CHAPTER 6. ASSESSMENT OF CRITICAL AREAS FOR SEA TURTLE BY-CATCH AND MANAGEMENT IMPLICATIONS

6.1 CHAPTER SUMMARY

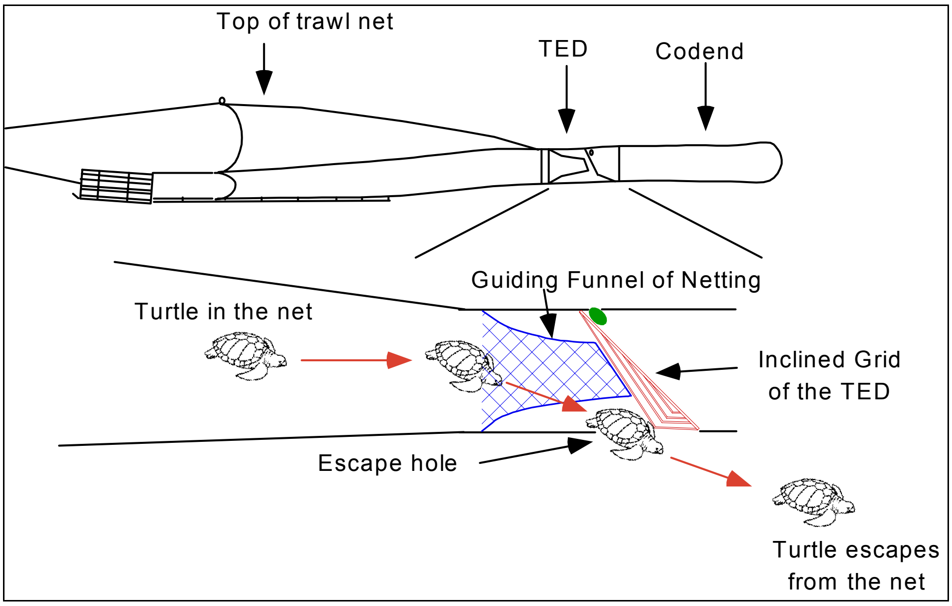
Turtle Excluder Devices (TEDs) are used generally as a major component to the solution of sea turtle by-catch in trawl fisheries. TEDs allow sea turtles to escape from trawl nets whilst enabling the trawl fishery to continue to operate and catch prawns. TEDs can be an effective solution to sea turtle by-catch, but the adoption and use of TEDs in a fishery needs to be monitored and enforced to ensure that the devices are having the desired outcome i.e., sea turtle exclusion. The geographic scale of Australian trawl fisheries makes broad scale monitoring impractical because of the cost of at-sea monitoring in remote areas. Combined with the uneven distribution of sea turtle by-catch, the more pragmatic approach to ensuring that TEDs are an effective solution is to target monitoring and enforcement efforts in critical areas where sea turtles and trawl fisheries interact and where the effective use of TEDs would have the greatest benefit to sea turtle conservation i.e., in areas where sea turtle by-catch or mortality is greatest.

I integrated the spatial distribution of effort for the Queensland East Coast Trawl Fishery in the year-2001 with the relative density of sea turtles to identify critical areas for sea turtle by-catch. Critical areas for sea turtle by-catch were similar regardless of the use of qualitative or quantitative methods. The results suggest that the most critical areas for monitoring and enforcing TEDs are the inshore waters of the Queensland east coast. Monitoring the effective use of TEDs in seven critical areas would enable fisheries managers to measure progress towards the management target of a 95% reduction in sea turtle by-catch and contribute to the sustainability of the fishery. The use of TEDs in non-critical areas should also be monitored, but because of the lower contribution of these areas to sea turtle by-catch, monitoring and enforcement could take place with less intensity. Critical areas for monitoring the effective use of TEDs may change if the spatial intensity of fishing effort changes and may become unnecessary should it be demonstrated that most fishers comply fully with TED regulations.

6.2 INTRODUCTION

The scale and impact of sea turtle by-catch in trawl fisheries has been acknowledged as a significant threat to the existence of sea turtle populations world-wide (Magnuson *et al.* 1990) and was demonstrated in Chapter 3 to have been of a scale sufficient to significantly contribute to the decline in the east Australian sub-population of *Caretta caretta.* Turtle Excluder Devices (TEDs) were developed in order to reduce sea turtle by-catch while permitting trawling to continue (Watson and Seidel 1980; Watson *et al.* 1994; Mounsey *et al.* 1995). TEDs do not prevent sea turtles from entering trawl nets, but exclude sea turtles from the mid-section of the trawl, preventing their entrapment in the codend (Figure 6.1).

Figure 6.1 Diagrammatic representation of a Turtle Excluder Device



Certification testing of TEDs in the USA indicates that TEDs can reduce sea turtle by-catch by greater than 97% (Watson *et al.* 1994). This efficiency has resulted in TEDs being the most common means of reducing sea turtle by-catch and associated mortality in trawl fisheries around the world for penaeid prawns (Lutcavage *et al.* 1996; Robins 1997). However, TEDs are relatively easy to disable temporarily so that they no longer function efficiently at excluding sea turtles (Mr Jack Forrester, NMFS personal communication 1997). Disabled TEDs can increase the time it takes for a sea turtle to escape from a submerged trawl net, and in a worst-case scenario, can prevent the sea turtle from escaping. Therefore, ensuring the effective use of TEDs, through monitoring and enforcement, is an important aspect of a compliance strategy that should be developed when TEDs are regulated into a trawl fishery for penaeid prawns.

6.2.1 Reduction targets for sea turtle by-catch

TEDs have been regulated into trawl fisheries for penaeid prawns of about 30 countries to address concerns about sea turtle by-catch (Robins 1997). Some countries have adopted TEDs to address concerns over declining sub-population sizes (e.g., USA), whilst other countries have adopted TEDs in order to maintain access to international markets (e.g., central and south American countries, Thailand, Malaysia). In Australia, TEDs were regulated into trawl fisheries for penaeid prawns primarily in response to concerns about declines in the size of the sub-population of *C. caretta* in eastern Australia, as well as general concerns about the impacts of prawn trawling on sea turtles as long-lived species (Limpus and Reimer 1994; Heppell *et al.* 1996; Tucker *et al*. 1997; Armstrong *et al*. 2000; Robins and Dredge 2000).

Specific targets for reductions in sea turtle by-catch have been set nationally as well as for the management jurisdiction of the major prawn trawl fisheries in northern Australia (Table 6.1). In general, they aim for a 95% reduction in the annual by-catch of sea turtles, using the estimated annual by-catch of sea turtles in the 1989, 1990, 1991 or 1992 as reference points. For example in the Queensland East Coast Trawl Fishery, the maximum incidental catch of sea turtles permitted under the management target is 265 individuals per year (Table 6.1). In addition, the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) requires that Australian fisheries resources be managed sustainably and specifically, that fishing activities be conducted in a manner that avoids the mortality of, or injuries to, endangered, threatened or protected species. The EPBC Act requires a fishery to: (i) collect information on the scale of by-catch of protected species; (ii) assess the impact of the fishery on protected species; and (iii) have measures in place to avoid the capture and mortality of protected species. Overall, the management regime of a fishery should contain objectives and performance criteria by which the effectiveness of the management arrangements are measured, contain the means for enforcing critical aspects of the management arrangements, be capable of assessing, monitoring, avoiding and mitigating adverse environmental impacts and require compliance with the relevant threat abatement plans, recovery plans and the National Policy on Fisheries By-catch. Sea turtle by-catch during "coastal otter-trawling operations in Australian waters north of 28°S has been listed as a key threatening process under section 188(4)c of the EPBC Act (EA 2003). Although key threatening processes usually require the preparation and implementation of a Threat Abatement Plan (TAP), a TAP was considered not to be warranted at the time of the listing because of the implementation of TEDs into the trawl fisheries of northern Australia. The necessity for a TAP and the listing of the key threatening process was recommended to be reviewed when TEDs were fully deployed (EA 2003).

Table 6.1 Reduction targets for sea turtle by-catch in trawl fisheries of northern Australia

Policy Instrument	Sea turtle by-catch targets in regards to trawl fisheries
The Queensland Fishery Management Plan: East Coast Trawl (QFMA 1998)	The reduction in marine turtle by-catch in the Queensland East Coast Trawl to 5% of 1991/92 levels i.e., 265 sea turtles using 5% of the 1991/1992 estimated total catch (Robins 1995).
Northern Prawn Fishery By-catch Action Plan (NORMAC1998)	"To eliminate to the greatest extent feasible, the catch of large animals such as turtles and stingrays," with a main objective to "reduce the number of turtles captured annually in prawn trawls in the NPF to about 5% of the average number (5,370) estimated to have been caught by NPF prawn trawlers in 1989 and 1990 (Poiner and Harris 1996)" i.e., a maximum catch of 286 sea turtles, and assuming 14% mortality, an annual mortality of 40 sea turtles.
The Draft National Recovery Plan for Marine Turtles in Australia (EA 1998)	"To reduce detrimental impacts on Australian stocks of marine turtles and hence promote their recovery in the wild", with the following criteria for success: • The reduction in marine turtle catch and mortality in the Queensland East Coast Trawl Fishery to 5% of 1991/1992 levels. • The reduction in marine turtle capture and mortality in the Northern Prawn Fishery to levels approaching 5% of 1989/1990 levels.
Guidelines for the Ecologically Sustainable Management of Fisheries (EA 2001)	Principle 2, Objective 2: "The fishery is conducted in a manner that avoids mortality of, or injuries to, endangered, threatened or protected species and avoids or minimises impacts on threatened ecological communities."
The National Policy on Fisheries By-catch (MCFFA 2000)	Core objectives are to ensure that by-catch species and populations are maintained at sustainable levels by reducing by-catch, protecting vulnerable or threatened species and minimising adverse impacts of fishing on the aquatic environment.

6.2.2 The use of TEDs in a fishery: identifying critical areas

TEDs have been regulated into Australian prawn trawl fisheries in a relatively harmonious manner, without the conflict that occurred in the southeastern USA (Margavio *et al.* 1993; Moberg and Dyer 1994). However, not all fishers agree with the use of TEDs and some will attribute reduced profitability to TED usage. Tucker *et al.* (1997, p 416) predicted, “in the event that TED regulations are imposed in Australian fisheries, adequate thought also will need to be directed toward efficient enforcement”. A spatial analysis of the relative density of sea turtles and the distribution of fishing effort would provide insights into where there is the greatest risk of sea turtle by-catch and mortality if TEDs are not used efficiently. This would allow fisheries management agencies to focus efforts to monitor and enforce TEDs in areas with the greatest conservation benefit to sea turtles.

Tangible measures of sustainable fisheries management have been suggested as a desirable feature of management objectives as they can be measured and thus enable an objective assessment of whether the target has been reached (Sainsbury *et al.* 1999). The current targets for reduction in sea turtle by-catch are desirable goals (see Table 6.1), but are difficult to measure because of the scale of trawl fisheries and the rarity of sea turtle captures. Therefore, it is likely that managers of the fishery will have difficulty in documenting and assessing whether the target has been met. More practical measures of reductions in sea turtle by-catch would be to monitor the TED compliance rates of commercial trawlers or the efficiency of TEDs in critical areas for sea turtle by-catch. These are tangible measures against which performance could be assessed by either checking the physical dimension of TEDs (i.e., enforcement of TEDs as defined by the regulations) or fishery-independent observers (i.e., monitoring the capture of sea turtles in nets fitted with TEDs). Tangible measures of the trawling industry’s progress towards the 95% reduction in sea turtle by-catch would provide “insurance” for the Australian prawn-trawling industry, which has agreed in-principle to address its impact on sea turtles. If TED compliance and sea turtle exclusion in critical areas are high, but sea turtle populations fail to recover, then the trawling industry would have independently documented performance measures of TED adoption and use. Without a measurable performance indicator, the trawling industry is open to accusations of non-compliance and continuing sea turtle by-catch mortality. If sea turtle populations fail to recover but the prawn-trawl fishery is documented to have high TED compliance in critical areas and low capture rates of sea turtles in TEDs, then it may be that other sources of mortality, such as incidental capture in longline fisheries, boat strikes or indigenous harvest, are causing the continuing decline.

6.2.3 Aims of this chapter

In this chapter, I assessed three methods of combining distributions of relative sea turtle density and fishing effort to identify potential areas where sea turtle interactions with prawn trawling was greatest i.e., critical areas for management responses. I then considered the implications of the location and scale of these areas for the monitoring and enforcement of TEDs.

