The Fin Blue Line
Quantifying Fishing Mortality Using Shark Fin Morphology

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Abstract

Overfishing is a major global concern. Many of the worlds fish stocks are currently over exploited and require immediate action toward effective management and recovery strategies. Sharks are especially susceptible to overexploitation as they are generally slow growing, late maturing and produce few young. As large predators, sharks play an important, but poorly understood, role in marine food webs. As such, the ongoing exploitation of shark stocks is likely to cause detrimental and lasting ecological shifts within many marine systems.

Within numerous fisheries, sharks are primarily targeted for their highly priced fins, and in many cases, they are the only body part retained by fishermen. This has created many issues for management as no practical methodologies currently exist to allow for the proper identification and quantification of individual species from fins alone. The high price of fin has resulted in an increased take of sharks, while also increasing the likelihood of illegal activity such as under-reporting and foreign fishing. Consequently, a large proportion of the total fishing mortality (from both commercial and illegal, unreported, and unregulated (IUU) fishing) appears to be unaccounted for, exemplified by an investigation of Australian shark fin export figures (Chapter 1). Confounding this, shark management receives low priority and limited funding. As a result, this has highlighted the immediate need for cost effective tools to quantify shark catch for both legal and illegal fisheries and, in the case of Australian fisheries, validate logbook data. Therefore, the major challenge is to develop cost effective methods for use in the field to identify sharks from fins alone, and to use these methods to generate data on catch composition. Morphological methods for identifying sharks from fins, if accurate, may be the most appropriate tool for such data collection. This premise is tested in this thesis; a major component is the development of methodologies to

identify shark species from isolated fins. These techniques were then trialled successfully on specimens from illegal confiscated catch from northern Australian waters to demonstrate the applicability of these protocols for assessing the status of shark species.

The majority of the methods investigated in the thesis rely on the analysis of shark fins from digital photographs. This is because digital images provide a cost effective and easy method to collect information about the morphological features of each specimen, and can be used both in field and lab situations. In order to justify the core methodologies used and to evaluate if robust methods could be developed, bias associated with this method were first investigated (Chapter 2). Fins can be wet (fresh) or in varying stages of dryness when identification is needed. As the majority (91.35%) of the confiscated IUU fins available to this study were wet, and there was a limited degree of drying in the foreign fishing vessel (FFV) catch, the identification protocols were developed using wet fins. In order to develop the identification protocols in Chapter 4, morphometric measurements, measured from digital images of the fin specimens, were used. On all fins, substantial changes in camera angle (from 0-20º) did not significantly affect any of the examined measurements. This result validated the use of a handheld camera as a practical tool for capturing images which are to be used for identify species of shark from isolated fins.

Dermal denticles, (minute tooth-like structures which cover the body and fins of sharks) have been used as a tool for species identification of whole sharks in many shark taxonomic studies and species guides. Quantitative criteria were assessed in order to test the hypothesis that the morphological characters of the denticles on the dorsal and pectoral fins can be used to distinguish species (Chapter 3). These criteria described denticle crown variation at four specific areas on the dorsal and pectoral fins of 13 species of shark that are common to northern Australian waters. Skin samples from a total of 56 individuals from these 13 species were examined. All but three (*Carcharhinus amblyrhynchoides*, *C. limbatus* and *C. tilstoni*) could be distinguished from all other species investigated by the denticles at one or more areas using dorsal fins, and all but two (*C. limbatus* and *C. tilstoni*) using pectoral fins. *Galeocerdo cuvier* could be distinguished from all

other species investigated at all areas on both dorsal and pectoral fins. The most useful area for dorsal and pectoral fins, in terms of percentage of species pairs distinguished (the proportion of all species pair combinations that could be differentiated) were identified. Using the character descriptions devised in Chapter 3, most species show differences in crown morphology at one area, or a combination of areas. Therefore, denticle crown morphology, when described using specific locations on the fin, provided an effective method of discriminating shark species from fins alone. Furthermore, denticles show markedly different crown morphologies with location on both the pectoral and dorsal fins, likely due to hydrodynamic and life-history adaptations. Therefore, when comparing denticles on the fin between adult specimens of different species, it is essential to specify the region that is used for comparison.

While the use of dermal denticles to differentiate between species of shark may be effective, it is not always the most appropriate method for the field. Differences in denticle morphology are often subtle and require magnification to investigate, while more obvious visual characters may be used for species differentiation in the field, such as fin tip colour, fin colour or distance measurements. In order to investigate such alternative methods, distance measurements, fin tip colour and fin colour were used to develop a protocol to identify 35 shark species, found in northern Australian waters, from their isolated dorsal fins (Chapter 4). A series of discriminant analyses (DA) were conducted using distance measurement and RGB colour data on dorsal fin samples from 541 specimens of known species. These were subsequently used to predict the group (species) membership of 93 dorsal fin samples from the seized catch of IUU fishing boats. The accuracy of this method was then tested by comparison with molecular species identifications from the same dorsal fin. This validation demonstrated a correct classification of 80.4% of these specimens. Furthermore, to predict shark size from the identified dorsal fin, the relationship between shark total length (TL cm) and dorsal fin base length (B mm) was examined using linear regression to generate predictive equations for 35 shark species. Although a high level of accuracy was achieved, the complicated nature of the method resulted in an identification system that is not conducive to use *in*

situ. The key to the future effectiveness of this method might be to incorporate measurements into an automated system (*e.g.* a computer program) that is applicable for easy use in the field.

Ultimately, the goal of developing identification methods for species is to generate data with which to estimate exploitation levels in order to manage these resources sustainably. The denticle and DA identification methods from Chapters 3 and 4, were used to provide the first detailed account of both the number and biomass of sharks from the seized catch (as represented by dorsal fins) of 15 illegal foreign fishing vessels apprehended in northern Australian waters between February 2006 and July 2009. The catch of 13 small Indonesian and two large Taiwanese vessels was quantified, resulting in the identification of 1182 individual sharks with a total estimated biomass of 67.1 tonnes. The catch of the Indonesian fleet, as characterised by the 13 vessels, was mainly composed of smaller inshore and benthic species such as Spot-tail Sharks (*Carcharhinus sorrah*), Whitecheek Sharks (*C. dussumieri*) and juvenile Blacktip Sharks (*C. limbatus/tilstoni*). This species composition was similar to the reported catch from commercial shark fisheries in northern Australia. The Taiwanese fleet, as represented by two vessels, was characterised by a far greater catch of larger, pelagic species such as Blue Sharks (*Prionace glauca*), Silky Sharks (*Carcharhinus falciformis*), Oceanic Whitetip Sharks (*C. longimanus*), and Smooth Hammerheads (*Sphyrna zygaena*). The catch composition of these vessels was markedly different to the northern Australian commercial shark fishery, due to the fishing activity of these vessels occurring in deeper, offshore waters. Results show that IUU fishing in northern Australia is likely to have detrimental impacts on shark stocks in the region. The estimated level of illegal fishing for sharks by Indonesian vessels for the year 2006 is between 289.6 and 1071.04 tonnes, which is comparable to the largest commercial shark fishery that was operating in northern Australian waters at that time. One of the important distinctions of this assessment was to highlight the inadequacy of current methods, which assess illegal fishing impact based on the number of fishing vessels. In this study, a single Taiwanese vessel was found to be capable of removing the same amount of shark biomass as between 96 and 166 Indonesian vessels. As such, future assessments should include vessel

characteristics (*e.g.* size, holding capacity) as large differences were highlighted both in terms of catch composition and volume of captured species.

Ecosystem models often use broad functional groups of species to describe the structure and function of an ecosystem, and predict changes to those ecosystems. Furthermore, species from the same functional group generally exhibit similar morphology, as the ability to move is of crucial importance in many ecological contexts. Therefore, characterization of the morphology of the locomotor apparatus of many organisms (*e.g.* shark fins), which are subject to suites of interacting selective pressures, may enable the characterization of the animal to a functional group. In order to investigate the difference in fin shape between three broad functional groups of carcharhinid sharks, *oceanic epipelagic*, *neritic epipelagic*, and *benthopelagic*, morphometric measurements from the dorsal, pectoral and caudal fins of 167 specimens from 19 carcharhinid species were compared via multivariate analysis. Results showed a significant difference between the fins between all three functional groups. SIMPER analysis identified the 'dorsal fin outer posterior margin' and the 'pectoral fin height' as the morphometric characters that most distinguished between the *oceanic epipelagic* and *neritic epipelagic* categories; the 'pectoral fin height' and the 'dorsal fin outer posterior margin' as best distinguishing the *oceanic epipelagic* and the *benthopelagic* categories; and the 'upper postventral margin' and 'width' of the caudal fin as best distinguishing the *neritic epipelagic* and the *benthopelagic* categories. Of the four stepwise discriminant analysis models, the model that used morphological variables from all three fin types was the most successful at discriminating the three functional groups, 82% of all hold-out specimens identified correctly. The ability to distinguish between broad functional groups may be important for collecting data that can be used for ecosystem models, in the absence of more specific data. Such models are applicable to many countries, where fisheries management practices are extremely limited, resulting in a paucity of species-specific data.

While this thesis has focused on sharks, overharvesting and exploitation are responsible for loss of species diversity globally. As the extent of a large amount of wildlife exploitation is not

quantified, the illegal wildlife trade, such as the shark example presented here, undermines national efforts to manage resources sustainably. Given the limited resources allocated for investigating and managing the wildlife trade, the future of effective species conservation relies on the development of innovative and cost effective techniques for quantifying exploitation. This thesis has developed and demonstrated both the practicality and applicability of an accurate and affordable method for quantifying the trade in shark fins using morphological techniques. These methods could potentially change the way that shark fisheries are managed, by enabling accurate identification of individual species within regulated and non-regulated, target and non-target shark fisheries. The resulting protocols will have wide reaching implications by altering practices within specific fisheries, and more importantly, by enabling accurate conservation assessments to be made on many exploited shark species on a national and global scale.

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Table of Contents

List of Tables

List of Figures

1

Shark-finning: The problem and the solution

1.1 Introduction

It has been ten years since the United Nations Food and Agriculture organisation (FAO) implemented an International Plan of Action for the Conservation and Management of Sharks (IPOA Sharks) because of concern about expanding global shark catch and the potential negative impacts on shark populations worldwide. Since that time, 466 shark species from 34 families have been assessed for the International Union for Conservation of Nature (IUCN) Red List of Threatened Species, ten shark species have been listed under the Convention On International Trade In Endangered Species (CITES), five have been listed under the Convention for Migratory Species

(CMS) and, in Australia, 13 have been listed under the Environment Protection and Biodiversity Conservation Act (EPBC act). Of the 466 shark species that have been assessed by the IUCN Red List, 15.6% were found to be Critically Endangered, Endangered or Vulnerable, 14.8% were Near Threatened and 44% were Data Deficient (IUCN 2009).

Despite global concern for the vulnerability of many sharks to overfishing, the level of reported catch remains high – with actual mortality estimated to be three times higher, attributed to illegal fishing, under-reporting and unregulated fishing (Camhi, *et al.* 1998, Clarke, *et al.* 2006). Because of the aforementioned concerns, it has been suggested that the truest estimate of fishing mortality can be obtained by examining trade data (Baker 2008). In the case of many shark species, this means quantifying shark catch as represented by the most retained product, shark fin.

This chapter will review the rationale for, developments of, and challenges to management since the implementation of IPOA Sharks, using Australian shark fisheries as an example. Secondly, this chapter will provide suggestions for obtaining more robust catch data via the quantification of shark mortality as represented by shark fin catch.

1.2 Concern for Shark Stocks

The importance of large predators, such as sharks, to marine ecosystems has been a topic widely discussed and documented in the literature (Duffy 2002, Estes, *et al.* 1998, Olsen 1959, Pace, *et al.* 1999, Paine 1980). Despite what is already known about tropic cascades there is still uncertainty about the effect of removing apex predators from marine food webs (Atz 1964, Bascompte, *et al.* 2005, Frank, *et al.* 2005, Pace, *et al.* 1999, Stevens, *et al.* 2000, Strong 1992). However, it is agreed that detrimental top down effects must be widely expected whenever entire functional groups of predators are removed (Estes, *et al.* 1998, Frid, *et al.* 2008, Myers, *et al.* 2007, Schindler, *et al.* 2002).

