our current understanding of dugong movements suggests that such immigration is likely (Marsh et al. 1999) a result supported by the 1999 aerial survey Marsh and Lawler (2001).

If recovery to an agreed target is to be achieved, all sources of impact will need to be addressed. At present, management focuses on reducing dugong mortality by banning Indigenous hunting south of Cooktown (15°S) (Marsh 2000) and reducing the probability of dugongs drowning in nets (including both shark nets set for bather protection (Gribble et al. 1998) and commercial gill and mesh nets (Marsh 2000). Dugong habitat protection has concentrated on banning trawling from the inshore seagrass beds. The Great Barrier Reef Marine Park Authority zoning plans and the Queensland Fisheries Management Authority coastal strip closures, restrict trawling activity to 55% of the seagrass beds within the entire Great Barrier Reef Marine Park (Wachenfeld et al. 1998). This percentage should be increased as a result of the Representative Area Program currently being conducted by the Great Barrier Reef Marine Park Authority (Jon Day pers comm. 2000).

So far little has been done to protect dugong habitat from land-based inputs of nutrients, sediments and herbicides. *Halophila*, a genus that is a preferred food of dugongs, appears to be particularly sensitive to light reduction. The duration and frequency (and possibly timing) of light-deprivation events such as plumes of muddy freshwater appear to be the primary factors affecting the survival of seagrasses in this genus in environments that experience transient light deprivation. Members of the genus *Halophila* occur at greater depths than other species of tropical seagrasses. This sensitivity to light reduction is a plausible explanation of the large-scale loss of deep-water seagrasses in Torres Strait (10°S) and Hervey Bay (25°S) after floods (Preen et al. 1995; Poiner & Peterken 1996; McKenzie et al. 2000).

The impact of extreme weather events on the dugong's seagrass habitat seems to be influenced by land-use. For example, anecdotal evidence suggests that the loss of seagrass from Hervey Bay following the 1992 floods was unprecedented in the past 100 years, even though the magnitude of the flood was not (Preen et al. 1995). Preen et al. concluded that the impacts of natural disturbance on seagrass beds can be exacerbated by poor catchment management. Catchment activities including vegetation clearing, grazing, agriculture, aquaculture and urban and industrial development may result in increased sediments and nutrients entering coastal waters. In the central Great Barrier Reef World Heritage Area for example, 39% of all nitrogen and 52% of phosphorous originate from river inputs (Cosser 1997). The increase in sediment and nutrient load from these activities may affect the ability of seagrass beds to recover from damage caused by natural events (Wachenfeld et al. 1998). The amount of sediments, nitrogen and phosphorous entering Queensland’s oceans each year has increased three to fivefold since European settlement (~1850), with most originating from large areas of agricultural land in central and northern Queensland (Moss et al. 1993). Probably the greatest threat to seagrass habitat is land run-off and its effect on water quality (Wachenfeld et al. 1998). Herbicide runoff from agricultural lands also

presents a potential risk to seagrass functioning adjacent to sugarcane production areas (Haynes et al. 2000a, b). Unfortunately data are not available to indicate the extent of change in seagrass habitats off the east coast of Queensland, over the 38 year time-frame reported here for dugongs. However, it is likely that the changes in water quality have reduced the depth range of at least some species of subtidal seagrasses in the region (Abal & Dennison 1996).

The development of management strategies to achieve an agreed target for dugong recovery will need to be more comprehensive than at present, and to pay particular attention to catchment management to reduce the influx of nutrients, sediments and herbicides into coastal waters from the land. These strategies will also need to be developed in the context of: (1) the likelihood of a change in the frequency of extreme weather events as a result of climate change, as well as (2) the aspirations and rights of the Indigenous communities in the region. The need to take a more comprehensive approach to dugong management than provided by Dugong Protection Areas is in accord with the generic recommendations regarding marine reserves of Allison et al. (1998). They ask several questions pertinent to dugong management in Queensland including:

1. Will reserve populations be able to persist despite greater fishing pressure outside the reserve (in this case the Dugong Protection Areas)?
2. Will reserve populations be able to persist despite episodic climatic events and directional climate change?
3. Will reserve populations be able to persist despite increases in threats from pollution, species introductions, and disease spread?

Implications for Determining the Status of Other Long-lived Species

Quantitative monitoring of dugong numbers was initiated in the southern Great Barrier Reef World Heritage Area (Marsh & Saalfeld 1990) and Hervey Bay (Preen & Marsh 1995) in the mid- to late 1980s, providing a relatively small temporal window in to the status of the dugong along the urban coast of Queensland (Marsh et al. 1994, 1996; Marsh & Lawler 2001). Catch data from the dugong by-catch of the Queensland Shark Control Program provides a longer-term perspective and confirms anecdotal evidence that the populations of the region were in far from pristine condition at the commencement of formal monitoring. This example emphasises the need for population assessments to be based on a synthesis of all available information, rather than relying solely on formal monitoring programs.