6.3 METHODS

6.3.1 Relative density of sea turtles

The relative density distribution of sea turtles was derived from the spatial analyses of trawl capture and aerial survey data presented in Chapter 5. Two estimates of relative density were used: (i) predicted sea turtle CPUE (sea turtles caught per day fished) per CFISH site (=6^2nm); and (ii) sighted sea turtle density (sea turtles sighted per km^2) per CFISH site. Specific analysis of individual species could be undertaken using the predicted sea turtle CPUE for each species, but for simplicity and illustration of the method, the analyses in this chapter have only drawn on the relative density of sea turtles for all species pooled.

6.3.2 Total fleet effort

Effort for the Queensland East Coast Trawl Fishery has been recorded in a compulsory logbook program since 1988. Average annual fleet effort and maximum annual fleet effort were considered as potentially useful measures of annual fleet effort for identifying critical areas for sea turtle by-catch. However, management arrangements for the Queensland East Coast Trawl Fishery changed significantly during 2000 with the implementation of a Fisheries Management Plan (QFMA 1998). Changes included: (i) permanent closure of selected areas with low or infrequent fishing effort; (ii) restricting the number of nights that individual vessels can work; (iii) major seasonal closures in the north and south of Queensland[15]; (iv) preferential access to fishing grounds dependent on a vessel not working anywhere during the major seasonal closures; (v) introduction of Vessel Monitoring Systems; (vii) reporting of catch and effort by CFISH sites (= 6^2nm) rather than by CFISH grids (=30^2nm); and (viii) the compulsory use of TEDs and By-catch Reduction Devices (BRDs). I used fishing effort for the year-2001 in the identification of critical areas for sea turtle by-catch, as it most accurately represents the distribution of fishing effort under the new management arrangements. However, in other fisheries where the management arrangements have been more stable, the average or maximum annual fleet effort might more appropriately represent the long-term spatial distribution of effort.

Total fleet effort was extracted from the CFISH database for the year-2001. Data without location or reported in land-locked areas (i.e., mis-reporting or data entry error) were excluded from the analysis (as per Chapter 3, section 3.3.2). Commercial fishers report commercial catch and effort data at one of three spatial scales: CFISH grid (= 30^2nm), CFISH site (= 6^2nm) or point position with a latitude and longitude (see Chapter 3, section 3.3.2). In the year-2001, about 72,700 days of fishing effort were reported in the Queensland East Coast Trawl Fishery. About 80% of fishing effort was reported at the scale of CFISH sites or point position, and about 20% was reported at the scale of CFISH grids. I estimated total fleet effort per CFISH site (= 6^2nm) by proportioning the spatial distribution of fishing effort reported at 30^2nm to the same spatial distribution as the fishing effort reported at 6^2nm, for individual CFISH sites contained within a particular CFISH grid (as per Pantus 1996 and Slater *et al*. 1998).

6.3.3 Identification of critical areas

The identification of critical areas of sea turtle by-catch considered the interaction between the relative density of sea turtles and the intensity of fishing effort (Figure 6.2).

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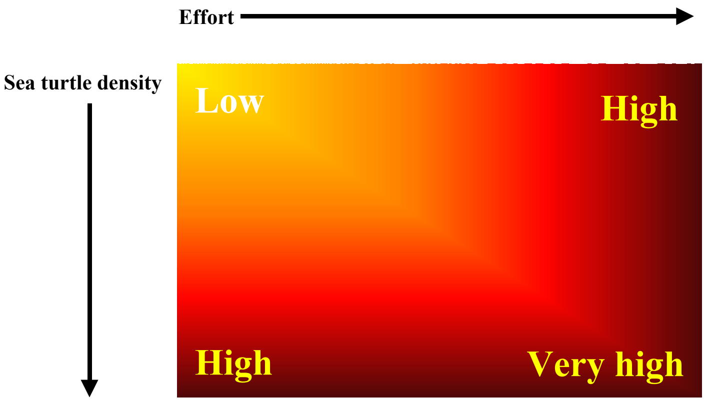
[15] Waters north of 15°S are closed to trawling from the 1st December until the 1st March in the following year. Waters south of 20°S are closed to trawling from the 1st October until the 1st November.

Three methods of integrating the relative density of sea turtles with fishing effort were explored. Method One used a qualitative index that combined the ranking of sea turtle density and fishing effort, as per McDaniel *et al*. (2000). Method Two used a quantitative index that was the product of sea turtle CPUE by fishing effort (i.e., predicted catch), as per Slater *et al*. (1998). Method Three used a quantitative index that was the product of sea turtle CPUE by fishing effort by sector-specific mortality rates (i.e., predicted mortality). The advantages and disadvantages of each method are discussed below.

Figure 6.2 Conceptual model of the interaction between sea turtle density and fishing effort



Method One. Qualitative combinations of sea turtle density and fishing effort

Method One was undertaken for estimates of the relative density of sea turtles based on: (i) predicted sea turtle CPUE (sea turtles caught per day fished) per CFISH site (= 6^2nm) derived from trawl captures; and (ii) sighted sea turtle density (sea turtles sighted per km^2) per CFISH site derived from aerial surveys. Qualitative categories of sea turtle density and fishing effort were combined to generate a matrix of 25 combinations, for predicted sea turtle CPUE (Table 6.2) and sighted sea turtle density (Table 6.3). McDaniel *et al*. (2000) used a similar method to assess aerial survey sea turtle densities overlaid with fishing effort in the Gulf of Mexico. McDaniel *et al*. (2000, p5) suggested, “this ranking system should allow for qualitative comparison among high and low areas of shrimping, as well as high and low sea turtle abundance”.

The division of sea turtle CPUE into five qualitative categories was based on the geometric progression of sea turtle CPUE (see Chapter 5, section 5.3.1, Table 5.1). The main consequence of this classification was that CFISH sites classified as ‘very high’ often had sea turtle CPUEs >0.143 sea turtles caught per day fished (i.e., one sea turtle caught per seven days of fishing). However, this thesis examines relative sea turtle density in the context of managing fishing impacts, and as such any CFISH site with a sea turtle CPUE >0.143 would be a priority for management.

The division of sea turtle sightings from aerial surveys into five qualitative categories was based on the classification used by Marsh and Saalfeld (1989), but with two extra classes (see Chapter 5, section 5.3.2, Table 5.2). One additional class distinguished between 'no sea turtles sighted' (i.e., zero sea turtles per km^2), and 'few sea turtles sighted' (i.e., <0.5 sea turtles per km^2). The other additional class divided areas where between 0.5 and 2.0 sea turtles per km^2 were sighted.

Table 6.2 Combinations of qualitative classes of sea turtle CPUE and fishing effort

Sea turtle CPUE[A] (sea turtles caught per day fished)	Annual fleet effort per CFISH site (days fished per year)				
	Very low (1 to 30)	**Low** (31 to 90)	**Medium** (91 to 180)	**High** (181 to 360)	**Very high** (>360)
Very low 0.00001 to 0.00549	Very low turtles / very low effort	Very low turtles / low effort	Very low turtles / med. effort.	Very low turtles / high effort	Very low turtles / very high effort
Low 0.00550 to 0.01111	Low turtles / very low effort	Low turtles / low effort	Low turtles / med. effort	Low turtles / high effort	Low turtles / very high effort
Medium 0.01112 to 0.03333	Med. turtles / very low effort	Med. turtles / low effort	Med. effort / med. turtles	Med. turtles / high effort	Med. turtles / very high effort
High 0.03334 to 0.14286	High turtles / very low effort	High turtles / low effort	High turtles / med. effort	High turtles / high effort	High turtles / very high effort
Very high >0.14286	Very high turtles / very low effort	Very high turtles / low effort	Very high turtles / med. effort	Very high turtles / high effort	Very high turtles / very high effort

[A] Mean sea turtle CPUE predicted from the GLM (Chapter 5).

Table 6.3 Combinations of qualitative classes of sea turtle sightings per km^2 derived from aerial surveys and fishing effort

Sea turtle sightings [A] (sea turtles sighted per km^2)	Annual fleet effort per CFISH site (days fished per year)				
	Very low (1 to 30)	**Low** (31 to 90)	**Medium** (91 to 180)	**High** (181 to 360)	**Very high** (>360)
Very low 0 (i.e., none sighted)	Very low turtles / very low effort	Very low turtles / low effort	Very low turtles / med. effort.	Very low turtles / high effort	Very low turtles / very high effort
Low 0.01 to 0.50	Low turtles / very low effort	Low turtles / low effort	Low turtles / med. effort	Low turtles / high effort	Low turtles / very high effort
Medium 0.51 to 1.00	Med. turtles / very low effort	Med. turtles / low effort	Med. effort / med. turtles	Med. turtles / high effort	Med. turtles / very high effort
High 1.10 to 2.00	High turtles / very low effort	High turtles / low effort	High turtles / med. effort	High turtles / high effort	High turtles / very high effort
Very high >2.00	Very high turtles / very low effort	Very high turtles / low effort	Very high turtles / med. effort	Very high turtles / high effort	Very high turtles / very high effort

[A] Derived from sighted sea turtle density (Chapter 5).

The advantages of Method One are that: (i) the resulting combinations (e.g., 'very high sea turtles / med. effort') are transparent as to the underlying data (i.e., sea turtle density or effort intensity); (ii) the method can be applied to sea turtle density estimates from either trawl capture or aerial survey data, thus allowing a comparison between sampling methods; (iii) the decision rules about critical areas could be decided upon by fisheries or conservation managers without major reclassification of the underlying data; (iv) the reassessment of critical areas in response to changing effort distribution would be relatively transparent, as effort intensity is explicitly included in the combinations. The disadvantages of Method One are that: (i) the difference between some combinations is difficult to interpret, although this is possibly a function of having 5x5 combinations rather than 3x3 combinations as per McDaniel *et al*. (2000); (ii) the implications of decisions rules about critical areas are qualitative in nature, thereby making it difficult to measure progress towards a quantitative management target, such as a 95% reduction in sea turtle by-catch; and (iii) any method that uses qualitative rankings must make a subjective choice as to where the cut-off of each category should occur and it is unlikely that all stakeholders involved in such an analysis will agree with the selected cut-offs.

Method Two. Quantitative estimate of relative density of predicted sea turtle captures
In Method Two, the predicted sea turtle CPUE was multiplied by year-2001 fishing effort per CFISH site to give an estimate of the relative density of predicted sea turtle captures. Slater *et al*. (1998) used a similar method to assess the risk of sea turtle capture in the Queensland East Coast Trawl Fishery[16], reporting that "due to the fact that there was insufficient information about populations sizes of various turtle species, the reported CPUE multiplied by the total trawl effort per grid cell was used as a substitute for the probability of a turtle being caught" (Slater *et al.* 1998, p 7).

The advantages of using Method Two (i.e., predicted sea turtle captures) are that: (i) a numeric value is generated that can be ranked (i.e., <1 to >200), providing clear visualisation of the areas in which the greatest numbers of sea turtles would be potentially caught if TEDs were not used correctly. The disadvantages of Method Two are that: (i) the reasons for the ranking of a CFISH site are not transparent (i.e., Is it due to sea turtle density or effort intensity?); and (ii) the method cannot be readily applied to

[16] Slater *et al.* (1998) used observed sea turtle CPUE per CFISH grids (=30^2nm), trawl effort per CFISH site (=6^2nm) for 1993 to 1996, nesting ground status and a qualitative ranking of conservation status.

aerial survey estimates of sea turtle density because of inherent differences in the units of measurement i.e., sea turtles sighted per km^2 and days fished.

Method Three. Quantitative estimate of relative density of sea turtle mortality
Sector-specific mortality rates were applied to the predicted sea turtle captures in a CFISH site (derived from Method Two), based on the mean tow duration of fishing sectors within the Queensland East Coast Trawl Fishery (see Chapter 3, section 3.4.6) and the most common species fished (i.e., fishing sector) in a CFISH site (see Chapter 5, section 5.2.3). The mortality rates applied to the predicted sea turtle captures included those calculated for: (i) observed dead sea turtles (i.e., direct mortality); (ii) observed dead and comatose sea turtles (i.e., potential mortality); and (iii) mortality rates reported for USA trawl fisheries (i.e., USA rates of mortality, Table 6.4). The advantages and disadvantages of Method Three are the same as Method Two. However, Method Three had an additional advantage of identifying where sea turtles are most likely to be killed in a trawl net, if TEDs are not used correctly.