Since the early 1990s, there have been global concerns that both target and non-target fishing has caused marked depletions in shark populations (Box 1.1). Many shark species have both

a low resilience to fishing mortality and an increased susceptibility to overfishing, due to K-selected life-history traits such as late maturation, low fecundity, and slow growth rates (Barker & Schluessel 2005, Camhi, *et al.* 1998, Frisk, *et al.* 2001, Hoenig & Gruber 1990, Holden 1974, Musick 2000, Smith, *et al.* 1998, Stevens, *et al.* 2000). Furthermore, for shark species with restricted distributions, and those that aggregate by age, sex, and reproductive state, this susceptibility is exacerbated (Baum, *et al.* 2003, Bonfil 1994, Graham, *et al.* 2001, Jukic-Peladic, *et al.* 2001, Musick 1999). Differential vulnerability to fishing pressure exists among shark and ray species, with species exhibiting large body sizes and low productivity generally being the most vulnerable (Cortes 1998, Stevens, *et al.* 2000) while some smaller, more fecund species such as the Gummy Shark (*Mustelus antarcticus*) can be harvested sustainably (Pribac, *et al.* 2005, Walker 1998). In western North Atlantic shark fisheries, populations of large slow growing shark species, such as the Sand Tiger (*Odontaspis taurus*), and Dusky Shark (*Carcharhinus obscurus*), have collapsed and show little sign of recovery. However, in the same fishery, faster growing and more fecund species such as the Sandbar Shark (*Carcharhinus plumbeus*), have enabled the fishery to continue, despite also showing signs of population reduction (Musick 1999, Musick, *et al.* 1993). Such examples illustrate the necessity of species-specific shark data collection and assessment for effective fisheries management.

Box 1.1 Examples of Collapsed Shark Stocks: Myers & Worm (2003) estimate that the biomass of large predatory fish in the world's oceans is only about 10% of what it was at pre-industrial levels. They also predict that declines of large predators in coastal regions are extending throughout the open ocean which could have potentially serious consequences for entire marine ecosystems (Myers & Worm 2003). A recent example of this is in the Gulf of Mexico, where Oceanic Whitetip (*Carcharhinus longimanus*) and Silky Sharks (*Carcharhinus falciformis*) have declined by over 99 and 90%, respectively (Baum & Myers 2004). Furthermore in the Atlantic, coastal shark populations have declined by up to 85% in the past two decades (Baum*, et al.* 2003, Camhi*, et al.* 1998), and in the USA, large coastal sharks are estimated to have declined from 8.9 million sharks in 1974 to around 1.4 million in 1998 (NMFS 1999). Well-documented species-specific examples of collapsed shark fisheries are the Porbeagle (*Lamna nasus*) fishery in the North Atlantic (Campana*, et al.* 2008), the School Shark (*Galeorhinus galeus*) fisheries off California and south eastern Australia (Olsen 1959, Punt & Walker 1998, Ripley 1946), most worldwide Basking Shark (*Cetorhinus maximus*) fisheries (Parker & Stott 1965) and the Spiny Dogfish (*Squalus acanthias*) fisheries both in the North Sea and off British Columbia (Holden 1968, Ketchen 1975).

Despite the necessity for species-specific catch data for shark management, very little archival, and almost no species-specific data on historical catches and landings for most shark species exist as historically shark products have been of low interest (Barker & Schluessel 2005, Castro, *et al.* 1999, Shotton 1999a, Shotton 1999b). In the last 15 years, more than 12 million tonnes (810 000 tonnes per annum) of sharks and rays have been reported by target fisheries throughout the world (Last & Stevens 2009). Despite such estimates of world shark catch, in 1997 chondrichthyan landings accounted for only 0.87% of the total world fish catch, with sharks comprising approximately half of this total (FAO 2002). As this represents only a small proportion of world fish catch, and therefore a small percentage of individual countries marine fisheries, sharks and rays have historically received low priority and limited resources for management purposes (FAO 2000, Musick 2000). With current rates of exploitation driven by the rising demand for highly priced shark fins, this proportion is beginning to increase. However, because shark fin represents the only lucrative economic windfall in shark fisheries, these fisheries continue to be a low priority for conservation and research (Barker & Schluessel 2005). Clarke *et al.* (2006) estimate that actual shark mortality could be four times higher than the reported catch, as a substantial

component can be attributed to unrecorded shark landings and a high frequency of shark-finning and carcass disposal at sea. This substantial under-reporting of shark harvest suggests that the take of sharks could be far more significant than previously thought. When combined with recent rises in the demand for shark fin, low management priority, and species identification problems, a considerable challenge is posed for the responsible management of shark fisheries on a global scale.

1.3 Managing the Shark Resource

In response to concern for shark stocks, a voluntary International Plan of Action (IPOA Sharks) was developed by the FAO (FAO 1999). The four elements of the IPOA Sharks are species conservation, biodiversity maintenance, habitat protection, and management for sustainable use (FAO 1999). IPOA Sharks outlines a process whereby individual states and regional fisheries management organisations (RFMOs) can identify regional issues and appropriately develop regional 'shark plans' (FAO 2000). The IPOA Sharks advises that each state and RFMO are to regularly carry out an assessment of the status of its shark stocks and implement their own shark management plan (FAO 2000). However, implementation has been patchy in both the number of countries adopting National Plans of Action (NPOAs) and the quality of those plans (Lack & Sant 2009). At present only 12 nations, the United Kingdom (2001), United States (2001), Australia (Shark Advisory Group & Lack 2004), Mexico (2004), Taiwan (2004), Ecuador (2005), Malaysia (2006), Canada (2007), Seychelles (2007), Japan (2009), Uruguay (2008), and Argentina (2009) have published shark management plans. The object of each national management plan is to assess the status of their shark stocks and provide a framework for management for sustainable use.

1.3.1 The Goal: Management for Sustainable Use

Sustainable use requires an understanding of the ecological and biophysical systems of the stock and requires maintaining the stock at, or restoring it to, levels above those capable of producing maximum sustainable yields (FAO 2000). Managing shark stocks for sustainable use involves a

synergy of monitoring, assessment, regulation, and enforcement. Monitoring and assessment of stocks (both within fisheries and independently) contribute data that leads to the implementation of informed and effective fisheries management arrangements; ensuring the harvest of species is set at sustainable levels. Enforcement of these regulations, and subsequent monitoring, are needed so that these management arrangements are effective.

1.3.2 Management Framework

The basic framework available for managing global shark resources comprises the following four conservation regimes: (1) the UN agreement on straddling and highly migratory fish stocks (1995), which provides rudimentary guidance and authority for international management; (2) the Convention on Biological Diversity (1992), which helps to promote the incorporation of shark conservation into domestic conservation programs; (3) Convention on the Conservation of Migratory Species of Wild Animals (also known as CMS or Bonn Convention), which encourages regional collaboration of management within the Economic Exclusion Zones (EEZs) of member states to protect listed species, including those that would significantly benefit from international cooperation; (4) CITES (1975), an international agreement to regulate trade in endangered species. Such agreements provide a comprehensive basis for developing 'customary law', which can assist authorities in constructing appropriate management frameworks (Caddy 1999).

The principle legislation for protecting threatened species in Australia, for example, is the '*Environment Protection and Biodiversity Conservation Act* 1999' (DEWHA 2008). The EPBC Act serves to identify and list threatened species and to 1) develop recovery plans, 2) register critical habitat, and 3) recognise and reduce the impact of key threatening processes, for those species that are listed. Currently, there are 13 elasmobranch species listed under the EPBC Act. The four criteria for listing a species under the Act require either evidence of population declines, evidence of restricted distributions, estimation of the total number of mature individuals, or an estimate of the probability of extinction in the wild (DEWHA 2008). As such, without historical species-specific

data to give evidence of population declines or species range restrictions, listing individual species remains a challenge. In this way, species-specific data collection is vital for identifying and protecting threatened species.

1.3.3 Data for Managing Shark Fisheries: Fishery-Dependent Sampling

Fisheries data for monitoring and assessment include ecosystem data, environmental data, fishery-independent survey data, and fishery-dependent data (National Research Council 2000). This chapter will focus on fishery-dependent sampling, which involves monitoring total catch estimates, fishing effort, and catch composition within a fishery, and is one of the most practical tools available to fisheries managers (Morgan & Burgess 2005, National Research Council 2000).

Catch estimates are used to illustrate the species composition of individual fisheries, investigate usage rates, monitor quotas, estimate fishing mortality, and to calculate catch per unit effort (CPUE) (Morgan & Burgess 2005). By using standard fisheries assessment techniques, mortality can be calculated and, along with an estimate on natural mortality, total mortality can be ascertained (Morgan & Burgess 2005). This allows fishery managers to determine the status of a stock, and to set quotas accordingly (Morgan & Burgess 2005). Catch estimate data can also be used to show historical trends in the fishery, build on existing quota systems and estimate population abundance. This information can be subsequently integrated into models to predict the outcome of future management plans or to predict the effect current management will have on the investigated stock (Morgan & Burgess 2005). Fishery-dependent sampling methods can generate data such as mortality and stresses caused by fishing and infer population structure, gear selectivity over time, behaviour of fish and fishermen, and stock declines. Fishery-dependent data can also provide direct measure of the effectiveness of management regulations.

Fishery-dependent sampling is subject to bias and management plans that are influenced or guided by such sampling are symbiotic to the quality of data that is collected during assessments (Morgan & Burgess 2005, National Research Council 2000). Thus, fishery-dependent data

collection must incorporate effort information, species composition, and species-specific size and sex data.

1.3.4 Methods for Obtaining Catch Data

Within regulated commercial fisheries, including numerous shark fisheries, catch data are most commonly obtained via logbooks, landing surveys, and onboard observers (National Research Council 2000). Logbooks are voluntary or compulsory information about catch and effort compiled by fishermen on a regular basis. Logbooks can provide abundant and cost-effective data, but are highly subject to inaccuracy or intentional biases in information (National Research Council 2000). Landings surveys and onboard observers provide essential data with which to compare and validate self-reported commercial data. Landing surveys are conducted at landing sites and fish markets with the purpose of collecting catch and species composition, associated effort, and other secondary data (Stamatopoulos 2002). Problems with this technique exist when appropriate sites (*e.g.* sites that give a full representation of boat types and gear) are not accessed or when target fisheries landing sites shift over time (Stamatopoulos 2002). Onboard observers provide detailed and unbiased information on catch data, as well as additional data including bycatch, discards and interactions with prohibited species. Furthermore, observers can also record effort information such as boat location and travel, depth of fishing, deployment times of gear, and gear type. The benefits of gaining observer data is balanced by the nature of collection as observers are expensive to employ and, as shark fisheries typically have low budgets for management, they may not provide adequate coverage of the fishery.

In the case of illegal shark fishing, such data collection cannot be employed and the catch must either be inferred from the catch of commercial fishers or investigated when vessels are seized (Box 1.2). In most cases of illegal shark fishing, including those in northern Australia, the catch consists almost entirely of removed fins with the carcass disposed of at sea (Figure 1.1). There is currently no protocol (beyond genetic methods) to identify shark species from the fins once they are

removed, and thus, no cost-effective way to collect species-specific data from confiscated IUU catch. Within northern Australian waters, where recent levels of illegal fishing, mainly by Indonesian fishers targeting sharks for their fins, managers are currently unable to produce reliable risk assessments on species in an otherwise tightly managed commercial fishery (Box 1.2) (Salini, *et al.* 2007b). In this way, the practice of shark-finning represents a particular challenge to shark fisheries managers.

Box 1.2 Case Study: Illegal Shark fishing in northern Australian Waters.

In the previous ten years, there has been an increase in illegal foreign fishing activity in northern Australian waters, mainly by small Indonesian vessels targeting sharks for their fins (Field*, et al.* 2009, Griffiths*, et al.* 2008, Salini*, et al.* 2007b, Salini*, et al.* 2007c). This activity peaked dramatically in 2005-2006 with 368 vessel apprehensions, with a steady decrease in vessel numbers to the present day (AFMA 2006, Griffiths*, et al.* 2008, Salini*, et al.* 2007c). Factors attributing to this decrease have been attributed to increased border security by the Australian Government (Salini*, et al.* 2007c), high petrol prices (Sumaila*, et al.* 2006), international government agreements and domestic policies (Vince 2007), or a decrease in the number of target species (Field*, et al.* 2009). However, the actual cause is currently unspecified. Despite reduced FFV numbers there is still illegal fishing activity in the region, and the past and current impact of such fishing on shark stocks remains unknown. This is largely due to the inability to identify shark species from isolated fins, which form a major component of the illegal shark catch. AFMA surveillance regularly intercepts some of these vessels and confiscates their catch, including dried fins. Identification of the shark species represented in these fin collections is crucial to Risk Assessment and exploitation rate estimates for north Australian sharks by fisheries managers, as the illegal take of sharks is likely to comprise a significant proportion of the total catch.