Table 6.4 Sea turtle mortality rates applied to the product of sea turtle CPUE by fishing effort, based on the mean tow duration of the fishing sector.

Fishing sector	Mean tow duration (mins.)	Applied sea turtle mortality rates		
		Direct mortality [C]	Potential mortality[D]	USA rates of mortality[E]
Tiger Prawn	144[A]	4.3%	10.8%	20.8%
Endeavour Prawn	146[A]	4.4%	10.9%	21.1%
Red Spot King Prawn	128[B]	3.4%	9.3%	18.1%
Eastern King Prawn	>120[B]	2.9%	8.6%	16.8%
Moreton Bay	76[A]	0.2%	4.6%	9.5%
Banana Prawn	71[A]	0.1%	4.1%	8.7%
Scallop	155[B]	5.0%	11.8%	22.6%

[A] Mean tow duration observed during the current study; [B] mean tow duration reported by Dredge and Trainor 1994, which was longer than that observed during the current study; [C] all species pooled, observed in current study, based on $Y=0.0603(X–72.4)$, where Y is the expected mortality rate and X is the mean tow duration in minutes; [D] all species pooled, observed in current study, based on $Y=0.0912(X-26.1)$, where Y is the expected mortality rate and X is the mean tow duration in minutes; [E] all species pooled, reported by Henwood and Stuntz (1987), based on $Y=0.165(X–18.18)$, where Y is the expected mortality rate and X is the mean tow duration in minutes; Further details on mean tow durations and estimated mortality rates are supplied in Chapter 3, section 3.4.6, Table 3.11.

6.3.4 Ranking of critical areas for predicted catch of sea turtles

The sea turtle by-catch target for the Queensland East Coast Trawl Fishery is a 95% reduction in the incidental capture of sea turtles compared to the number estimated to be caught in 1991/1992 (QFMA 1998). This equates to a maximum incidental catch of 265 sea turtles per year. The spatial extent of areas that would require high TED compliance in order to achieve this target were identified by ranking CFISH sites in descending order, according to their percent contribution to the cumulative predicted catch of sea turtles. Fishing effort (days fished) was calculated for the CFISH sites that contributed to sea turtle catch in the critical areas. The number of vessels fishing in each critical area could not be calculated because of the encryption process of the CFISH database that masks the identity of individual vessels.

6.3.5 Assumptions and inherent difficulties of these methods

Total fleet effort

Fishing effort distribution was based on the effort reported by fishers. Anecdotal reports suggest that there may be some errors in the effort dataset i.e., over- or under-reporting of effort. However, from 1st January 2001, all vessels within the Queensland East Coat Trawl Fishery were required to be fitted with Vessel Monitoring Systems (VMS) and the fleet was polled at least once per day. This practice, in combination with vessel-specific limitations to the number of nights that can be fished is likely to have reduced the degree of mis-reporting of trawling effort in the year-2001 data used here.

Sea turtle density

Predicted sea turtle CPUE (sea turtles caught per day fished) was used as an index of the relative density of sea turtles in waters adjacent to the Queensland east coast. This distribution was based on the significant relationship between sea turtle catch rates, target species trawled and water-depth (see Chapter 5, section 5.5.3), but should be considered as predicted data until validated with field observations. The spatial recommendations for priority enforcement of TEDs thus should be viewed with some caution, particularly at fine spatial scales (i.e., single CFISH sites).

6.4 RESULTS

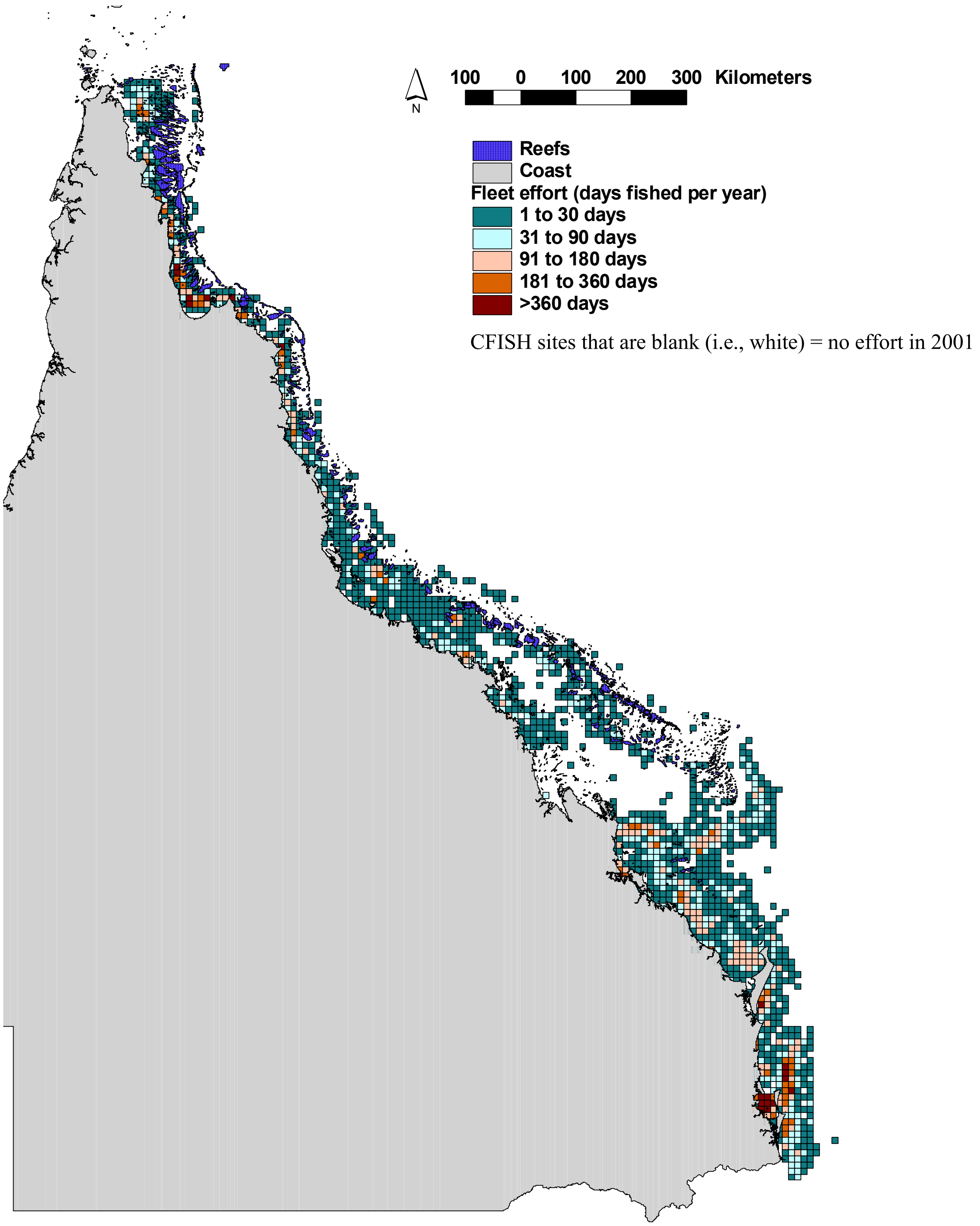
6.4.1 Total fleet effort per CFISH site

Effort was reported for 1,523 CFISH sites in the year-2001, but was not uniformly distributed throughout the Queensland East Coast Trawl Fishery (Figure 6.3). Trawling was highly concentrated, with a small number of CFISH sites having more than 360 days of fishing effort expended within them, whilst about 2/3^{rds} of CFISH sites had fewer than 31 days of fishing effort (Table 6.5).

Table 6.5 Distribution of year-2001 fishing effort

Annual fishing effort	Number of CFISH sites	Percentage of CFISH sites
1 to 30 days	1,011	66.4%
31 to 90 days	307	20.2%
91 to 180 days	126	8.3%
181 to 360 days	58	3.8%
>360 days	21	1.4%

Figure 6.3 Year-2001 total fleet effort (days fished) per CFISH site (6^2nm)



6.4.2 Identification of critical areas

Method One. Qualitative combinations of sea turtle density and fishing effort

USING PREDICTED SEA TURTLE CPUE (SEA TURTLES CAUGHT PER DAY FISHED)

A qualitative combination of sea turtle density based on predicted sea turtle CPUE and fishing effort was calculated for 1,523 CFISH sites (Figure 6.4). Fewer than 50 of the CFISH sites that were fished in the year-2001 were identified as having high to very high rankings of both sea turtle density and fishing effort (Table 6.6). Based on these rankings, critical areas for sea turtle by-catch occurred in the following general areas: (i) Moreton Bay; (ii) Hervey Bay; (iii) Bundaberg to Rodds Bay; (iv) Keppel Bay; (v) Edgecumbe Bay; (vi) Cairns to Lookout Point; (vii) Cape Melville to Shelburne Bay; and (viii) Oxford Ness (Figure 6.4).

Table 6.6 Number of CFISH sites per qualitative class of sea turtle CPUE and fishing effort

	Number of CFISH sites with various levels of annual fleet effort (Days fished per year)				
Sea turtle CPUE[A] **(Sea turtles caught per day fished)**	**Very low** (1 to 30)	**Low** (31 to 90)	**Medium** (91 to 180)	**High** (181 to 360)	**Very high** (>360)
Unknown (i.e., no estimate of sea turtle CPUE)	54	2	0	0	0
Very low 0.00001 to 0.00549	306	91	29	13	4
Low 0.00550 to 0.01111	112	48	15	7	0
Medium 0.01112 to 0.03333	72	29	13	6	1
High 0.03334 to 0.14286	276	77	36	11	2
Very high >0.14286	191	60	33	21	14

[A] Mean sea turtle CPUE predicted from the GLM (Chapter 5, section 5.3.1, Table 5.1).

USING SIGHTED SEA DENSITY FROM AERIAL SURVEYS (SEA TURTLES SIGHTED PER KM^2)

The qualitative combination of sea turtle sightings per km^2 with trawl effort was calculated for 553 CFISH sites (Figure 6.5). Fewer than 10 CFISH sites were identified as having high to very high rankings of both sea turtle sightings and fishing effort (Table 6.7). Based on the aerial survey sightings, critical areas for sea turtle by-catch included: (i) eastern Moreton Bay; (ii) the Cape Melville area; and (iiii) Princess Charlotte Bay.

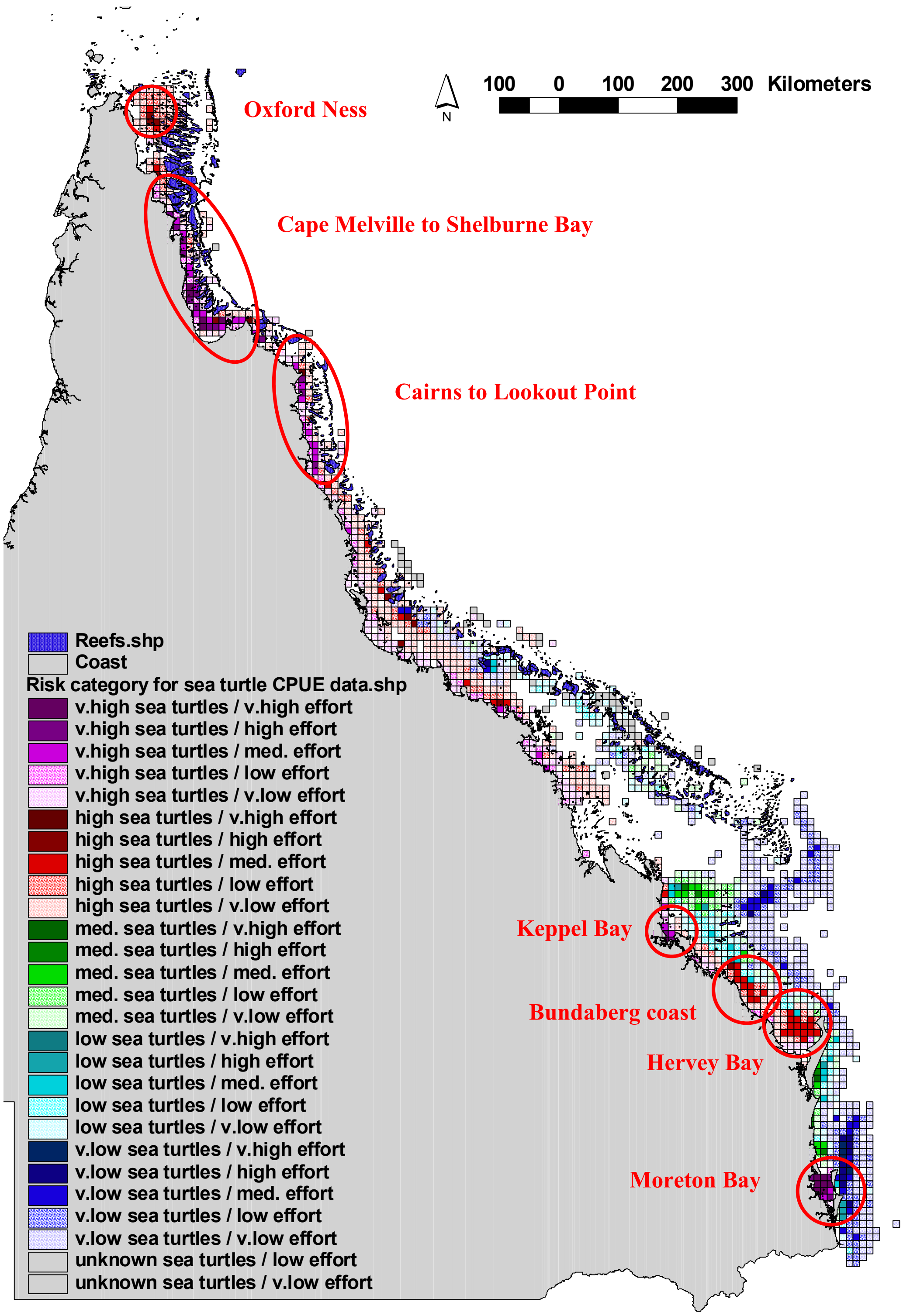
Table 6.7 Number of CFISH sites per qualitative class of sea turtle sightings per km^2 derived from aerial survey and fishing effort

Sea turtle sightings per km^{2} [A]	Number of CFISH sites with various levels of annual fleet effort (Days fished per year)				
	Very low (1 to 30)	**Low** (31 to 90)	**Medium** (91 to 180)	**High** (181 to 360)	**Very high** (>360)
Very low 0 (i.e., none sighted)	140	38	23	7	4
Low 0.01 to 0.50	91	33	32	9	8
Medium 0.51 to 1.00	42	14	3	4	2
High 1.10 to 2.00	41	7	3	4	1
Very high >2.00	35	6	4	4	1

[A] Derived from sighted sea turtle density (Chapter 5, section 5.3.2, Table 5.2).

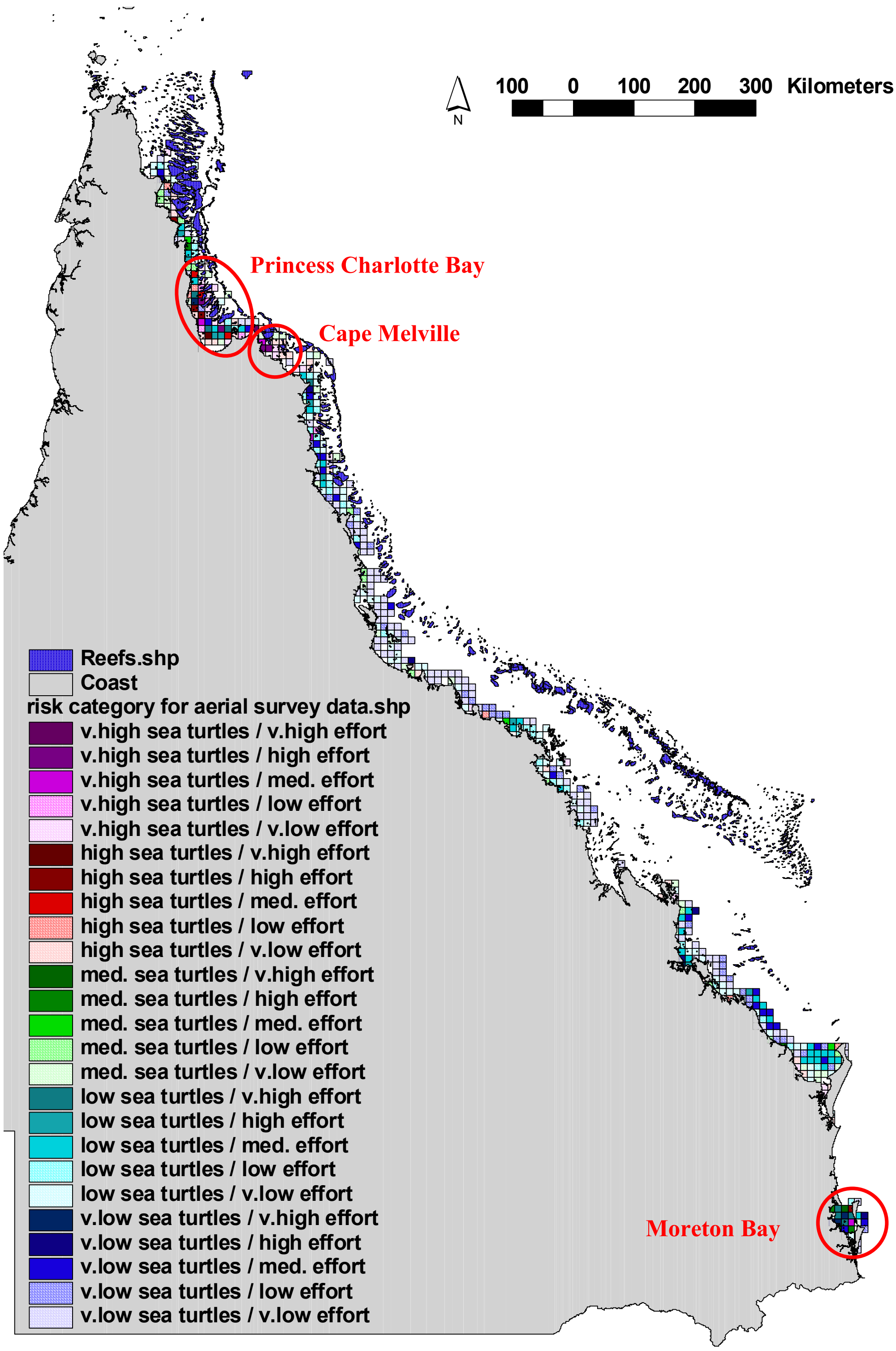
The maps presented here offer the opportunity to compare critical areas identified on the basis of trawl captures and aerial survey sightings. In general, the aerial survey estimates of relative sea turtle density did not represent the same degree of relative density as the trawl capture estimates. This could be a function of the classification system applied to each method, but could also reflect the different biases in the two sampling methods. Additionally, aerial surveys identified areas where sighted sea turtle density was high (see Chapter 5, section 5.4.2), but that have no trawling effort in the year-2001 because of spatial closures (i.e., Great Sandy Strait, Shoalwater Bay) or complex bottom structure (i.e., non-trawlable habitats such as the reef-shoal complexes in Princess Charlotte Bay). The comparison of critical areas derived from trawl capture data and aerial surveys suggests that restricting fishing operations (particularly by in-water closures) for the conservation of sea turtles should not be based solely on aerial survey data, as it is likely that some deep or turbid water areas will not be adequately represented.

Figure 6.4 Qualitative combination of sea turtle CPUE derived from trawl captures and fishing effort per CFISH site (6^2nm)



CFISH sites that are blank (i.e., white) = no effort in 2001

Figure 6.5 Qualitative combination of sea turtle sightings derived from aerial survey and fishing effort per CFISH site (6^2nm)



CFISH sites that are blank (i.e., white) = no effort in 2001

Method Two. Quantitative estimate of relative density of predicted sea turtle captures

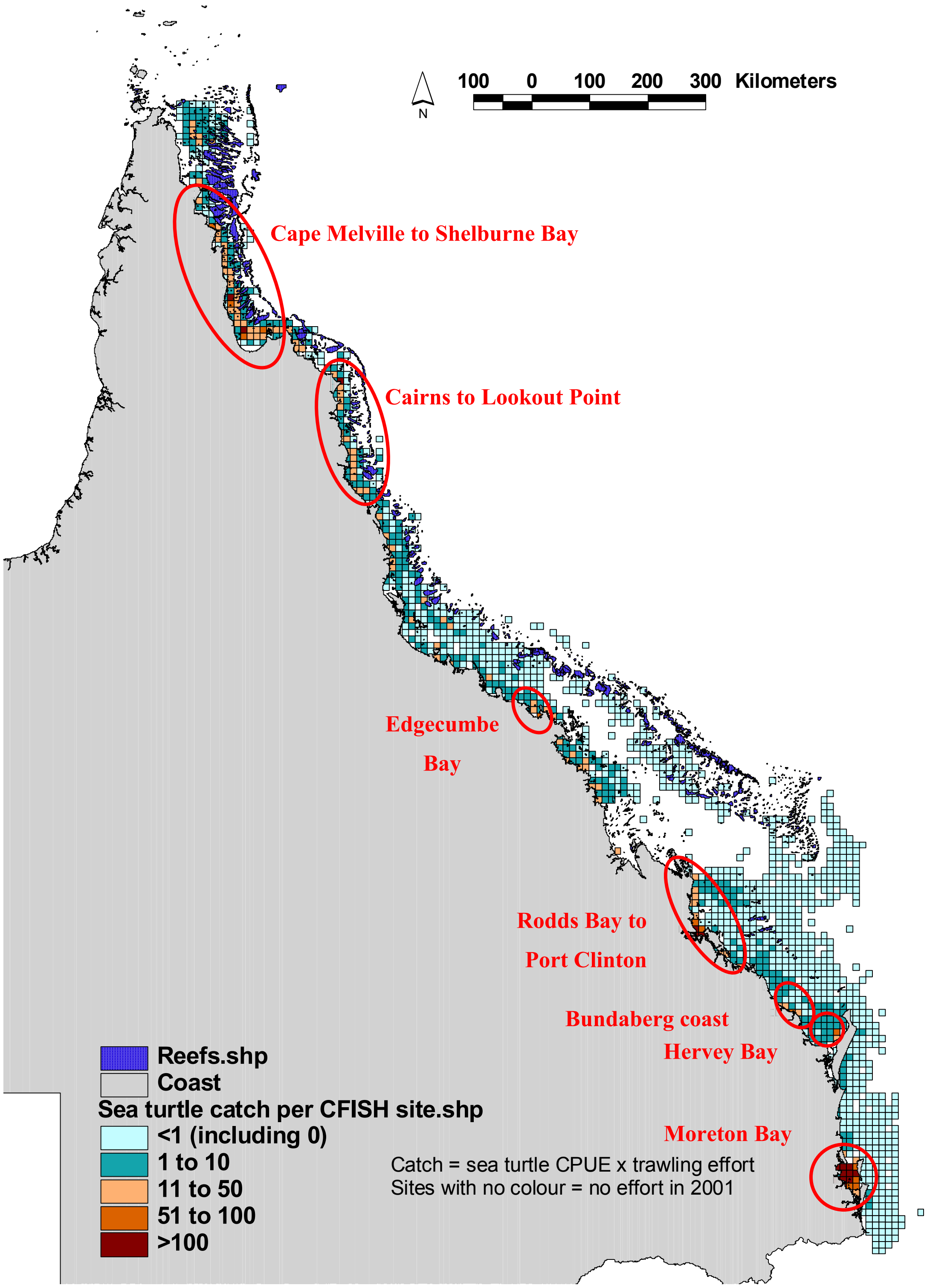
The majority of CFISH sites fished in the year-2001 were estimated to have a predicted sea turtle catch of less than one sea turtle per year (Table 6.8). Critical areas where the combination of sea turtle CPUE and fishing effort resulted in a relatively high predicted catch of sea turtles included: (i) Moreton Bay; (ii) the Bundaberg coast; (iii) Rodds Bay to Port Clinton; (v) Edgecumbe Bay; (vi) Cairns to Lookout Point; and (vii) Cape Melville to Shelburne Bay (PCB) (Figure 6.6).

Table 6.8 Number of CFISH sites per level of predicted sea turtle catch

Predicted catch of sea turtles per year	Number of CFISH sites [A]	Percent of CFISH sites
<1	986	64.7%
1 to 10	345	22.7%
11 to 50	104	6.8%
51 to 100	16	1.1%
>100	16	1.1%

[A] Excludes 56 CFISH sites for which catch could not be estimated because there was no estimate of sea turtle density. Fifty-four of these CFISH sites had <31 days of fishing effort (i.e., ‘very low’) and two had between 31 and 90 days of fishing effort (i.e., ‘low’).