1.4 The Challenge of Mitigating Shark-finning

1.4.1 The Shark Fin Trade

In the last ten years, soaring demand for shark fin has resulted in an increase in shark mortality due to the increased target of sharks and a decrease in the release of live sharks caught as bycatch. Shark fins are one of the most expensive fish products in the world and commonly retail for over $400 USD kg^{-1} in Hong Kong (Camhi*, et al.* 1998, Clarke*, et al.* 2005, Vannuccini 1999). Their use is of a traditional nature and the market is virtually exclusive to Chinese ethnic groups throughout the

world (Vannuccini 1999). Hong Kong is the centre for the world trade in shark fin as an entrepôt for Mainland China, with major export markets being the south-east Asian markets of Hong Kong and Singapore (Vannuccini 1999). Due to the increasing wealth of the Chinese middle class since the mid 1980s, shark fin is no longer a delicacy limited to the wealthy. This has greatly amplified the world price of shark fin and its trade (Rose & McLoughlin 2001, Rose 1996). Demand further escalated in Hong Kong during the 1990s with the establishment of a large number of specialty shark fin restaurants. Today, shark fin is readily accessible, served at dinner parties, weddings and other important functions to express the respect of the host toward their guests (Lai Ka-Keong 1983, Vannuccini 1999).

Figure 1.1 The shark catch of an Indonesian fishing vessel, apprehended in northern Australian waters. Shark catch on such vessels typically consists of excised fins, with the remainder of the carcass discarded at sea. Photo provided by the Australian Fisheries Management Authority (AFMA).

Shark fins predominantly consist of soft collagen and elastin fibres called ceratotrichia, commonly referred to as fin rays or fin needles, which are used to prepare shark fin soup and other shark fin dishes (Musick 2005, Rose 1996, Vannuccini 1999). There are typically six types of fin on a shark, the first and second dorsal, caudal, anal, pelvic (paired), and pectoral (paired) fins (Figure

1.2). All fins are traded, however, the most valuable are the dorsal, lower caudal and pectoral fins due to their high needle content (Musick 2005, Rose & McLoughlin 2001, Vannuccini 1999).

Quality conscious buyers have led to grading and processing of obtained fins being an important aspect of the market and fin price. Shark fins are graded according to colour (black, white or brown), fin type, size, species, moisture content, smell and cut (Rose & McLoughlin 2001, Vannuccini 1999). To use the valuable fin needles, fins must be processed to give an end product of dried fin. Drying methods vary from traditional methods of sun drying or salting (either on the fishing vessel or after landing), or by drying fins mechanically. Mechanically drying fins is usually carried out by large-scale fin processors, who buy large volumes of wet fins and process these before export or subsequent sale (Vannuccini 1999). Due to premium post-harvest technology, Australia is considered to produce high-quality shark fin, whilst countries such as Indonesia, which are more traditional in their harvesting and processing methods, are considered to produce lower-quality fin (Vannuccini 1999). Shark fin product can be purchased at many stages of processing including wet fins, raw fins, semi-prepared, fully-prepared, frozen-prepared, in brine, fin net, and ready-to-eat or cook (Musick 2005, Vannuccini 1999). However, the majority of fins are traded dried and imported for further processing in Hong Kong, Singapore, or Taiwan. Upon import the skin, denticles and cartilaginous platelets are removed and the processed fins are then used domestically or re-exported (Musick 2005, Rose & McLoughlin 2001, Vannuccini 1999).

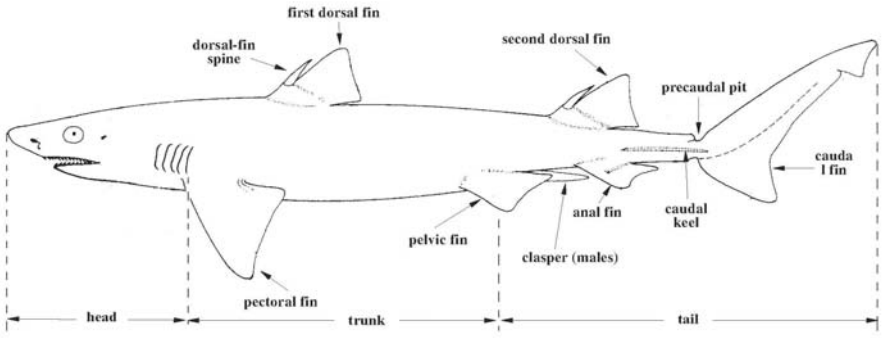


Figure 1.2 Lateral view of a shark showing fins and other external terminology (Last & Stevens 2009).

The price of a fin depends largely on size and the amount of fin needles present in the underlying tissue, with species with large amounts of fin needles commanding higher market prices (Rose & McLoughlin 2001). Fins from the wedgefishes (Family: Rhynchobatidae) are considered the highest value in the shark fin trade (Vannuccini 1999). Other highly sought after shark species include the Tiger Shark, Mako Shark, sawfish, Sandbar Shark, Bull Shark, hammerhead, blacktip, Porbeagle, Blue Shark, and thresher sharks (Vannuccini 1999). Despite this, all species of sharks with fins containing fin needles are traded, including embryos that are removed from the mother upon capture (Dr W. White, pers obs; L. Marshall, pers obs).

1.4.2 Management: Australian Shark Fisheries

Shark-finning is a global concern, however many of its management issues are shared between numerous countries. The particular example of shark-finning in Australian waters illustrates many of these common issues. Comparatively, Australia is not a major shark fishing nation, however elasmobranch species constitute an important part (~5%) of the total quantity of Australia's wild fish production (FAO 2007, Lack & Sant 2009). Furthermore, Australian vessels regularly take sharks as target and non-target catch (Shark Advisory Group & Lack 2004). Within the region there are seven recognised commercial fisheries that target shark (Shark Advisory Group & Lack 2004). Additionally, sharks are targeted in two shark control programs, and by recreational and charter fishers. In more than 70 other Australian commercial fisheries sharks are taken as bycatch, with many of these fisheries increasingly retaining sharks for their high value fins (Shark Advisory Group & Lack 2004). Shark fisheries within Australia are managed under both Commonwealth and State/Territory jurisdiction. The Australian Fisheries Management Authority (AFMA) is responsible for the management of Commonwealth fisheries, while each of the State/Territory Governments is responsible for management of fisheries resources within their waters (3 nm), with additional management being implemented under joint authorities between the States/Territory and the Commonwealth. The complex and differing nature of fisheries management regimes across

Australian jurisdictions results in a lack of uniformity in enforcement powers and, therefore, an increased likelihood of illegal activity (Putt & Anderson 2007). Currently, there is no uniform reporting format for Australian fisheries. In terms of Australia's shark catch, management is hindered by IUU fishing by Foreign Fishing Vessels (Box 1.2), under-reporting and lack of species-specific catch data for sharks. In the last three years, effort has been made to improve species-specific reporting in many fisheries via more detailed shark logbooks, onboard observers, and identification workshops. However, due to the unreliable nature of logbook data, the low budget for shark management and the high cost of onboard observers, other tools are urgently needed to validate logbook data.

1.4.3 The Finning Issue

The practice of shark-finning is characterised by the removal of fins from the torso of the shark with the rest of the shark discarded at sea. This practice is banned in all States and Territories in Australia and on vessels under bilateral agreements within the Australian Fishing Zone (AFZ) (Shark Advisory Group & Lack 2004) (Table 1.1). The rationale for this ban was to enable adequate species identification of landed sharks, monitor compliance with by catch limits, monitor the catch of protected species, ensure compliance with legal size limits, prohibit the practice of finning live sharks, and to encourage the full use of the whole carcass (Shark Advisory Group & Lack 2004). Awareness about the effect of the price of shark fin on global shark fishing became apparent when FAO reported that global fin production exceeded 6000 tonnes in 1997, well above previously reported levels (Rose & McLoughlin 2001, Rose 1996, Shivji, *et al.* 2002). In Australia, shark fin can fetch from between AU$30 to AU$100 per kg for wet unprocessed fin (Dr S. Taylor, pers obs 2008) and up to AU$700 per kg for dried, skinless fin (L. Marshall, pers obs 2007). As previously mentioned, the high value of shark fin has resulted in a heavy increase in shark mortality both of targeted species and those that were traditionally released as a large component of commercial fishery bycatch (Rose & McLoughlin 2001).

Table 1.1 Fisheries regulation regarding shark-finning for the six Australian States and Territories where such regulations are specified.

State / Territory	Finning Legislation	Reference
NSW	Shark can be headed and gutted at sea, but the fins must remain attached until the shark is brought ashore.	(Rose & Mcloughlin 2001; Brooks 2006).
VIC	Shark can be headed and gutted at sea, but the fins must remain attached until the shark is brought ashore.	(Rose & Mcloughlin 2001; Brooks 2006).
TAS	"…a person must not, in State waters, be in possession of shark fins without the trunks or bodies from which they came"	(Rule 130, Fisheries (Scalefish) Rules 2001).
NT	Shark product on board a vessel must conform to a series of percentage ratios for fin vs. whole, trunk or fillet weight for both dry and wet fins, and 'No shark trunk, fillet or meat (is) to be allowed on board a vessel upon commencement of the next voyage'	(Shark product licence conditions for all offshore net and line fishery licenses 2005).
WA	Shark can be processed at sea, as long as all parts of the sharks other than head and guts are retained.	(Section 16B, Fish Resources Management Regulations 1995)
QLD	The practice of 'finning' sharks (*i.e.* keeping the fins but throwing away the body of the animal) is prohibited for all shark and ray species in Queensland. It is an offence for a fisher to possess a shark or ray fin on a boat without also possessing the body of the same shark or ray.	(Queensland Government 2009).

Within Australian commercial fisheries the effectiveness of shark-finning bans and the extent of illegal shark-finning has not been assessed. Despite the aforementioned legislation, AFMA has advised that there is evidence of illegal finning within the commercial domestic fleet (Senate Rural and Regional Affairs and Transport Committee 2005). As such, there is concern about the effectiveness of shark-finning bans to reduce shark mortality due to current lucrative fin prices. Protection of sharks therefore, must go beyond shark-finning bans, as a ban on shark-finning will lead to an increase in the use of whole shark, not a decrease in mortality (Clarke, *et al.* 2007).

Compounding the exploitation of shark species is that shark fin, as a high-value and low-volume product, is vulnerable to organised criminal exploitation. Indeed, a recent report on criminal activity in Australian commercial fisheries identified shark fin as one of three fisheries products most likely to be affected by criminal activity, *e.g.* non-reporting or under-reporting of catch, co-mingling of illegal with legal catches, take in excess of the allowable quota, and IUU Foreign

Fishing action (Putt & Anderson 2007). For example, in the Northern Territory, stakeholders considered that large scale and well-organised shark-finning had developed in northern Australia, with involvement ranging from small family groups to larger scale commercial companies (Putt & Anderson 2007).

Poor documentation of shark catch was first highlighted by an investigation into the extent of shark-finning in Australian fisheries (Rose & McLoughlin 2001). The study reported Australian exports of dried shark fin to be 92 tonnes, valued at more than AUD$5.5 million, between 1998 and 1999, with around a third of this figure derived from unrecorded shark catch. Ten years later, shark fin exports appear to have doubled, with reported figures of around 206 tonnes of shark fin exported between January 2007 and February 2008 (AQIS 2008), the majority of fin being exported from Melbourne (Table 1.2). Using a standard conversion of 2% of wet fin weight to 98% whole shark (Rose & McLoughlin 2001), these shark fin export figures represent 10,329 tonnes of whole shark. However, using average conversion rates of 1.62% (wet fin to whole carcass) and 0.73% (dry fin to whole carcass) derived from Salini *et al.* (2007b), the estimate inflates to 8,934t (for wet fin) and 8,467t (for dry fin), a total of 17,403t of whole shark represented by fin exports in 2007. This figure is more than double that of the reported FAO figures of 7,269 tonnes for Australia's shark production for the year 2007 (Table 1.3). Considering the main category reported to FAO was undifferentiated 'sharks, rays, skates, *etc.* not elsewhere indicated', this category would also contain rays, skates and chimeras that do not contribute to the shark fin trade. Indeed, Clarke *et al.* (2006) estimated this category, globally, to contain 45% chondrichthyans potentially used in the shark fin trade. Despite the large variation (depending on conversion factor used) these figures indicate significant under-reporting of shark catch within the commercial sector of Australia.

Table 1.2 Australian fin exports in tonnes between January 2007 and February 2008. Source: The Australian Quarantine Inspection Service (AQIS).

Loading Port	Destination City		Frozen	Dried	Total
Brisbane	Cebu		16.21	2.47	18.67
	Hong Kong		2.18	5.02	7.2
		Total	18.39	7.48	25.87
Cairns	Cebu		0	10.93	10.93
	Hong Kong		0.96	42.73	43.69
		Total	0.96	53.66	54.62
Darwin	Hong Kong		0	0.68	0.68
		Total	0	0.68	0.68
Melbourne	Cebu		117.92	0	117.92
	Singapore		7.48	0	7.48
		Total	125.4	0	125.4
Total			144.75	61.83	206.58

For many cases, trade data can provide a truer representation of mortality (Baker 2008). This may be particularly true in the case of shark-finning, due to its association with under-reporting and illegal fishing. When sharks are harvested, the fins are most likely retained body parts. As previously mentioned, the dorsal, pectorals and caudal fins are the most valuable and thus, the most likely to be kept. As such, the most accurate representation of shark mortality can be obtained by investigating the catch and trade from any of these fins.