Figure 6.6 Relative density of predicted sea turtle capture per CFISH site (6^2nm)



Method Three. Quantitative estimate of relative density of predicted sea turtle mortality

DIRECT MORTALITY

The majority of CFISH sites fished in the year-2001 were estimated to have a predicted direct mortality of less than one sea turtle per year (Table 6.9). Three CFISH sites were identified to have predicted direct mortality of between 5.1 and 10.0 individuals per year. These CFISH sites were all located in inshore waters north of Cairns (i.e., Lookout Point, and Princess Charlotte Bay, Figure 6.7). Lower levels of direct mortality were predicted for 43 CFISH sites, distributed throughout the inshore waters of the Queensland east coast (Figure 6.7).

Table 6.9 Number of CFISH sites per level of predicted sea turtle mortality

Predicted mortality of sea turtles per year	Number of CFISH sites with various levels of predicted mortality [A]		
	Direct mortality	Potential mortality	USA based mortality
<1	1,421	1,339	1,257
1 to 5	43	104	149
6 to 10	3	11	39
11 to 50	0	12	17
51 to 100	0	1	5
>100	0	0	0

[A] Excludes 56 CFISH sites for which catch could not be estimated because there was no estimate of sea turtle density. Fifty-four of these CFISH sites had <31 days of fishing effort (i.e., 'very low') and two had between 31 and 90 days of fishing effort (i.e., 'low').

POTENTIAL MORTALITY

The majority of CFISH sites fished in the year-2001 were predicted to have a potential mortality of less than one sea turtle per year (Table 6.9), but 13 CFISH sites were predicted to have a potential mortality of between 10.1 and 100.0 individuals per year. CFISH sites with the highest levels of predicted potential mortality were located in: (i) Moreton Bay; (ii) inshore waters north of Cairns; and (iii) Keppel Bay. CFISH sites where the potential mortality was predicted to be between one and five individuals per year were located in inshore waters along the Queensland east coast (Figure 6.8).

USA RATES OF MORTALITY

The majority of CFISH sites fished in the year-2001 were predicted to have a total mortality of less than one sea turtle per year, even when the mortality rates of trawl caught sea turtles were based on USA rates of mortality (Table 6.8). About 190 CFISH sites were predicted to have a total mortality of between 1.0 and 10.0 sea turtles per year and 22 CFISH sites were predicted to have a total mortality of between 10.1 and 100.0

sea turtles per year. Critical areas for the sea turtle mortality were: (i) Moreton Bay; (ii) inshore waters north of Cairns; (iii) Keppel Bay; and (iv) eastern Hervey Bay; as well as isolated CFISH sites associated with most coastal bays of the Queensland east coast (Figure 6.9).

Figure 6.7 Relative density of predicted sea turtle mortality per CFISH site (6^2nm), based on direct mortality rates per fishing sector

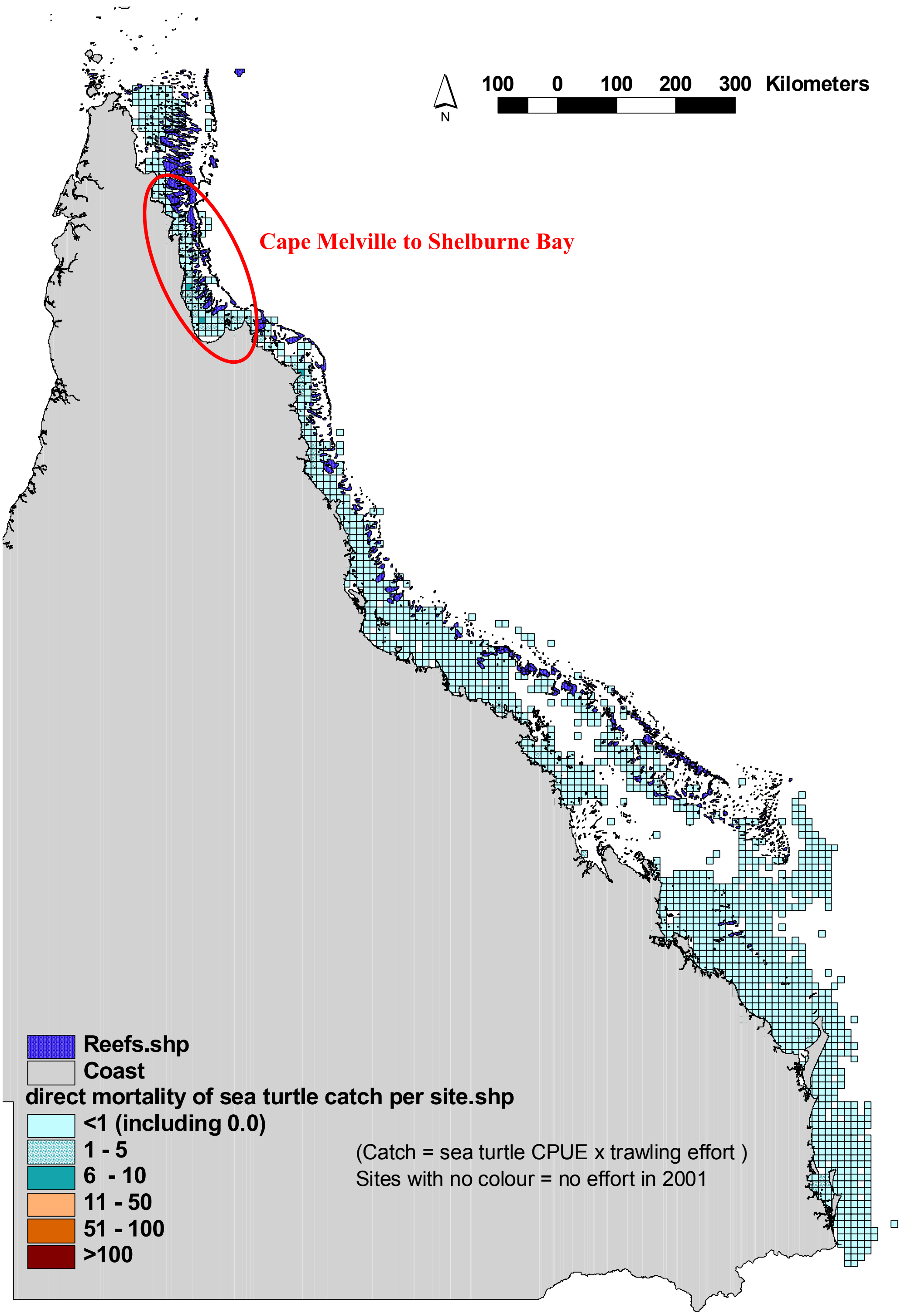


Figure 6.8 Relative density of predicted sea turtle mortality per CFISH site (6^2nm), based on potential mortality rates per fishing sector

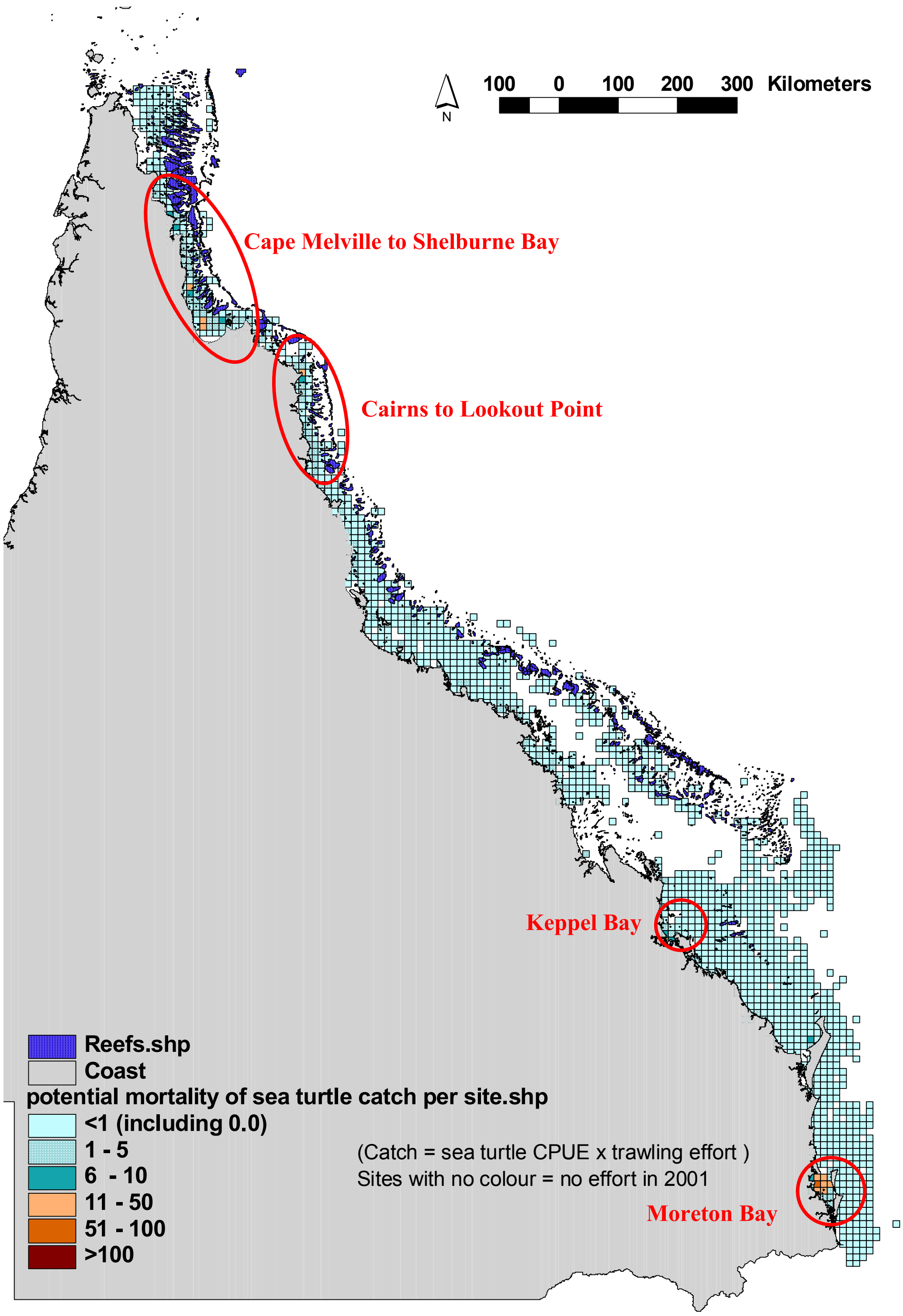
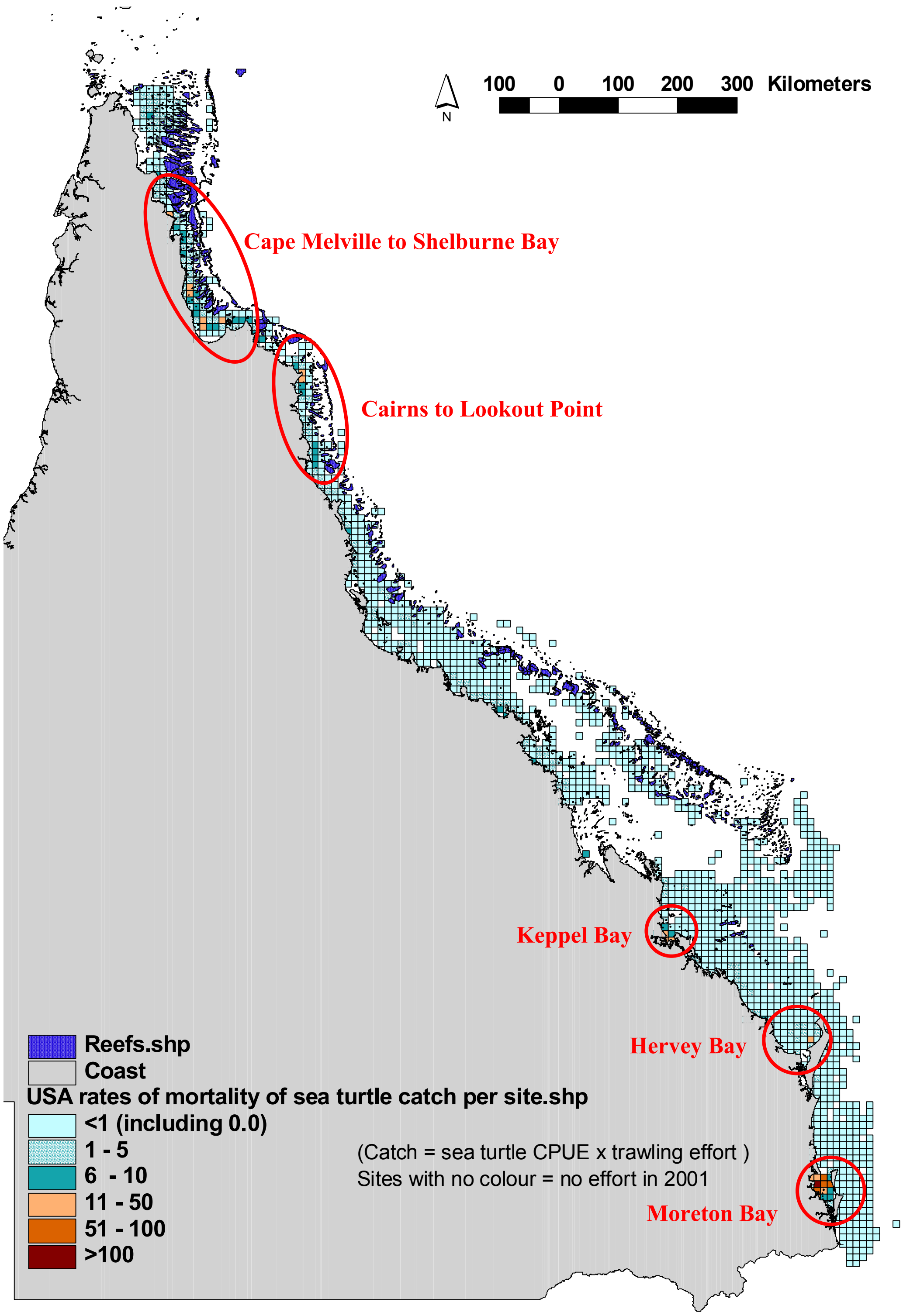


Figure 6.9 Relative density of predicted sea turtle mortality per CFISH site (6^2nm), based on USA rates of mortality applied to Queensland fishing sectors



6.4.3 Ranking of critical areas for predicted catch of sea turtles

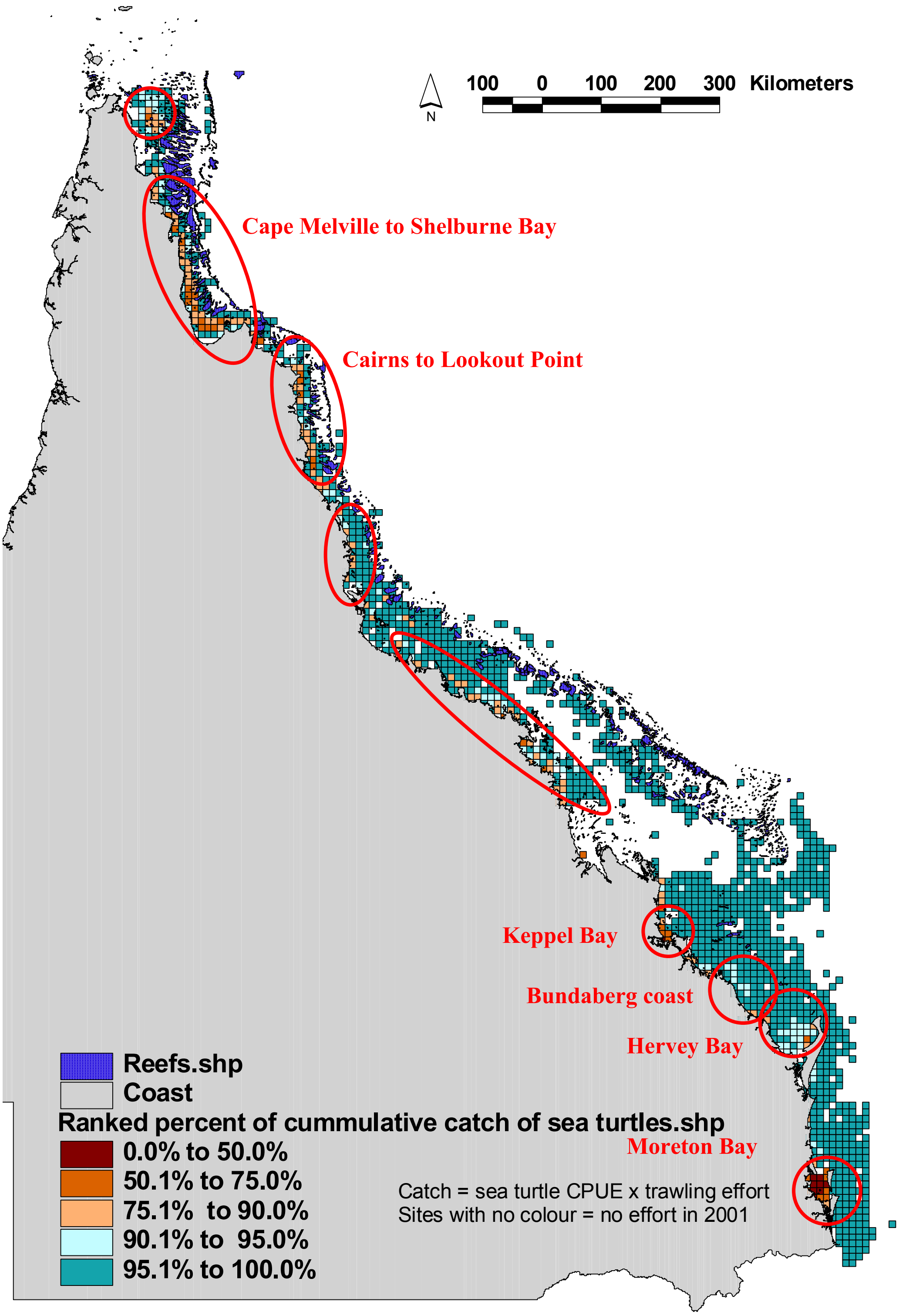
The data suggested that 268 CFISH sites contribute 95% of the cumulative total annual catch of sea turtles and that the 1,199 CFISH sites contribute less than 5% of the cumulative total annual catch of sea turtles (Table 6.10). As expected, the CFISH sites that contributed most to the total annual sea turtle catch were mostly located in inshore waters of the Queensland east coast (Figure 6.10). Seven of the eight most critical CFISH sites were located in Moreton Bay, with the other most critical CFISH site located in Keppel Bay. The 268 CFISH sites that contributed to 95% of the total sea turtle catch were located throughout the inshore water of the Queensland east coast (Figure 6.10). In order to achieve the 95% reduction in sea turtle catch, TED compliance in these 268 CFISH sites would need to be very high.

Table 6.10 Number of CFISH sites contributing to the ranked cumulative catch of sea turtles

Ranked percent cumulative catch of sea turtles	Number of CFISH sites [A]	Cumulative number of CFISH sites [A]	Year-2001 fishing effort (Days fished) [B]	Cumulative year-2001 fishing effort (Days fished) [B]
0 to 50.0%	8	8	9,380	9,380
50.1 to 75.0%	43	51	11,112	20,492
75.1 to 90.0%	106	157	10,250	30,742
90.1 to 95.0%	111	268	8,017	38,759
95.1 to 100.0%	1,119	1,387	33,577	72,336

[A] Excludes 56 CFISH sites for which catch could not be estimated because there was no estimate of sea turtle density. Fifty-four of these CFISH sites had <31 days of fishing effort (i.e., ‘very low’) and two had between 31 and 90 days of fishing effort (i.e., ‘low’). [B] Excludes 387 days of fishing effort in the 56 CFISH sites where sea turtle catch could not be estimated.

Figure 6.10 Ranked percent cumulative catch of sea turtles in the Queensland East Coast Trawl Fishery



6.5 DISCUSSION

6.5.1 Identification of critical areas

All methods based on sea turtle CPUE were useful and produced similar results in terms of identifying critical areas for sea turtle by-catch (Table 6.11). The qualitative ranking of combined categories (i.e., Method One) had the advantage of being very transparent as to the underlying data. This might be important when fisheries management agencies consult with other stakeholders (i.e., conservationists or fishers) as the reasons why an area has been identified as critical can be discussed (i.e., high sea turtle density or high fishing effort).

Table 6.11 Summary of critical areas identified by methods one, two and three

	Method of identifying critical areas					
	Method One – Qualitative		**Method Two - Quantitative**	**Method Three – Quantitative**		
	Sea turtle density and Fishing effort		Sea turtle CPUE by Fishing effort	Sea turtle CPUE by Fishing effort by Mortality rate		
Critical areas	Trawl catch rates	Aerial survey sightings		Direct mortality	Potential mortality	USA mortality
Oxford Ness	*	Not surveyed	*	-	-	-
Cape Melville to Shelburne Bay	*	*	*	*	*	*
Cairns to Lookout Point	*	-	*	-	*	*
Edgecumbe Bay	*	-	*	-		*
Keppel Bay	*	-	*	-	*	*
Bundaberg to Rodds Bay	*	-	*	-	-	-
Hervey Bay	*	-		-	-	*
Moreton Bay	*	*	*	-	*	*

Methods Two and Three produced quantitative estimates of the predicted sea turtle by-catch and predicted sea turtle mortality in various areas of the fishery. Quantitative estimates are more amenable for measuring progress towards a management target (Sainsbury *et al*. 1999). For example, the results from Method Two were ranked in order of their contribution to the cumulative sea turtle by-catch to identify those areas where TED compliance would need to be high in order to achieve the 95% by-catch reduction target. The use of TEDs in critical areas could be monitored through enforcement checks (i.e., at sea vessel boarding) or fishery-independent observers.

The distributions of predicted sea turtle mortality (from Method Three) identify those fishing sectors of the Queensland East Coast Trawl Fishery that have the greatest potential impact on sea turtles and where from a conservation perspective, TEDs would need to be most effective. The critical areas identified by Method Three were the same as (if only a subset of) the critical areas identified by Method Two. Current management targets for sea turtle by-catch in the Queensland East Coat Trawl Fishery relate to total catch not total mortality (QFMA 1998, EA 1998). Therefore, whilst the mortality distributions are interesting from a conservation and total impact perspective, the critical areas identified by Method Two are most relevant to developing a spatially explicit TED monitoring and enforcement strategy for the Queensland East Coast Trawl Fishery in order to measure progress towards the legally binding management targets. However, if the management target for sea turtle by-catch was related to total mortality, then the relative distribution of predicted sea turtle mortality (i.e., Method Three) would be useful in identifying where monitoring of TEDs would be most critical in order to asses progress towards the management target. In the case of the Queensland East Coast Trawl Fishery, the critical areas for predicted sea turtle mortality (i.e., by Method Three) were very similar to the critical areas for predicted sea turtle catch. Therefore in this case, a TED monitoring and enforcement program focused on critical areas for sea turtle catch would also encompass the critical areas for predicted sea turtle mortality. Whether this overlap is translatable to other prawn trawl fisheries is unknown, but is likely to be the case in fisheries where high sea turtle density, high fishing effort and long tow durations overlap.

The critical areas identified by the analysis in this chapter for the Queensland East Coast Trawl Fishery may change if the distribution of fishing effort changes over time, or if the relative density of sea turtles changes over time as populations recover. The analyses developed in this chapter could be re-analysed to accommodate changes in fishing effort, but could not account for or predict changes in sea turtle distribution. It will be difficult to determine if the broad scale relative density of sea turtles changes in the future, because aerial survey and rodeo-capture sampling methods cannot adequately sample sea turtles in deep (i.e., >10m) or turbid waters (see Chapter 5, section 5.5.3).