Table 1.3 FAO Fishstat Capture Production data (tonnes) for Australia for the year 2007 for the three elasmobranch reporting categories that are likely to contain species that would contribute to the fin trade. Source: FAO, Fishstat Plus (v. 2.3), Capture Production 1950-2007 (Release date: February 2009).

	Region			
Reporting Category	Indian Ocean Eastern	Pacific Southwest	Pacific Western Central	Total
Sharks, rays, skates *etc.* (not otherwise indicated)	1,493	273	2,564	4,330
Smooth-hounds (not otherwise indicated)	2,644	19		2,663
Tope shark	276			276
	4,413	292	2564	7,269

1.5 Summary and Thesis Structure

The practice of shark-finning creates many issues for the management of shark stocks, both in Australia and globally. The high price of fin has resulted in an increased take of sharks, while also increasing the likelihood of illegal activity such as under-reporting, and foreign fishing. Consequently, a large proportion of the total fishing mortality (from both commercial and IUU fishing) appears to be unaccounted for. Confounding this, shark management receives low priority and limited funding. As a result, this has highlighted the immediate need for cost effective tools to quantify IUU catch and, in the case of Australian fisheries, validate logbook data. Morphological methods for identifying sharks from fins, if accurate, may be the most appropriate tool for such data collection.

This study aims to develop and test morphological methods for identifying shark species from their fins, and demonstrate the use of these methods by quantifying the catch of a subset of Foreign Fishing Vessels apprehended in northern Australia. Additionally, this study will investigate why such differences in fin shape exist in an ecomorphological context. The methods developed will have application for compliance and data collection for fisheries management for illegal and commercial fisheries, both in Australia and globally. For IUU fisheries these methods will develop tools with which to quantify the illegal component of shark catch, providing fisheries managers with a better knowledge of the total catch in their waters, allowing them to make inferences about the sustainability of the current take of sharks. For commercial shark fisheries, these methods will develop tools to monitor catch reporting through validation and to quantify catch where species identification is poor or where key taxonomic features are absent (*e.g.* beheading).

- **Chapter 2** describes and justifies core methodologies used to develop these methods.
- **Chapter 3** uses quantitative criteria to describe denticle crown variation on the dorsal and pectoral fins of 13 species of shark, common to northern Australian waters, and aims to assess the usefulness of these characters for discriminating between species. Additionally, this chapter

will investigate how interspecific crown variation in shape and location relates to ecomorphological requirements such as protection or hydrodynamic function.

- **Chapter 4** uses discriminant analysis of morphometric characters to identify 34 shark species from dorsal fins.
- **Chapter 5** will demonstrate how the methods developed in Chapter 4 can be used to quantify the shark catch of a number of illegal fishing vessels apprehended in northern Australian waters. It will also provide the first account of the shark catch composition of such vessels in Australia.
- **Chapter 6** will investigate why such differences in fin shape, evident in Chapter 4, exist between different shark species in terms of their ecomorphology, by comparing fin shapes (as represented by morphological measurements) between different ecomorphological groups.

2

Evaluation of Morphological Techniques for Photograph-based Shark Fin Identification

2.1 Introduction

Sharks, as large marine predators, are fundamental to the health of marine ecosystems, yet they are extremely vulnerable to fishing pressure due to their biology. Historical catch data for sharks is

scarce and models for fisheries outcomes are largely unreliable (Barker & Schluessel 2005, Castro, *et al.* 1999, Shotton 1999a). Nonetheless, significant worldwide declines have been reported for many shark species (Baum & Worm 2009, Ferretti, *et al.* 2008, Myers & Worm 2003, Walker 1998). In the last ten years, the rapid demand for shark fin products has been driving these declines for many shark stocks, via regulated and unregulated commercial fisheries and target and non-target shark fisheries.

Whole sharks are often difficult to identify to species level. As a result, the lack of species-specific catch data is a major hindrance to the management of shark fisheries (Lack & Sant 2009). This problem is confounded when whole sharks are reduced to parts that are traded, such as shark fins, as there are fewer protocols with which to identify shark species from such parts. Individual fins form a major component of the world shark catch, especially in illegal shark fisheries (Clarke 2008). As the price for shark fin, driven by the Chinese fin trade, is much higher than for shark meat, shark-finning (removing the fins from the shark and discarding the body) is common unless anti-finning laws are in place and rigorously enforced (Clarke, *et al.* 2007). Illegal Unreported and Unregulated (IUU) shark fishing in northern Australian waters is a typical example of how a large amount of unregulated and unquantified shark-finning has resulted in fisheries managers being unable to make accurate risk assessments and management strategies for their otherwise closely-managed commercial shark fisheries (Salini, *et al.* 2007b). Deficiencies in data collection in countries that target sharks, and a failure to meet international responsibilities to provide accurate and comprehensive catch and trade data to the Food and Agriculture Organization (FAO) or to Regional Fisheries Management Organisations (RFMOs), is a significant challenge to global shark management (Lack & Sant 2009). Improvement of data quality is needed to provide more accurate and more affordable means of shark identification, which can then be used to quantify levels of exploitation.

One of the major aims of this thesis is to develop robust and field-friendly techniques for generating catch data from detached fins, and to use these methods to quantify the shark catch from

a subset of IUU foreign fishing vessels apprehended in northern Australian waters. The approach was: 1) to develop morphological methods to identify shark species from fins using a set of 'known' fin samples; 2) to test the methods on a set of 'unknown' fin samples; 3) to verify the accuracy of the methods using genetic results; 4) describe the catch composition of sharks from a subset of foreign fishing vessels apprehended in northern Australian waters. Digital images are a simple, field-friendly and inexpensive method for at sea fisheries observers, or officers, to collect a large quantity of data in the field. Therefore, the focus was to use measurements taken from digital images of shark fins in order to develop the identification protocol. There are also various sources of bias that need to be addressed when using measurements from digital images, such as error resulting from image capture and distortion of the fin shape (*e.g.* from drying or irregular fin cut). This chapter describes and justifies core methodologies used in subsequent sections of this thesis, and to demonstrate that robust methods were developed without these major biases.

2.2 Methods

2.2.1 Sample Collection

Fin sets from specimens whose identification had been confirmed ('known' fins) were used to develop the identification methods in this thesis. These methods were then use to identify a number of fins collected from foreign vessels apprehended in northern Australian waters ('unknown' fins). To gauge the success of the methods, a subset of the 'unknown' fins were identified to species using genetic techniques and the resulting genetic identifications were compared to the morphological identifications generated by the methods developed in this thesis (Chapter 4).

Known Samples

A total of 501 fin sets were collected from 'known' specimens representing 45 species as a part of this thesis (Table 2.2). 'Fin sets' were defined as any number of fins from the same specimen

(Figure 2.1). Sets were classified as 'known' if species identifications were confirmed either by examination of the whole specimen or by genetic verification.

Figure 2.1 An example of a 'known' fin set from a 1.65 m TL, male bull shark (*Carcharhinus leucas*). The fins were donated by Australian Seabird Rescue Inc. after the specimen was found dead from a hook injury at Lennox Head, QLD. Known fin sets can contain one, or a combination of the above fins, a) caudal fin, b) second dorsal fin, c) first dorsal fin, d) left pectoral fin (ventral side), e) right pectoral fin (dorsal side), f) anal fin, g) pelvic fin with clasper attached (ventral view) and h) left pelvic fin with clasper attached (dorsal view).

Sampling was opportunistic, and fin sets were acquired from a variety of sources including donated material from shark researchers and from opportunistic field trips during the course of the thesis (Table 2.1). Most samples (59%) were collected within Australian waters, as part of an earlier project (Salini, *et al.* 2007a). These Australian specimens were sourced from a variety of locations within northern Australian coastal waters, incorporating Western Australia (Exmouth Gulf to the Kimberly Region), the Northern Territory (Cape Ford), Queensland (Weipa to Moreton Bay) and New South Wales (Stockton to Ulludulla) (Figure 2.2). The remaining samples (41%) were collected from various fish markets in Thailand, from both the east coast (Gulf of Thailand) and the

west coast (Andaman Sea). Where possible, donated fin sets were accompanied by data such as total length (cm), sex, maturity status, and location of capture.

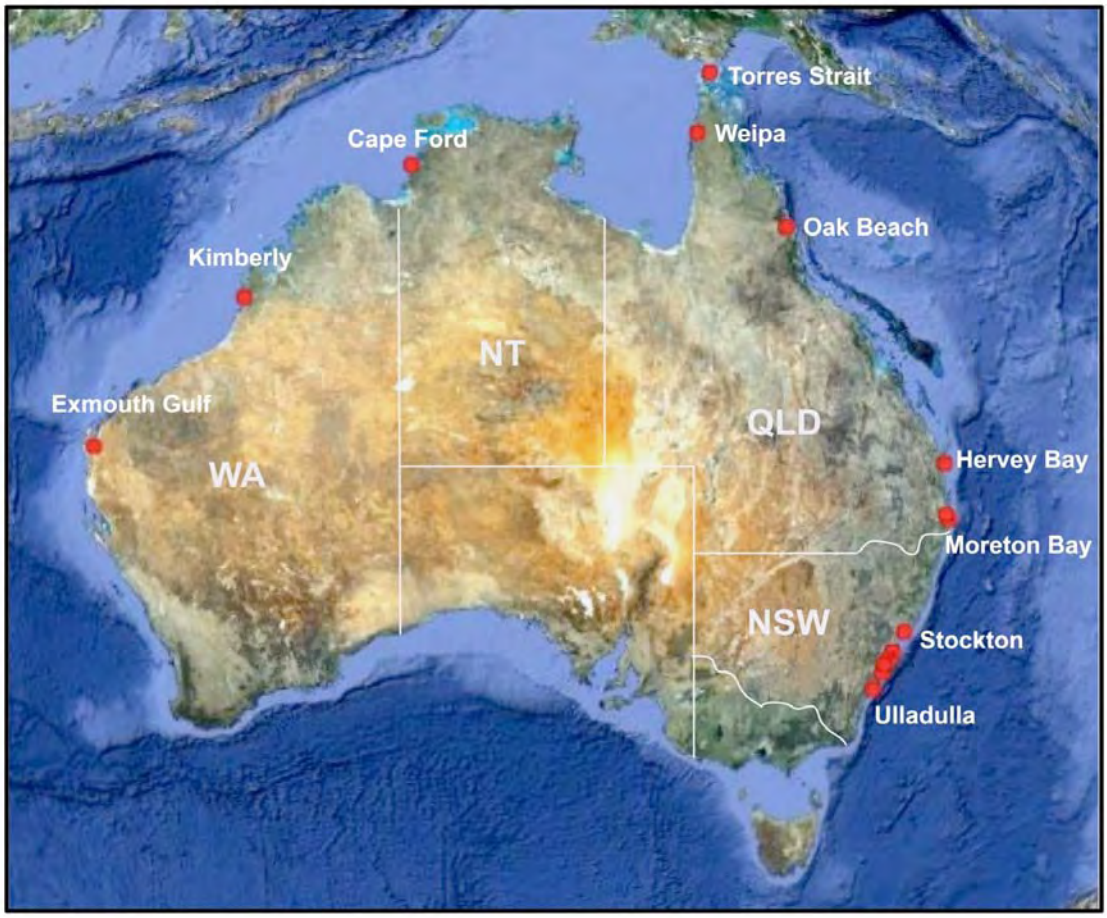


Figure 2.2 Map showing the various locations within Australia where specimens from the 'known' category of fin samples were obtained. Map sourced from Google Earth.

Table 2.1 The number of fin sets (*n*) collected for the 'known' category, and the six different sources from which they were obtained. Table shows the number of fin sets (*n*) collected from each source (Sample Source). Each fin set was collected from a single shark specimen.

Sample Source	*n*
Thailand Fish Markets	201
CSIRO Phase 1 (Salini, *et al.* 2007a)	130
Donation by other researchers	125
Shark Control Program NSW	35
Shark Control Program QLD	6
National Fish Collection	4
	501

Table 2.2 All specimens collected for the 'known' fin category. For each species the total number of specimens (*n*) and, for those specimens with accompanying length data, the size range (total length in cm) is shown. The total number of specimens (*n*) is further expressed as the number of females (F), males (M) and sex unknown (?). Data from all specimens were collected as images, or as measurements of total length and fin base length (BL). The status of each species (RL), as assessed for The IUCN Red List of Threatened Species™, is shown as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), Lower Risk (LR), Near Threatened (NT), Least Concern (LC), Data Deficient (DD), Not Evaluated (NE).

				Images			BL		
Species	Common name	*n*	TL (cm)	?	F	M	F	M	RL
Alopias pelagicus	Pelagic Thresher	**1**	234.3			1			NE
Carcharhinus albimarginatus	Silvertip Shark	**26**	80.5–211.5		15	10	1		NE
Carcharhinus altimus	Bignose Shark	**3**	88.5–235		1	2			NE
Carcharhinus amblyrhynchoides	Graceful Shark	**20**	84–153.5		13	7			NT
Carcharhinus amblyrhynchos	Grey Reef Shark	**16**	82–181	4	8	4			NT
Carcharhinus amboinensis	Pigeye Shark	**14**	91–222	1	6	7			DD
Carcharhinus brachyurus	Bronze Whaler	**3**	303	3					NT
Carcharhinus brevipinna	Spinner Shark	**24**	66.5–209.2	2	10	4	5	3	NT
Carcharhinus cautus	Nervous Shark	**21**	55–141.5	1	15	5			DD
Carcharhinus dussumieri	Whitecheek Shark	**21**	53.5–80.5		12	9			NT
Carcharhinus falciformis	Silky Shark	**18**	83.5–260		11	4	3		LC
Carcharhinus fitzroyensis	Creek Whaler	**2**	97		2				LC
Carcharhinus leucas	Bull Shark	**20**	82.5–290	1	8	11			NT
Carcharhinus limb/tils	Blacktip Shark	**4**	101–230	3	1				NT
Carcharhinus limbatus	Common Blacktip Shark	**44**	62.4–330	18	18	7		1	NE
Carcharhinus macloti	Hardnose Shark	**1**			1				NT
Carcharhinus melanopterus	Blacktip Reef Shark	**8**	67.9–145.5	2	4	2			NT
Carcharhinus obscurus	Dusky Shark	**10**	105–390	2	4	4			NT
Carcharhinus plumbeus	Sandbar Shark	**3**	90–165		3				NT
Carcharhinus sorrah	Spot-Tail Shark	**52**	43.5–153.5	2	21	17	6	6	NE
Carcharhinus tilstoni	Australian Blacktip	**14**	102–164.5		14				LC
Carcharias taurus	Grey Nurse Shark	**7**	223.8–290	1	4	2			**VU**
Carcharodon carcharias	Great White Shark	**10**	178–250	5	1	4			**VU**
Chiloscyllium punctatum	Bamboo Shark	**8**	91.4–117.7	2	1	5			NE
Eusphyra blochii	Winghead Shark	**3**	116–152			3			NT
Galeocerdo cuvier	Tiger Shark	**20**	90–380	1	11	5	1	2	NT
Glyphis garricki	Northern River Shark	**1**	148			1			**CR**
Glyphis glyphis	Speartooth Shark	**1**				1			**EN**
Hemigaleus australiensis	Sickle Fin Weasel Shark	**12**	70.3–107.2	7	1	4			LC
Hemipristis elongata	Fossil Shark	**5**	49.1–160		2	3			NE
Isurus oxyrinchus	Shortfin Mako	**4**	120–250	4					NT
Isurus paucus	Longfin Mako	**1**	230	1					**VU**
Loxodon macrorhinus	Sliteye Shark	**2**	61–63		2				LC
Negaprion acutidens	Sharptooth Lemon	**8**	67–265	4	3	1			**VU**
Odontaspis ferox	Sand Tiger	**2**	280–300	1	1				NE
Prionace glauca	Blue Shark	**9**		9					NT
Rhina ancylostoma	Shark-Ray	**6**	90.4–221		3	3			NE
Rhincodon typus	Whale Shark	**1**		1					NE
Rhizoprionodon acutus	Milk Shark	**25**	61–92	18	2	5			LC
Rhizoprionodon taylori	Australian Sharpnose	**10**	40–79.4		7	3			LC
Rhynchobatus spp.	Wedgefish	**17**	52.4–166.3		9	8			NE
Sphyrna lewini	Scalloped Hammerhead	**13**	56–233		3	10			NT
Sphyrna mokarran	Great Hammerhead	**5**	151.7–248	2	2	1			**EN**
Sphyrna zygaena	Smooth Hammerhead	**2**	140–150	2					NT
Triaenodon obesus	Whitetip Reef Shark	**4**	122–145		1	3			NT
		501							

Unknown Samples

The ‘unknown’ samples consisted of a total of 2465 fins (both dorsal and pectoral), collected from illegal foreign fishing vessels (Figure 2.3, Table 2.3). These fins were seized from 12 vessels, which were apprehended in northern Australian waters between February 2006 and July 2009. An additional three bags of fin, named as FFVLM_11, FFVLM_13, and FFVLM_15, were known to be seized in 2006 from Indonesian foreign fishing vessels but could not be linked to a specific vessel (Table 2.3). These bags were treated as individual ‘vessels’, making 15 vessels in total. For vessels with a considerable amount of catch, only either the left or the right pectoral fins were processed in order to reduce processing time. This was assumed to represent one pectoral fin from each individual shark in the catch.

Figure 2.3 An example of an illegal Indonesian fishing vessel, which was apprehended in Australian waters. The vessel contained a cargo of shark fins confiscated by the Australian Fisheries Management Authority (AFMA), and used in this study as part of the ‘unknown’ shark fin category.

Table 2.3 Fin samples collected for the 'unknown' fin category by vessel. Samples were collected from illegal foreign fishing vessels apprehended in northern Australian waters between February 2006 and July 2009.

		Fin Type			
Vessel ID	Flag	First Dorsal	Left Pectoral	Right Pectoral	*n*
FFVLM_1	Taiwanese	699	710	1	1410
FFVLM_3	Indonesian	22			22
FFVLM_5	Indonesian	24			24
FFVLM_6	Indonesian	4			4
FFVLM_7	Indonesian	2			2
FFVLM_9	Taiwanese	145	129	2	276
FFVLM_10	Indonesian	30	30		60
FFVLM_11	Indonesian	2	3	1	6
FFVLM_12	Indonesian	135	93	57	285
FFVLM_13	Indonesian	2	1		3
FFVLM_14	Indonesian	10	1	9	20
FFVLM_15	Indonesian	5	110		115
FFVLM_19	Indonesian	11	8	13	32
FFVLM_20	Indonesian	52	51		103
FFVLM_24	Indonesian	60	42	1	103
		1203	1178	84	2465

2.2.2 Processing Procedure

For both ‘known’ and ‘unknown’ samples, individual fins were cleaned, photographed and a tissue sample removed for genetic analysis. Fin photographs were taken using a handheld Pentax Optio W10 digital camera (Chiari, *et al.* 2008) from directly above the subject, leaving a wide border which was later cropped to avoid edge distortion (Zelditch 2004). Each photograph contained a scale, specimen number and, for images used to analyse fin colour, a standard blue mat as a background. When photographed, fins were placed to represent the natural position of the fin (*e.g.* Figure 2.4).

A randomly selected subsample of fins was then dried in an oven at 50°C overnight and re-photographed (see section ‘Fin Drying’). This was intended to approximate the distortion resulting from drying fresh fins.

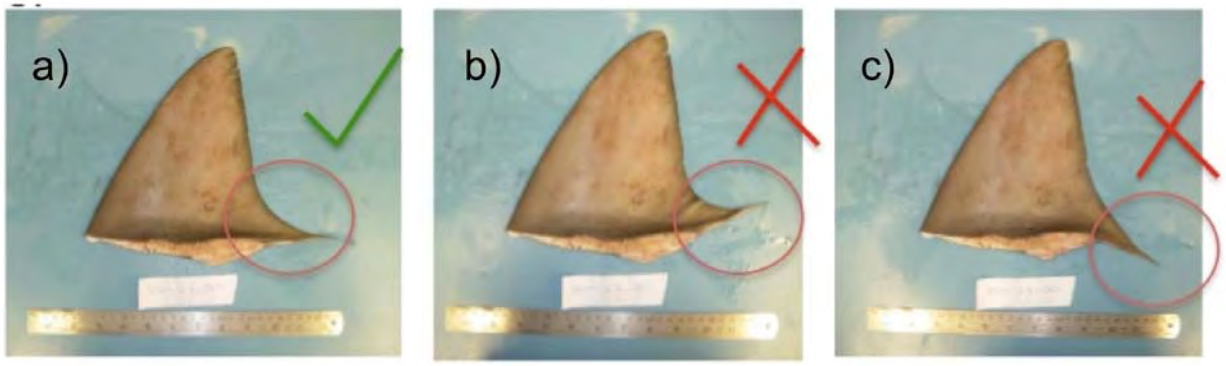


Figure 2.4 Three images of the same dorsal fin sample showing arrangement for photography (a), and incorrect placing of the free rear tip (b and c).

2.2.3 Measuring Procedure

All fin measurements were taken from digital images using *SigmaScan Pro.* 5 software (SPSS Inc. 1998), excepting a number of fins where the base length (B) (Figure 2.5 and Figure 2.6) was recorded directly from the sample using a handheld tape measure. Images were imported into *SigmaScan Pro.* 5 and calibrated using the aforementioned scale. Primary measurements are those taken from easily located points on the fin (primary landmarks) (Figure 2.7). Secondary measurements are those taken from 'primary apex landmarks' located using the primary landmarks (Figure 2.8). Tertiary measurements are those taken from secondary apex landmarks' located using the apex landmarks (Figure 2.8). A series of 17 linear distance measurements were taken for dorsal fins (Figure 2.5), and 21 linear distance measurements were taken for pectoral fins (Figure 2.6).

Accurate location of both the primary and secondary apex landmarks was carried out in *SigmaScan Pro.* 5 using the 'annotation lines tool' to locate apex landmarks using perpendicular distances (Figure 2.8).

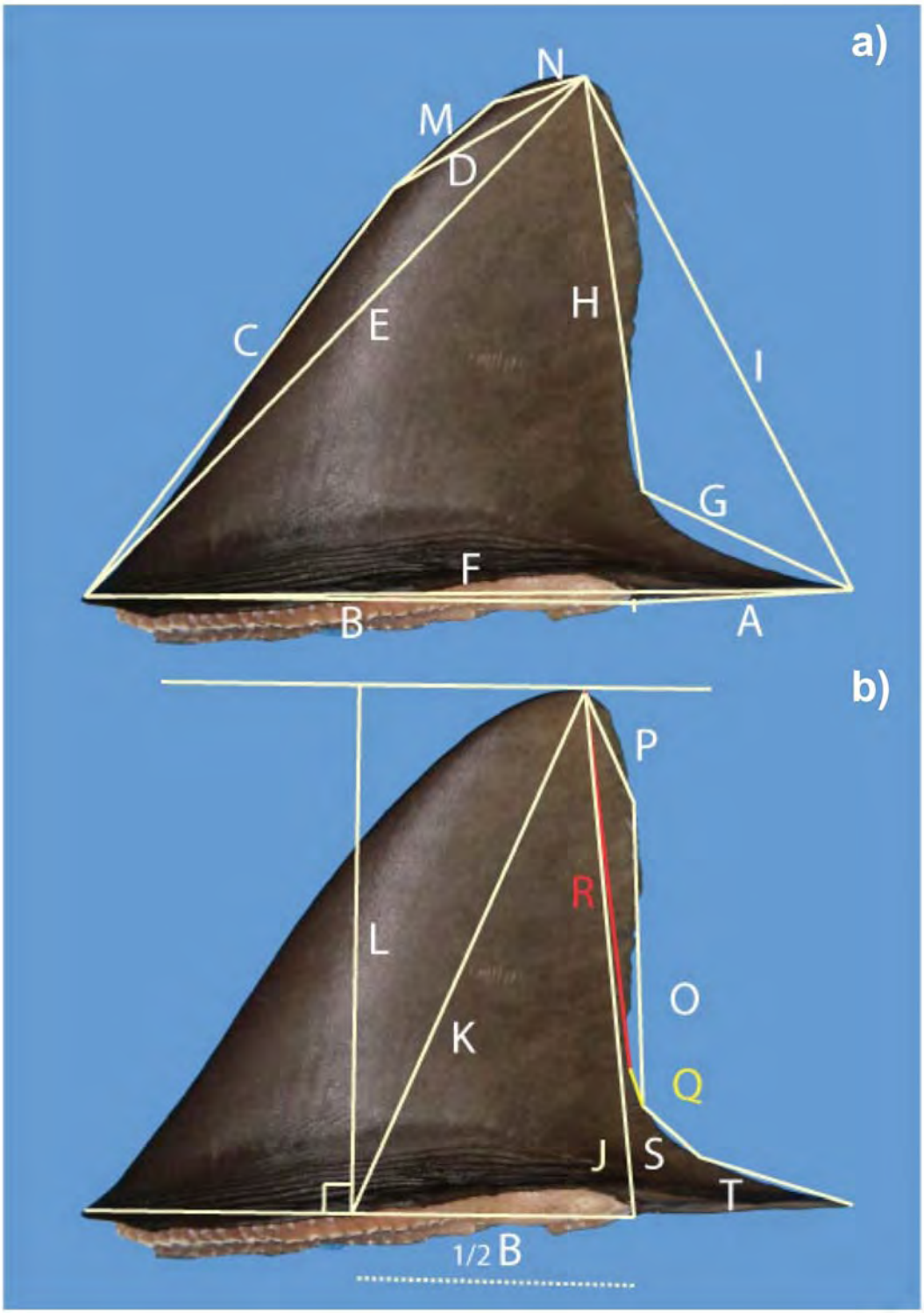


Figure 2.5 The 20 linear distances measured on each dorsal fin for both 'known' and 'unknown' fins. a) A^1 (inner margin), B^1 (fin base), C^2 (upper anterior margin), D^2 (lower anterior margin), E^1 (anterior margin), F^1 (total fin width), G^2 (lower posterior margin), H^2 (upper posterior margin), I^1 (posterior margin), M^3 (lower outer anterior margin), N^3 (upper outer anterior margin). b) J^1 (fin height), K^1 (direct mid fin height), L^1 (absolute fin height), O^3 (lower outer posterior margin), P^3 (upper outer posterior margin), Q^3 (lower inner posterior margin), R^3 (upper inner posterior margin), S^3 (lower outer free rear tip margin), T^3 (upper outer free rear tip margin). [1]primary measurements, [2]secondary measurements, [3]tertiary measurements.