6.5.2 Challenges for a TED compliance program

Monitoring TED compliance and effectiveness presents challenges in a fishery as large and widely distributed as the Queensland East Coast Trawl Fishery, despite the identification of critical areas for sea turtle by-catch. The results presented in this chapter have identified that TED compliance efforts should be focused on 268 of 1,523 CFISH sites in which the Queensland East Coast Trawl Fishery operates annually. However, fishing effort in these CFISH sites accounts for 38,759 days fished (i.e., about half of the fishing effort expended annually in the Queensland East Coast Trawl Fishery). Assuming that on average, 200 days are fished by each vessel that fishes within the 268 CFISH sites identified as critical areas, then at least 194 vessels must be checked for TED compliance or monitored for sea turtle captures. Currently, the enforcement section of the Queensland Fisheries Service i.e., the Queensland Boating and Fisheries Patrol (QFBP) is the main agency responsible for checking compliance with TED regulations. At present the QFBP employs 122 staff. Assuming that each QFBP officer is available for work five days a week for 48 weeks per year, then at most the QBFP has 29,280 person days available for enforcement activities. If half of these days were dedicated to TED compliance, then about 1/3rd of the days fished in critical areas could be checked. If only 10% of these days were dedicated to TED compliance, then about 13% of the days fished in critical areas could be checked. The QFBP presently does not have a dedicated enforcement strategy or identified number of days for TED monitoring enforcement. Rather, checking of TEDs is carried out as part of enforcement activities for a broad range of offences under the Queensland *Fisheries Act 1994* (Mr Peter Tanner, QBFP, personal communication 2002). The numbers suggested above serve to illustrate that while the spatial extent of areas in which TED compliance and monitoring could be focused, the temporal component is challenging because it refers to almost 39,000 days of fishing effort.

If TED compliance was measured as being low in critical areas, then spatial or temporal closures would need to be considered. Spatial or temporal closures could be implemented only to address fisheries management targets (i.e., the 95% reduction in sea turtle by-catch) or could be part of the broader program to protect representative areas of the Great Barrier Reef from extractive use (GBRMPA 1999). However, the closure of critical areas for sea turtle by-catch may lead to the displacement of fishing effort into other areas (QFMA 1996). Therefore, if spatial or temporal closures are introduced as a means of achieving the target reduction in sea turtle by-catch, then either fishing should be reduced correspondingly or changes in fishing effort should be monitored closely to ensure that new critical areas do not appear as a function of increased fishing effort. Alternatively, if TED compliance was consistently high in critical areas because fishers were using TEDs correctly, then TED compliance checks may be unnecessary. In the case of the Queensland East Coast Trawl Fishery, another essential aspect of a TED compliance strategy would be to ensure that TED regulations precluded the use of ineffective designs (e.g., have sufficiently large escape openings Epperly and Teas 2002) and are written in a manner that ensures offenders can be prosecuted.

6.6 CONCLUSIONS

TEDs are a pragmatic solution to the problem of sea turtle by-catch because they allow trawling operations to continue whilst minimising the effect of trawl capture on sea turtles. However, the effectiveness of TEDs as a solution to sea turtle by-catch is largely dependent on the efficiency of the devices used in practice and the compliance rate of fishers with TED regulations. The spatial integration of the relative density of sea turtles and fishing effort clearly identified seven critical areas for sea turtle by-catch in the Queensland East Coast Trawl Fishery. It also demonstrated the value of having baseline data on the spatial distribution of sea turtle catch rates and fishing effort. A stratified compliance and monitoring program for TEDs that uses enforcement checks and fishery-independent observers would enable the spatial allocation of limited resources to areas in which sea turtle conservation will have the greatest benefit. A management target for the Queensland East Coast Trawl Fishery is a 95% reduction in sea turtle by-catch. A performance measure of this target could be TED compliance by vessels operating in the critical areas identified here. Whilst monitoring the compliance of vessels with TED regulations or the effectiveness of TEDs during fishing operations would not guarantee the achievement of the management target, these would be a tangible measures against which management and industry progress could be measured. This is the first time that a spatial-specific strategy has been developed for measuring a fishery’s progress towards the minimisation of sea turtle by-catch.

CHAPTER 7. CONCLUSIONS AND IMPLICATIONS

7.1 CHAPTER SUMMARY

Sea turtles are charismatic species of high conservation significance. Australian continental waters offer some of the few remaining areas of the world where sea turtle populations have been subject to relatively low levels of harvest and where nesting- and feeding-ground habitats remain essentially intact. However, the exploitation of fisheries resources in northern Australia by demersal trawling has directly impacted on five species of sea turtle. Managing the impacts of fishing on endangered and threatened by-catch species is necessary in order to protect biological diversity and maintain ecological processes, which are goals of the sustainable development of marine resources. Turtle Excluder Devices (TEDs) have been regulated into Australian prawn trawl fisheries to mitigate sea turtle by-catch. TEDs can be an effective solution, but the adoption and use of TEDs in a fishery should be monitored to ensure that a genuine outcome is achieved. The present study has contributed to the sustainable management of sea turtle by-catch by developing a comprehensive approach to understanding the interaction between prawn trawling and sea turtles. In this thesis, I have:

(i) Estimated of the number and species composition of sea turtles caught and killed in the Queensland East Coast Trawl Fishery, which combined with estimates from other trawl fisheries in northern Australia, indicates that the use of TEDs is warranted;

(ii) Investigated the behavioural responses of sea turtles post-release from trawl captures; no evidence of delayed mortality was found, but indications are that recovering sea turtles may be more susceptible to boat strikes and have altered feeding patterns;

(iii) Predicted the relative density of sea turtles in waters adjacent to the Queensland east coast to generate quantitative broad scale maps of the relative density of sea turtles, based on the significant relationship between sea turtle density, water-depth and benthic species trawled; and

(iv) Developed a spatially explicit strategy for monitoring the performance of TEDs (i.e., compliance and efficiency) by integrating the predicted sea turtle density and fishing effort.

7.2 CONTRIBUTIONS TO KNOWLEDGE

In Chapter 1 (section 1.3.1), I identified that to sustainably manage sea turtle by-catch, the following information was needed: (i) the relative distribution of sea turtles; (ii) the relative distribution of fishing effort; and (iii) the scale and nature of sea turtle by-catch. I also identified that post-trawl mortality had potential to increase the impact of incidental capture on sea turtle populations (see Chapter 2, section 2.6) and that a comprehensive approach to the management of sea turtle by-catch was needed in order to ensure a genuine outcome for the sustainable management of fishing activities and sea turtle conservation (see Chapter 1, section 1.2 and 1.3). My contributions to these aims are discussed below for each of the objectives specified in Chapter 1, section 1.4 and 1.5.

7.2.1 Estimated catch and mortality

It is accepted that populations of sea turtles are highly susceptible to anthropogenic impacts because sea turtles are long-lived species and have an inherently low recovery potential (Crouse 1999; Musick 1999; Heppell *et al.* 1999; Hall *et al.* 2000). The "conspicuous absence of data on location, catch rate and species composition of the incidental turtle catch from the Queensland East Coast Trawl Fishery" identified by Dredge and Trainor (1994, p141) and Limpus and Reimer (1994) has been filled by results presented in Chapter 3 of this thesis. I estimated that about 5,900 sea turtles were caught annually in the waters adjacent to the Queensland east coast, with about 50% being *C. caretta*. Between ~100 to ~400 *C. caretta* were estimated to be killed annually in the prawn trawl fisheries of northern Australia (Chapter 3, section 3.5.3), which is of sufficient magnitude to have caused the documented 50% to 80% decline in nesting numbers of *C. caretta* (Heppell *et al.* 1996; Chaloupka and Limpus 1998). The trawl-related mortality of *C. caretta* combined with the mortality of other sea turtle species, particularly *N. depressus* (between ~200 and ~1,100 individuals per year) and *L. olivacea* (between ~50 and ~250 individuals per year) support the mandatory use of Turtle Excluder Devices (TEDs) in the demersal prawn trawl fisheries of northern Australia. I estimated that between 60 and 80% of the sea turtle catch was of immature size classes, depending on species (Chapter 3, section 3.4.4). This quantitative information on the maturity status of trawl-caught sea turtles will assist modelling of the potential population response to the use of TEDs (e.g., Crowder *et al.* 1994) and for the first-time, there are now estimates of the proportion of immature and adult *N. depressus* and *L. olivacea* in Australian feeding-grounds. Understanding the distribution and demographics of sea turtles in feeding-grounds, such as those of the Queensland east coast, is essential if anthropogenic impacts are to be effectively managed and sea turtle populations monitored to ensure that management measures achieve the desired outcomes.

7.2.2 Responses of sea turtles to capture

Most sea turtles are alive when they are released back into the water after a capture. However, the forced submergence associated with a trawl capture is thought to be a stressful event, which may make sea turtles die at a later stage. There is limited quantitative information on the post-release response of sea turtles to trawl capture. The results presented in Chapter 4 offer some understanding of how sea turtles respond to capture events. Even from the limited number of sea turtles monitored in the present study (i.e., five trawl-caught and two rodeo-caught sea turtles), there was evidence that non-fatal captures significantly affected the behaviour of sea turtles and could increase the risk of secondary mortality as a consequence of boat strikes or predation by sharks. Trawl-caught sea turtles required extended periods of time to recover (possibly >100 hours, Chapter 4, section 4.5.2), during which it is speculated that normal feeding activities were not undertaken. This suggests that the nutrition and growth and subsequent breeding of sea turtles in heavily trawled areas might be impacted by frequent but non-lethal trawl-captures. The use of TEDs in the Queensland East Coast Trawl Fishery should minimise such non-lethal impacts associated with trawl capture, assuming that interactions with TED-equipped nets are less stressful than forced submergence. The dive patterns displayed by trawl-caught and rodeo-caught sea turtles suggest that sea turtles are stressed by interactions with humans to a much greater degree than previously understood and that recovery periods potentially are much longer than previously thought.

7.2.3 Spatial distribution of sea turtles

It is well known that sea turtles are widely distributed throughout tropical and sub-tropical waters, but are not uniformly distributed throughout feeding-ground habitats. The results presented in Chapter 5 provide quantitative broad scale maps of the relative distribution of sea turtles, particularly in deep and turbid waters that are difficult to sample by the established methods of rodeo-capture (Limpus and Reed 1985a; Chaloupka and Limpus 2001) and aerial survey (Marsh and Saalfeld 1989; Epperly *et al.* 1994, 1995a; Preen *et al*. 1997; McDaniel *et al.* 2000). The trawl capture and aerial survey sightings of sea turtles in waters adjacent to the Queensland east coast provided maps of the observed in-water relative densities of sea turtles in specific areas (i.e., those sampled by the fishers participating in the sea turtle by-catch monitoring program and coastal waters covered by the aerial surveys). The significant relationship between sea turtle densities, water-depth and benthic species trawled (i.e., prawn and scallop species) provided a model by which the relative density of sea turtles could be predicted for most continental shelf waters of the Queensland east coast. Predicting the spatial distribution of a species based on habitat parameters has been undertaken for terrestrial species, particularly birds (Manel *et al.* 1999; Milsom *et al.* 2000; Huettman and Diamond 2001). This type of analysis is being extended into marine areas, with species catches from trawl-surveys being used to infer the distribution of seafloor habitats (Auster *et al*. 2001), but the results presented in Chapter 5 represent the first time this method has been applied to sea turtles. The predicted spatial distribution of sea turtle density needs validation through ground-truthing. Water-depth and benthic species trawled have been used as surrogates for information about aquatic habitats because of the availability of such information at broad spatial scales. More specific indicators of the aquatic habitats of sea turtles may develop as benthic mapping is implemented in waters of the Queensland east coast.

7.2.4 Assessment of critical areas for sea turtle by-catch and management implications

Sea turtle by-catch in most trawl fisheries of the world is managed most commonly through the mandatory use of TEDs because this approach allows trawling to continue whilst the number of sea turtles caught and killed is minimised. Tucker *et al*. (1997) identified that enforcement is necessary to ensure a genuine outcome for sea turtle conservation from the regulation of TEDs into a fishery. There is a distinct lack of discussion in the grey and published literature on how to monitor TEDs in a fishery to measure performance against management targets. Any strategy to monitor the performance of TEDs must consider the efficiency of the devices used in the fishery and the practicalities of monitoring TEDs at the spatial or temporal scale of the fishery. The results presented in Chapter 6 provide a spatially explicit consideration of options to monitor the performance of a fishery against management targets for reductions in sea turtle by-catch. In Chapter 6, three methods of identifying critical areas where the effective use of TEDs would have the greatest conservation benefit were explored. A management target for Queensland East Coast Trawl Fishery is the 95% reduction in sea turtle by-catch. A performance measure of this target would be TED compliance by vessels operating in the seven critical areas identified in Chapter 6. Whilst monitoring the compliance of vessels with TED regulations or the effectiveness of TEDs during fishing operations would not guarantee the achievement of the management target, they would be a tangible measure against which management and industry progress could be assessed. This is the first time that a spatially specific strategy has been developed for measuring a fishery's progress towards the minimisation of sea turtle by-catch.