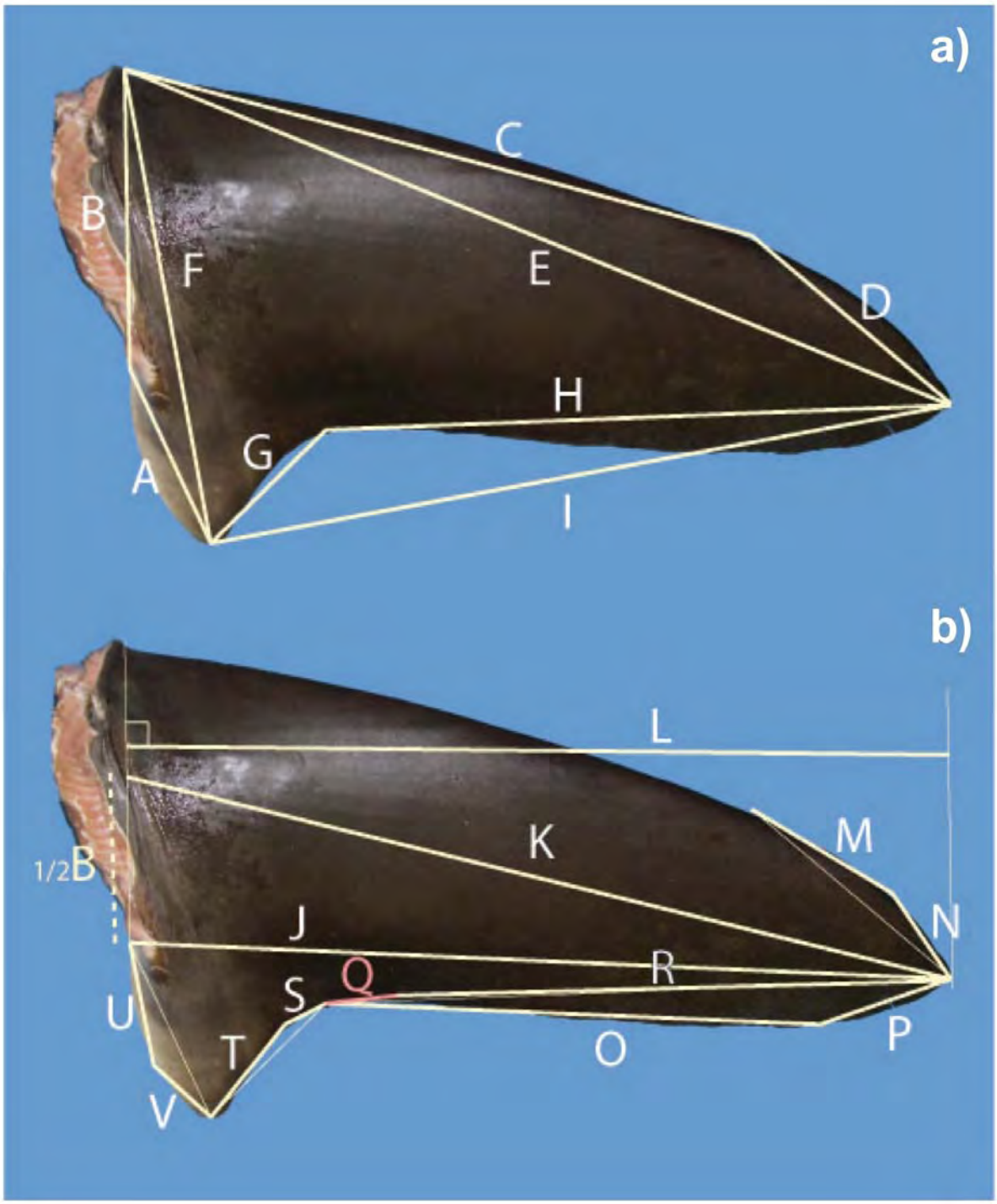


Figure 2.6 The 22 linear distances measured on each pectoral fin for both 'known' and 'unknown' fins. a) A^1 (inner margin), B^1 (fin base), C^2 (upper anterior margin), D^2 (lower anterior margin), E^1 (anterior margin), F^1 (total fin width), G^2 (lower posterior margin), H^2 (upper posterior margin), I^1 (posterior margin), M^3 (lower outer anterior margin), N^3 (upper outer anterior margin). b) J^1 (fin height), K^1 (direct mid fin height), L^1 (absolute fin height), O^3 (lower outer posterior margin), P^3 (upper outer posterior margin), Q^3 (lower inner posterior margin), R^3 (upper inner posterior margin), S^3 (lower outer free rear tip margin), T^3 (upper outer free rear tip margin), U^2 (lower inner margin), V^2 (upper inner margin). [1]primary measurements, [2]secondary measurements, [3]tertiary measurements.

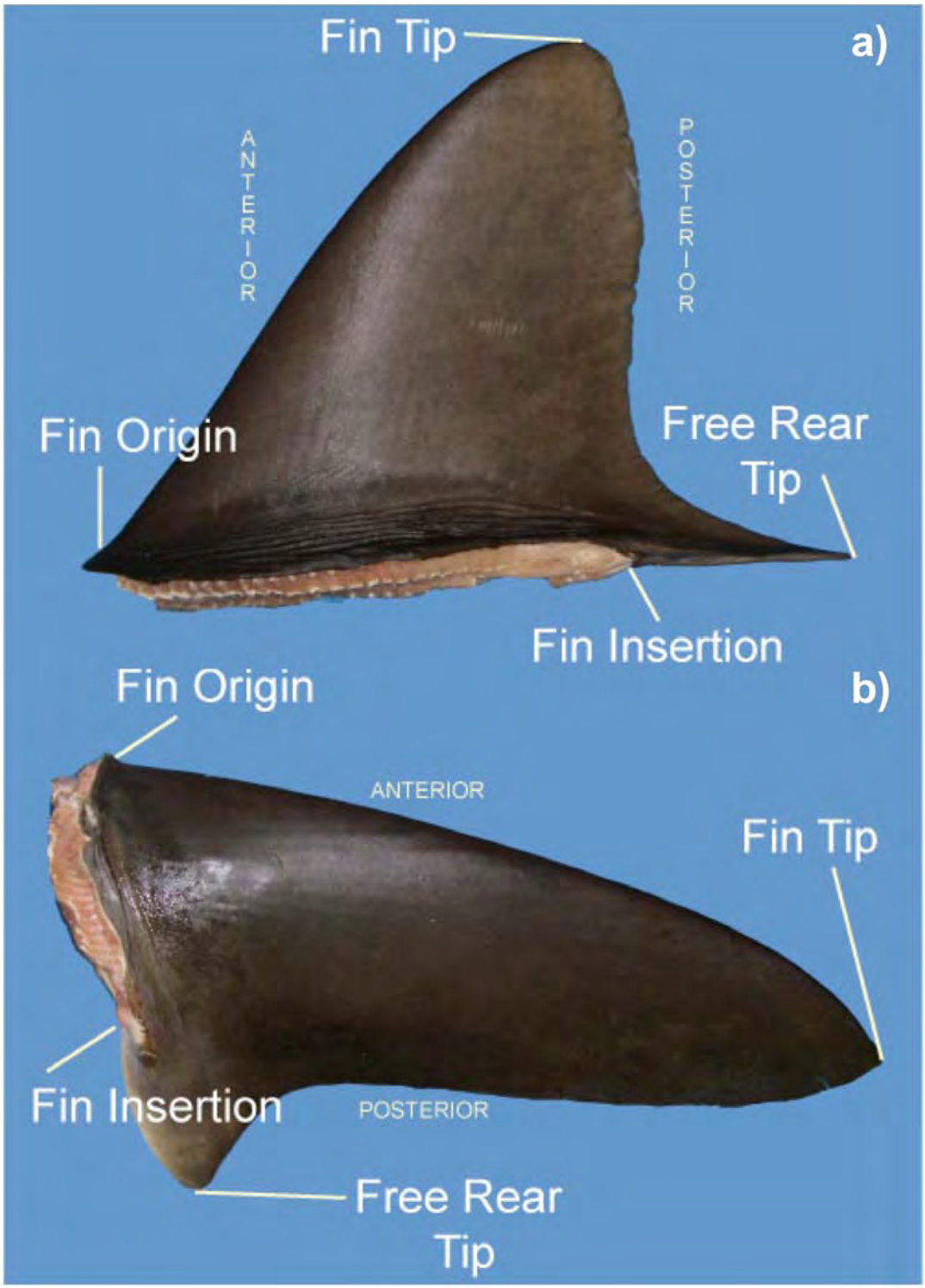


Figure 2.7 Location and terminology of the four primary landmarks on any shark fin from which all primary measurements are based, for a) dorsal fins (Figure 2.5) and b) pectoral fins (Figure 2.6). Fin ‘‘origin’’ refers to the anterior-most point at which the margin of a fin meets the profile of the body; ‘‘insertion’’ is the posterior-most point of attachment of the base of the fin to the body; “tip” the distal tip or apex, which can be acutely pointed to broadly rounded (see Figure 2.10); “free rear tip” refers to the posterior tip of the fin that is closest to the most posterior point of the fin base.

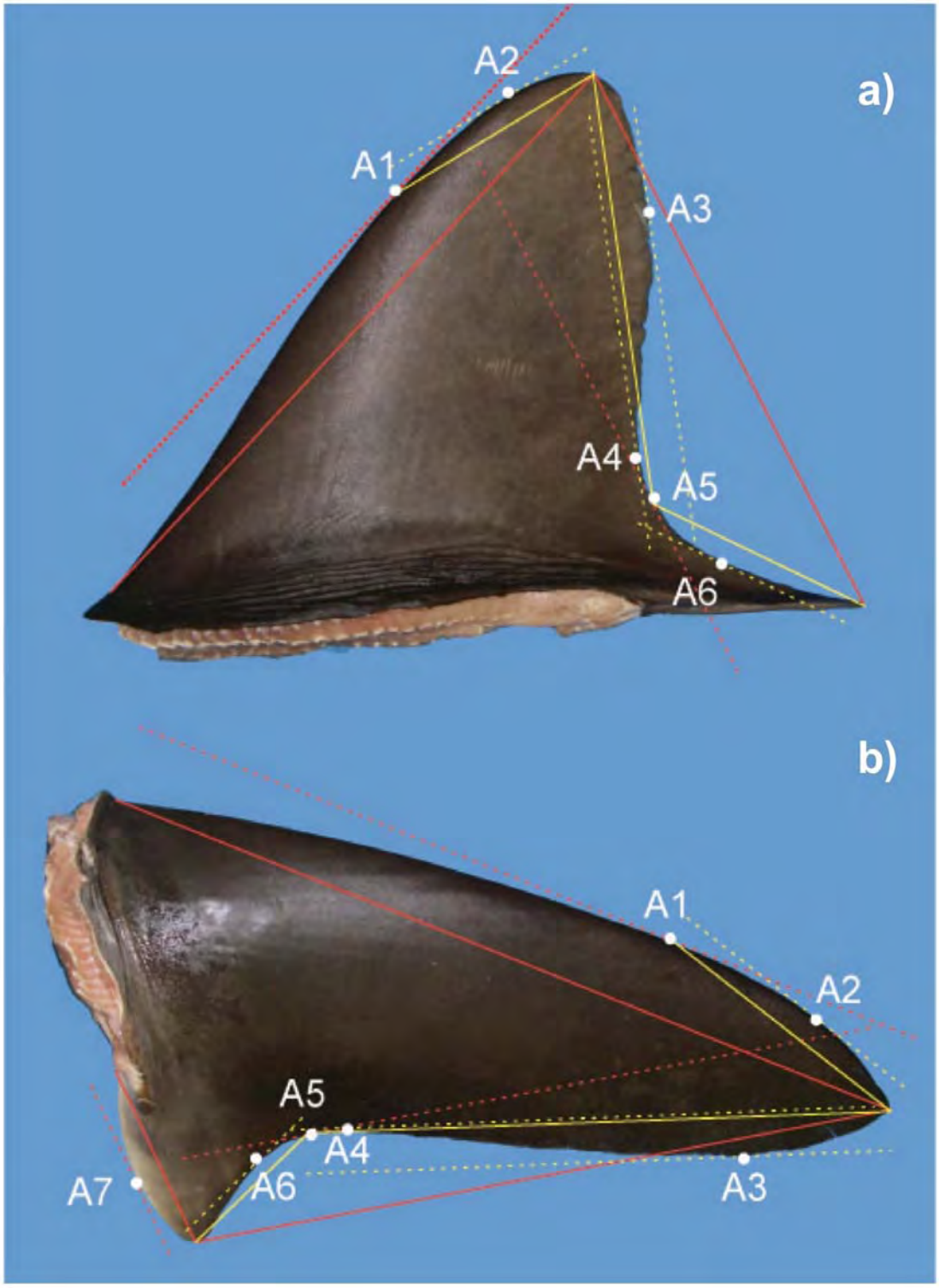


Figure 2.8 Location of the apex landmarks (white circles) for which all secondary and tertiary distance measurements are based for a) dorsal and b) pectoral fins. Solid lines represent the original primary (red) or secondary (yellow) measurements and dotted lines represent the largest perpendicular distance from these to the edge of the fin, by which the apex landmark is located. Labels correspond to: A1 (major convex anterior apex), A2 (minor convex anterior apex), A3 (minor convex posterior apex), A4 (minor concave posterior apex), A5 (major concave posterior apex), A6 (concave free rear tip apex), A7 (convex inner margin apex).

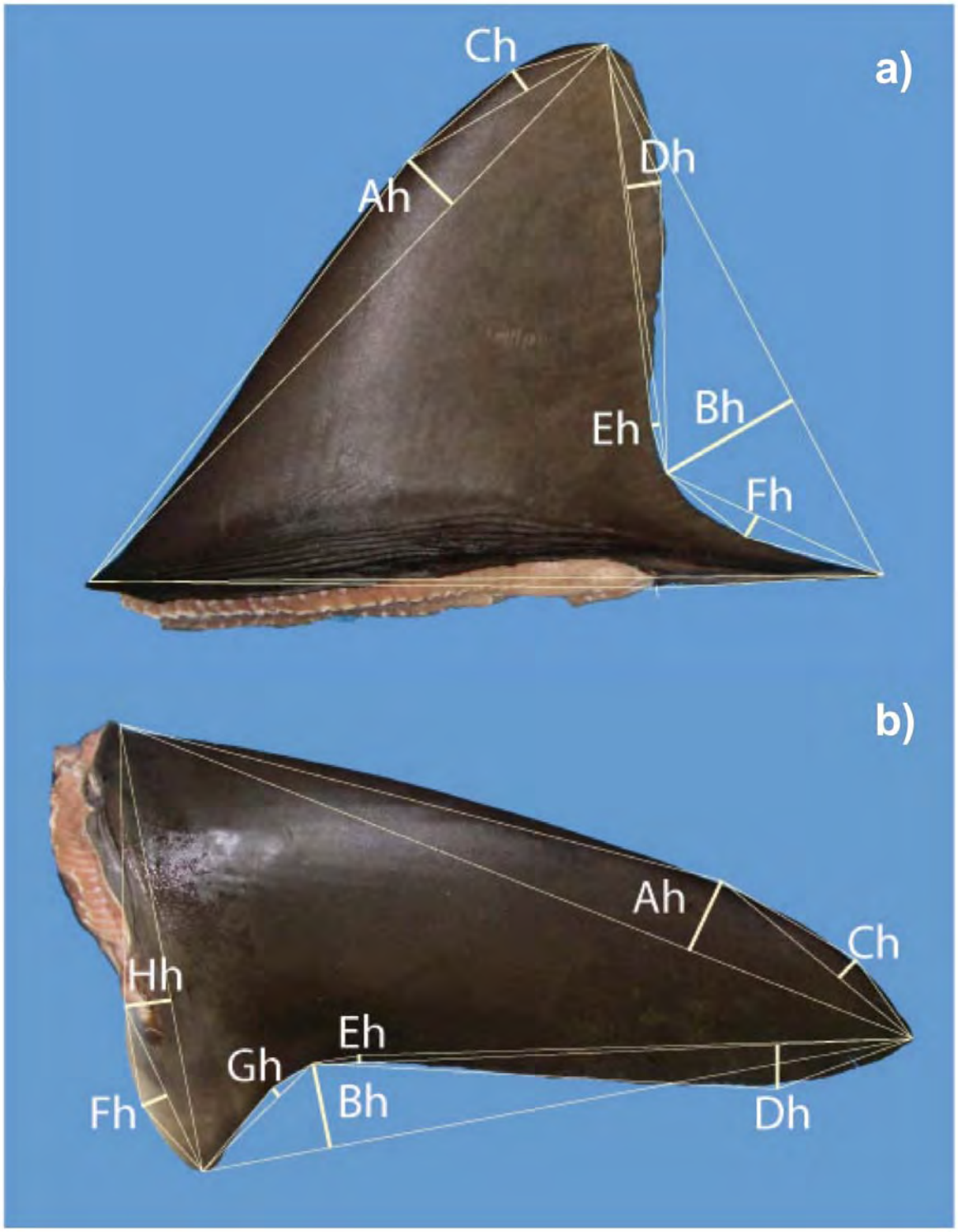


Figure 2.9 Height measurements that were calculated from the length measurements in Figure 2.5 Figure 2.6 using Heron's Formula for a) dorsal fins and b) pectoral fins. Ah (anterior margin height), Bh (posterior margin height), Ch (outer anterior margin height), Dh (outer posterior margin height), Eh (inner posterior margin height), Fh (free rear tip margin height), Gh (inner free rear tip margin height), Hh (free rear tip depth).

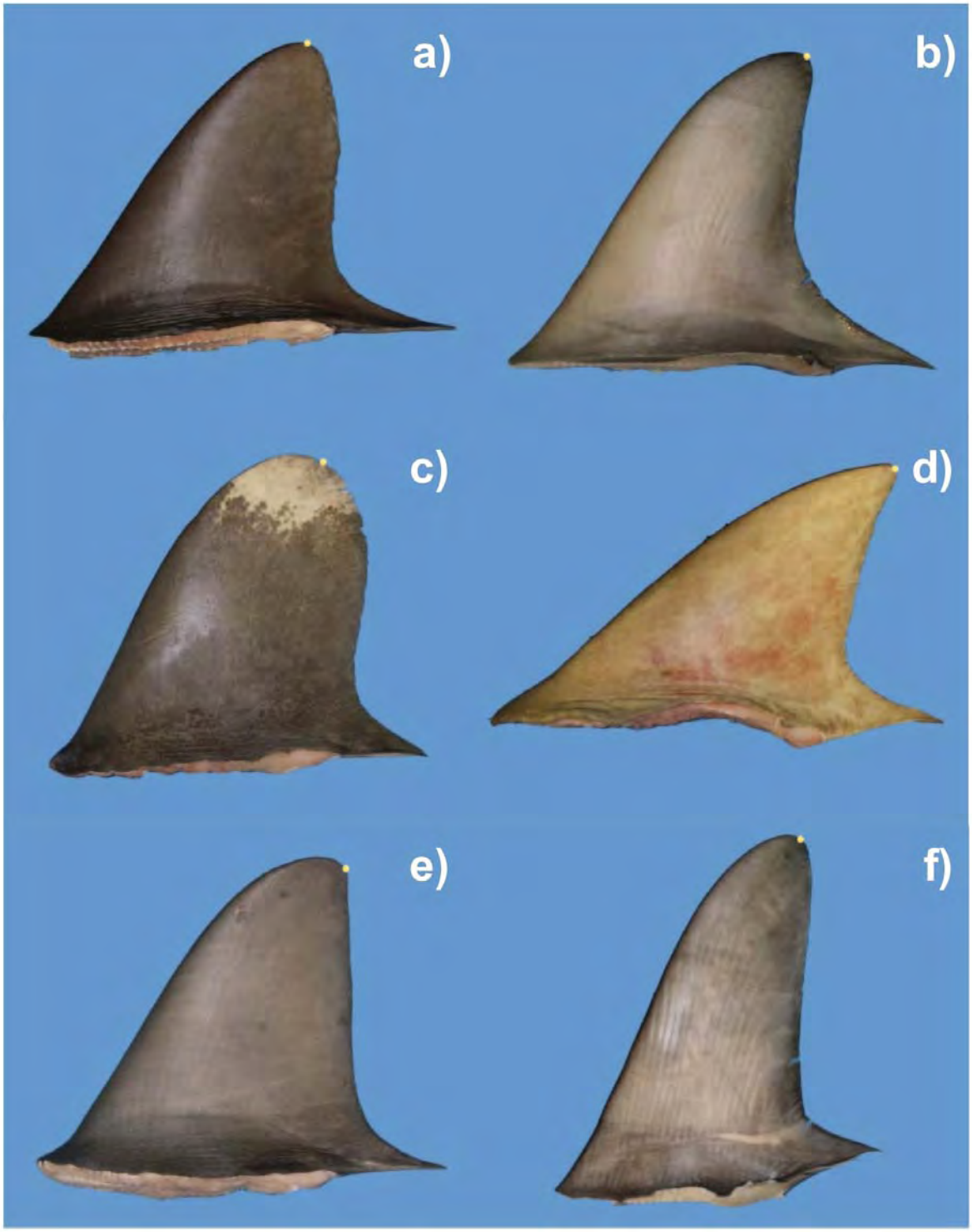


Figure 2.10 Examples of fin-tip location on the dorsal fins of shark species with differing tip shapes. Yellow dot delineates the location of the tip when taking measurements. For pointed fins (a, d and e) the tip is located at the point. For rounded fins (b and c) tip is located at the apex of the rounded edge.

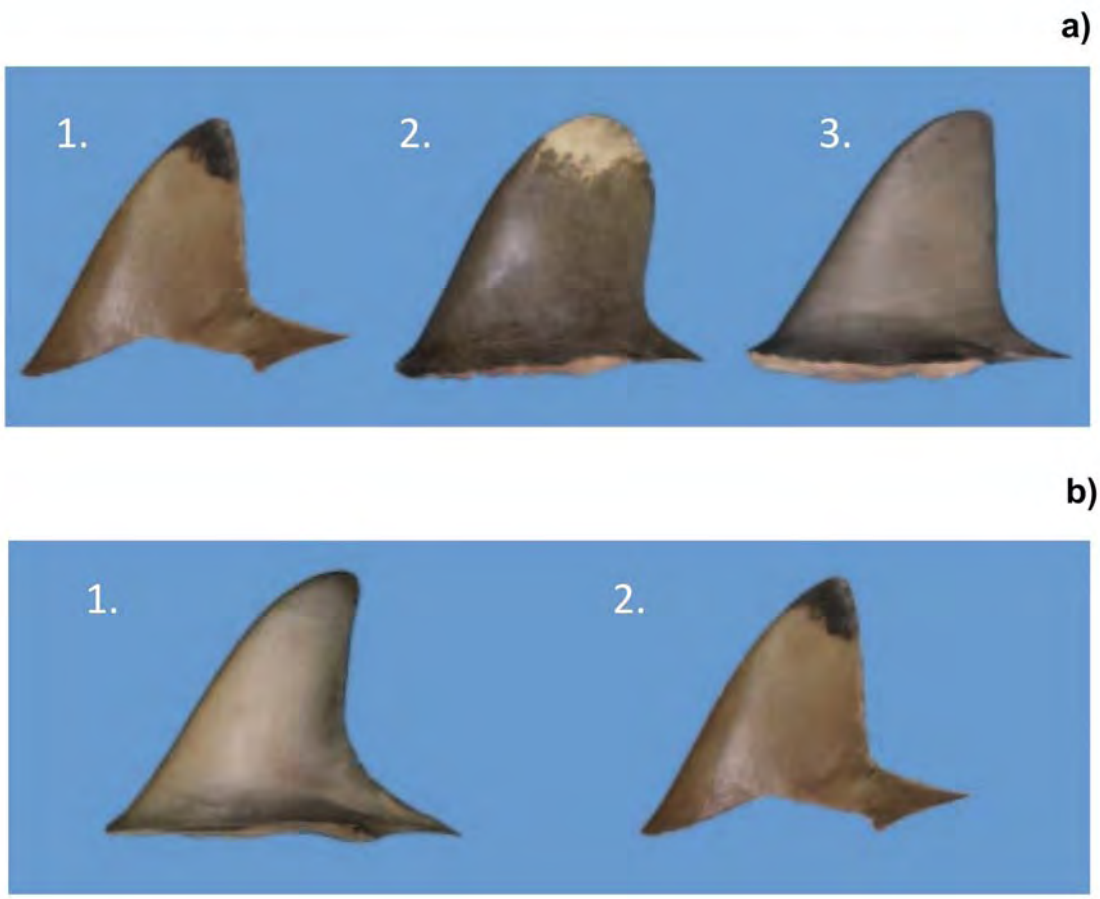


Figure 2.11 Examples of inter-specific variation in fin-tip colour that can occur on both dorsal and pectoral fins as a) fin-tip colour (1. black, 2. white and 3. no tip colour) and b) nature of fin-tip colour (1. dusky and 2. sharp).