7.3 LIMITATIONS

The estimates of catch and mortality and relative density of sea turtles in waters associated with the Queensland East Coast Trawl Fishery are based on information returned by commercial fishers who volunteered and whom I vetted on the basis of interest and consistency of returns. An inherent criticism of fishery-dependent sampling is the possibility of bias from small or unrepresentative sampling and if based on logbooks, inaccurate reporting by the fishers involved (Murphy and Hopkins-Murphy 1989). Bias in the sample or inaccurate reporting should be minimised by the number of fishers from whom information was collected (i.e., ~100). I acknowledge that a some specific areas of the fishery were under-represented by the sample fleet (i.e., waters off the Gold Coast, which is located between Brisbane and the state border between Queensland and New South Wales). However, estimates of total catch and mortality were stratified by fishing sector and season, thereby using interpolation from areas with similar conditions (i.e., benthic species trawled and fishing operations). Likewise, estimates of sea turtle catch per unit effort were stratified by fishing sector and water-depth and the predicted relative densities were interpolated from areas with similar conditions. Interpolation is the basis for research sampling and analysis as it is impossible to sample the entire population.

In spite of these limitations, the estimates of catch and mortality and relative density of sea turtles in waters associated with the Queensland East Coast Trawl Fishery comprise the best information currently available. The preliminary estimates of catch associated with this thesis (Robins 1995) have been used to set legally binding management targets for the state of Queensland (QFMA 1998) and incorporated into the Draft National Recovery Plan for Marine Turtles (EA 1998). The predicted relative density of sea turtles generated by this thesis are being considered for use by the Great Barrier Reef Marine Park Authority in the assessment of candidate areas for protection under the Representative Areas Program (GBRMPA 1999) as my estimates of predicted sea turtle density[17] are the only quantitative fine-scale maps of sea turtle distributions for the majority of waters on the continental shelf of the Queensland East Coast.

7.4 IMPLICATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

7.4.1 By-catch

Sustainable management of by-catch

The sustainable management of by-catch in fisheries throughout the world requires: (i) understanding and quantification of by-catch problems; (ii) evaluation of appropriate by-catch management strategies; and (iii) monitoring to ensure adopted by-catch management strategies are effective in achieving their objectives. To date, major intervention into the management of fisheries for by-catch issues has focused on 'charismatic' species i.e., dolphins, seals, sea birds and sea turtles (Harris and Ward 1999; Hall *et al.* 2000). However, the principles of ESD require that the impacts of fishing on all types of by-catch species be managed for sustainability.

The comprehensive approach presented in this thesis could be applied to other by-catch species. One of the greatest challenges facing the sustainable management of by-catch

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[17] Slater *et al.* (1998) based their maps of the spatial risk of sea turtle to trawl capture on the sea turtle CPUE data collected in the current thesis. The sea turtle CPUE used by Slater *et al.* (1998) is observed sea turtle CPUE at a relatively coarse scale (i.e., per CFISH grid = 30^2nm) and has limited coverage (see Chapter 5, Figures 5.5 to 5.10) whereas the predicted relative density of sea turtles is based on sea turtle CPUE at a relatively fine scale (i.e., per CFISH site = 6^2nm) and is interpolated to most areas of the Queensland east coast continental shelf through interpolation using the type of species trawled (i.e., fishing sector) and water-depth (see Chapter 5, Figures 5.17 to 5.22).

in trawl fisheries is the overwhelming number of species caught, especially in tropical demersal trawl fisheries, and the lack of baseline data for many by-catch species (Alverson *et al* 1994).

Stobutzki (*et al.* 2001a) proposed that the ability of a species to sustain by-catch impacts depends on two factors: (i) the ‘susceptibility’ of a species to capture and mortality; and (ii) the capacity of a species to ‘recover’ once the population is depleted. These factors can be assessed within a risk assessment framework to determine the potential sustainability of fisheries impacts on by-catch species where knowledge of life-history parameters or by-catch impacts is poor (see Chapter 1, section 1.2.2). However, the analysis and interpretation of data collected in this thesis demonstrates that baseline information on the scale, species composition and maturity status of individuals caught and killed incidental to fishing operations is valuable to making informed decisions on by-catch management and monitoring. Such information is fundamental to understanding the impact of fishing on by-catch populations and is important to understanding the potential recovery of the affected populations. Understanding recovery rates is important for situations where it is difficult to measure changes in the population that are directly a consequence of management intervention, e.g., the use of TEDs to reduce sea turtle mortality and assist in the recovery of populations of sea turtles (Crowder *et al.* 1994; Crowder *et al*. 1995). Baseline knowledge provides the scientific basis for identifying the most effective strategy to mitigate the impact of fisheries on by-catch species. Such knowledge also allows the development of spatially stratified monitoring and enforcement strategies that permit fisheries managers to deploy resources in areas that will have the greatest benefit.

Estimating relative density distributions of by-catch species

In this thesis, I used readily available information (i.e., water-depth and benthic species trawled) to assess the relative capture rates of a by-catch species in areas sampled by a select group of fishers. This information was then used to predict the relative density of a species for which there was no quantitative information on relative distribution in most areas of the Queensland east coast. Predicting the spatial distribution of a species based on habitat parameters has been undertaken for some terrestrial species (Manel *et al*. 1999; Milsom *et al*. 2000; Huettmann and Diamond 2001). It is likely that a similar method to that applied to sea turtles in this thesis could be used to predict the relative density of other aquatic species associated with aquatic habitat types that can be differentiated by water-depth and benthic species trawled. Research into this area is expanding and Auster *et al*. (2001) report that the distribution of trawl-caught species can be used as surrogates for the distribution of co-occuring species in seafloor habitats. For the Queensland east coast, sea snakes and pipefishes are two species for which there is significant concern about the potential impacts of fishing (QFMA 1996), but for which there is little information on their relative distribution. Such information could be important in addressing by-catch concerns as sea snakes and syngnathids (e.g., pipefish) are not effectively excluded by TEDs or BRDs (Milton 2001) and it is likely that spatial closures would be necessary in order to reduce by-catch impacts (Ward 2000).

7.4.2 Sea turtles

In-water sampling

Sea turtle research in feeding-ground habitats is important to compliment the information gained at nesting-ground habitats. However, sea turtles are inherently difficult to survey in feeding-ground habitats, particularly in deep or turbid waters. The analysis and interpretation of trawl survey data in this thesis demonstrates the value of in-water surveys of sea turtles at broad geographic scales. Demersal trawling appears to be a relatively effective method for sampling sea turtles in areas that are unable to be sampled by rodeo-capture or aerial survey (TEWG 2000). Dedicated research surveys using trawl nets could provide a wealth of information on sea turtles in areas that have been previously difficult to access. The use of conventional trawls to sample sea turtles could validate predicted relative densities, such as those estimated in this thesis, as well as provide essential demographic information on the size composition, maturity status and genetic stock structure of sea turtles in the surveyed areas. Submergence mortality could be minimised by using short tow durations (i.e., 30 minutes) and resuscitation techniques. Alternatively, trawl nets could be modified so as to have absolutely no risk of submergence mortality through the use of open-ended nets or nets fitted with efficient TEDs. In this case, sea turtles would need to be non-extractively sampled using technology such as stereo-video cameras (Dr Euan Harvey, University of Western Australia, personal communication 2002), which could provide measurements of relative density as well as size of individuals.

If in-water sampling of sea turtles in feeding-grounds by trawl survey is not feasible for political or conservation reasons, then the conservation of sea turtle populations must rely on information collected at feeding-grounds by other techniques. Therefore, selected feeding-grounds become critical in monitoring sea turtle populations. Feeding ground studies such as those conducted by the Queensland Turtle Research Group have collected data on the rate of recruitment of juveniles to neritic feeding-grounds (Chaloupka and Limpus 2001). This is an index of trends in population size that provides feedback on whether a population is increasing or decreasing decades earlier than indices collected at the nesting beach. The rate of recruitment of juvenile *C. caretta* to feeding-grounds along the Queensland east coast will be the only short-term measure of whether TEDs are having an effect on the population sizes of sea turtle. Unfortunately, if the recruitment rate of juvenile *C. caretta* does not increase, it will be difficult to determine whether this is a consequence of ineffective TED use or other sources of anthropogenic mortality e.g., mortality in longline fisheries or delayed effects of fox predation.

TEDs in trawl fisheries

Detailed information on the spatial and temporal extent of sea turtle by-catch is not available for all prawn trawl fisheries of the world. Lack of resources, constitutional arrangements and political indifference to the usefulness of baseline data have resulted in the regulation of TEDs into most trawl fisheries without consideration of what is the management target (i.e., sea turtle catch or mortality and to what level) and how the effectiveness of TEDs can be monitored given the resources of the managing agency and the spatial and temporal difficulties of specific fisheries. This is not to say that the regulation of TEDs into a fishery should be delayed because of a lack of data, but rather raises the question of how can the effectiveness of TEDs be measured in trawl fisheries to ensure that sea turtle captures are being minimised? This problem would not be so great if the current indices of the population size of sea turtles (i.e., number of sea turtles nesting on a beach) responded in an immediate and identifiable manner to the use of TEDs. However, the current indices of population size cannot determine the cause of trends (up or down) in the number of nesting sea turtles. For example, are nesting trends the consequence of effective TED use in trawl fisheries or headstarting efforts or nest-protection efforts or reduced human harvest? Therefore, research into the status of sea turtle populations must adopt a multi-facetted approach, gathering information at nesting-grounds as well as feeding-grounds. Development of techniques for in-water research should be supported so that efforts to conserve sea turtle populations do achieve a genuine outcome.

Conservation in feeding-grounds

Sea turtles have a complex life cycle spilt between nesting- and feeding-grounds and oceanic and continental waters (see Chapter 2, section 2.3). In general, all species of sea turtle spend about two thirds of their life on feeding-grounds, many of which are associated with the coastal waters used by humans for a variety of purposes (e.g., fishing, recreational boating, shipping). Many of these activities impact upon sea turtles (Lutcavage *et al.* 1996). The scale and temporal exposure of sea turtles to such impacts suggests that human sources of mortality at feeding-grounds play a critical role in the fate of sea turtle populations. Also contributing to the issue of sea turtle conservation in feeding-grounds is our lack of understanding as to those features of the aquatic environment that are essential for critical sea turtle habitats. Developing a model for predicting the distribution of sea turtles based on features of aquatic habitats, such as the model developed in Chapter 5 of this thesis, may provide a way forward in identifying critical sea turtle habitats in the absence of broad scale in-water surveys of the relative abundance or density of sea turtles. Greater understanding of the distribution of sea turtles in feeding-grounds would enable effective planning for the conservation and management of critical sea turtle habitats as well as the effective management and monitoring of human impacts on sea turtle populations. This thesis has provided information on the relative distribution of sea turtles in waters adjacent to the Queensland east coast at a spatial scale relevant to management. Such information will contribute to the conservation management and planning of sea turtle populations in northern Australia to ensure their recovery and perpetuity.

7.5 FINAL REMARKS

The issue of sea turtle by-catch has progressed significantly since work on this thesis began in 1991. TEDs have been regulated into many prawn trawl fisheries, potentially providing a pragmatic solution to sea turtle by-catch, i.e., by permitting the fishery to continue whilst minimising sea turtle mortality that results from forced submergence. However, TED regulations by themselves do not guarantee a genuine outcome. The challenge facing the prawn trawling industry and its management agencies is how to monitor TEDs to demonstrate that sea turtle by-catch targets are being met. Monitoring management performance is particularly relevant in Australian prawn trawl fisheries, which must be assessed for their sustainability under the Commonwealth *Environment Protection and Biodiversity Conservation Act* 1999. Monitoring the effectiveness of TEDs in Australian prawn trawl fisheries is important to assessing whether the 95% reduction target for sea turtle by-catch has been met. To this end, the results of this thesis are being made available to the Queensland Fisheries Service to assist in developing measures to assess whether the regulation of TEDs has achieved a genuine outcome for sea turtle conservation in waters of the Queensland east coast.

In conclusion, sea turtle by-catch in prawn trawl fisheries has been a high profile issue in prawn trawl fisheries worldwide. Whilst the issue generated significant amounts of controversy, the most effective outcomes were achieved when scientists, managers and fishers worked together to develop an effective solution. The sustainable development of marine fisheries requires that we find solutions to by-catch problems so that all marine species can be conserved for the benefit of future generations.