From these measurements, an additional five height measurements for dorsal fins and eight for pectoral fins (Figure 2.9) were calculated using Heron Formula (Heath 1921):

$$A = \sqrt{\frac{(a+b+c)(a+b-c)(b+c-a)(c+a-b)}{16}} \quad (1)$$

where, A is the area of a triangle with sides a, b, and c, and determining the triangle height using the standard formula:

$$height = \frac{A}{\frac{1}{2} \times base} \quad (2)$$

Along with these measurements, a number of other descriptive characteristics were recorded for each fin including fin-tip colour (dorsal fins), fin-tip colour on dorsal and ventral surfaces (pectoral fins), fin-tip colour margin and fin-tip area (Table 2.4).

Additionally, fin colour was quantified in images by measuring the average RGB (red, green and blue) channel levels from an area of the fin using *SigmaScan Pro.* 5 (SPSS Inc. 1998).

Table 2.4. Descriptive characters recorded for all 'known' and 'unknown' samples of dorsal and pectoral fins.

Character	Description
Dorsal fin tip colour	Colour of the tip of the dorsal fin: 1) black, 2) white, or 3) no colour. (Figure 2.11b).
Pectoral fin tip colour (dorsal)	Colour of the tip of the dorsal side of the pectoral fin: 1) black, 2) white, or 3) no colour.
Pectoral fin tip colour (ventral)	Colour of the tip of the ventral side of the pectoral fin: 1) black, 2) white, or 3) no colour.
Fin-tip colour margin	Nature of the tip colour: 1) sharply demarcated or 2) dusky (Figure 2.11c).
Fin-tip area	Area covered by the tip colour expressed as a percentage of the whole fin area.

2.2.4 Measurement Bias

Sources of measurement bias such as those from the photograph angle (image perspective), fin cut and fin drying were investigated and discussed below.

Photograph Angle

As fin identification methods were intended to allow easy use in the field, images captured using handheld digital cameras were used. A handheld camera (as opposed to a mounted camera) allows less control of the angle between the camera and the subject, which could result in distortion of the shape of the subject (Zelditch 2004). As all measurements in subsequent chapters (Chapter 4, 5 and 6) are taken from digital images derived from handheld cameras, the significance and effect of differing camera angles was tested to evaluate the suitability of handheld methods for taking fin photographs.

The same measurement taken on the same fin may yield significantly different values if measurements are taken from images that are photographed at different camera angles. In order to investigate the effect of camera angle on fin measurements a series of photographs of a single pectoral fin were taken using a *Pentax Optio W10* digital camera. The camera was mounted on a copy stand at a standard height of 70 cm, which was fitted with an angle meter. Six photographs

were taken at each angle at 4° intervals from -20° to 20°. A subset of ten distance measurements (A, C, D, E, F, G, K, Figure 2.6) was measured on each of the resulting photographs (see section 2.2.3). For each measurement (A–K) the equality of the means at all camera angles was tested using a one-way ANOVA, and the difference of the means at each camera angle to the control (0˚) was tested using a *post hoc* Dunnet test.

Fin Cut

As the ability to locate the fin origin and the fin insertion (Figure 2.7) is fundamental for accurately determining fin measurements for morphometric analysis, it is imperative that these two locations are preserved when fins are removed. To estimate the proportion of fins in the foreign catch that are cut in a manner that preserves these critical positions (*i.e.* the fin origin and the fin insertion can be located after the fin is removed from the shark), the percentage of the 'unknown' dorsal fins sampled from foreign vessels fitting this criteria was calculated.

Fin Drying

As fins are dried during processing for trade, the effect of fin drying on distance measurements was investigated. As this was a preliminary investigation, it was not yet known which fins would be most suitable for designing the identification protocols. Therefore, pectoral fins were arbitrarily chosen for the fin drying exercise. The pectoral fins of 25 'known' specimens were photographed when wet (*i.e.* fully hydrated). These samples were then dried overnight in an oven at 50°C and re-photographed. The resulting images of dry and wet fins were then measured using *SigmaScan Pro.* 5 (SPSS Inc. 1998) as in Section 2.2.3. This resulted in fully dried fins, which was assumed to correspond with the level of desiccation of fins that were dried on the decks of foreign fishing vessels.

For each of the 21 fin measurements (Figure 2.6 - excluding 'V'), the difference after drying with fin size was represented visually by plotting the wet *vs* dry values for each fin sample. A

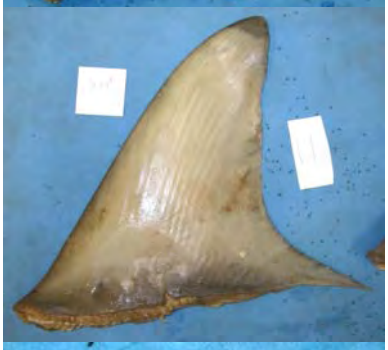
pairwise t-test was used to test the difference in the 21 measurements after drying. For measurements that did not fit the assumption of normality for the pairwise t-test, they were tested using the Wilcoxon Signed Rank test, with significance defined as $P < 0.05$.

To obtain an estimate of the extent of fin drying in the IUU catch in northern Australia, all 'unknown' dorsal fins were allotted to one of five categories that relate to an estimate of the observed state of desiccation of the fin (Table 2.5).

2.2.5 Fin Type

In order to develop the identification protocols in Chapter 4, dorsal and pectoral fins were considered the most appropriate fins to investigate, as they are most likely to be retained by fishers (Table 2.3). Although caudal fins are also largely retained, they were not considered useful as the lower caudal fin is often removed from the remaining caudal fin soon after capture. This is because the lower part of the caudal fin, unlike the upper part, contains the fin needles used to make shark fin soup (see Chapter 1). Consequently, there are no reliable reference points (*e.g.* 'fin origin' and 'fin insertion') on the detached lower caudal lobe.

Table 2.5 Description of the five categories used to describe the extent of drying for each shark fin in the IUU catch. An example image of a dorsal fin sample from each category is provided. Fins are not from the same species.

Category	Description	
Dry	No Moisture in flesh. Rigid to touch.	
Partially Dry to Dry	No moisture in flesh. Flexible to touch.	
Partially Dry	Very little moisture in flesh. Flexible to touch.	
Wet to Partially Dry	Flesh may be moist, but extremities of fin desiccated. Flexible to touch.	
Wet	Flesh moist. Extremities of fin moist. Thawed or fresh.	

2.3 Results

2.3.1 Photograph Angle

There was no significant difference ($p>0.05$) between proportional measurements taken between all angle groups and between each angle and the control (0°) for seven of the measurements (A, C, D, E, F, G, K). The maximum deviation from the control was 8.3%, for measurement I at 16° (Table 2.6).

2.3.2 Fin Cut

In the majority of cases (98%, $n = 1179$), foreign fishers cut dorsal fins in a way that preserved the fin origin and insertion. Thus, for most fins, measurements could be taken from all points. The remaining 2% ($n = 24$) of fins were not used in further analysis.

2.3.3 Fin Drying

For most measurements (*i.e.* 13 of the 21 measurements), the change in length after drying was small (Figure 2.12). However, some measurements showed random changes in length with drying (*e.g.* N, P, S, T and U, Figure 2.12) and others showed a marked distortion pattern (*e.g.* Q, and R, Figure 2.12). There was a positive correlation between wet and dry fin states and total length for all measurements, except for the tertiary measurements N, P, Q, and R (Figure 2.12). Additionally, there was a significant difference ($P < 0.05$) between dried and wet fin for all measurements except the secondary measurements D and U, and the tertiary measurements M, N, O, and Q.

Most measurements showed a decrease in length with fin drying (Figure 2.13). The greatest average difference between wet and dry fins was seen in the tertiary measurements P, S, and R, with an average percent change of 1380.33, 359.69 and -71.98 %, respectively, after drying. P and S showed an increase in length with fin drying, and R a decrease in length (Figure 2.13).

Table 2.6 Average difference (cm ± SE) of each measurement (A-K), taken from a singe pectoral, fin from the control (0°) with varying camera angle. Brackets indicate the average difference from the control (0°), expressed as a percentage of the control.

	-20°	-16°	-12°	-8°	-4°	0°	4°	8°	12°	16°	20°
A	0.36 ± 0.19 (0.26)	0.42 ± 0.10 (3.14)	0.64 ± 0.11 (4.75)	0.44 ± 0.14 (3.20)	0.61 ± 0.14 (4.59)		0.43 ± 0.08 (3.18)	0.38 ± 0.06 (2.84)	0.50 ± 0.12 (3.68)	0.54 ± 0.13 (4.02)	0.55 ± 0.10 (4.10)
B	0.18 ± 0.05 (2.72)	0.24 ± 0.04 (3.51)	0.16 ± 0.02 (2.38)	0.22 ± 0.10 (3.09)	0.20 ± 0.04 (2.86)		0.24 ± 0.05 (3.49)	0.18 ± 0.03 (2.67)	0.28 ± 0.07 (4.02)	0.28 ± 0.11 (4.17)	0.30 ± 0.06 (4.34)
C	0.43 ± 0.20 (2.15)	0.36 ± 0.09 (1.81)	0.55 ± 0.12 (2.77)	0.43 ± 0.14 (2.15)	0.77 ± 0.15 (3.89)		0.27 ± 0.06 (1.37)	0.35 ± 0.06 (1.75)	0.41 ± 0.12 (2.09)	0.47 ± 0.16 (2.36)	0.35 ± 0.10 (1.78)
D	0.18 ± 0.06 (2.16)	0.15 ± 0.03 (1.88)	0.20 ± 0.08 (2.53)	0.20 ± 0.09 (2.49)	0.28 ± 0.07 (3.53)		0.11 ± 0.04 (1.42)	0.15 ± 0.04 (1.86)	0.19 ± 0.06 (2.37)	0.18 ± 0.06 (2.20)	0.13 ± 0.03 (1.59)
E	0.38 ± 0.21 (1.99)	0.24 ± 0.07 (1.26)	0.45 ± 0.09 (2.37)	0.39 ± 0.09 (2.05)	0.63 ± 0.15 (3.32)		0.18 ± 0.04 (0.97)	0.25 ± 0.06 (1.32)	0.33 ± 0.11 (1.74)	0.46 ± 0.10 (2.41)	0.34 ± 0.08 (1.81)
F	0.35 ± 0.20 (1.98)	0.23 ± 0.05 (1.36)	0.41 ± 0.10 (2.38)	0.33 ± 0.08 (1.92)	0.62 ± 0.14 (3.61)		0.11 ± 0.03 (0.67)	0.23 ± 0.05 (1.37)	0.25 ± 0.07 (1.44)	0.32 ± 0.10 (1.88)	0.30 ± 0.07 (1.75)
G	0.26 ± 0.10 (2.10)	0.24 ± 0.06 (1.97)	0.37 ± 0.07 (3.05)	0.29 ± 0.11 (2.34)	0.44 ± 0.11 (3.62)		0.16 ± 0.04 (1.31)	0.24 ± 0.06 (1.95)	0.27 ± 0.08 (2.20)	0.28 ± 0.09 (2.27)	0.20 ± 0.05 (1.64)
H	0.31 ± 0.09 (2.57)	0.35 ± 0.11 (2.85)	0.50 ± 0.11 (4.13)	0.39 ± 0.12 (3.20)	0.40 ± 0.11 (3.31)		0.31 ± 0.05 (2.53)	0.29 ± 0.07 (2.43)	0.27 ± 0.09 (2.29)	0.26 ± 0.04 (2.11)	0.46 ± 0.14 (3.81)
I	0.33 ± 0.11 (5.89)	0.19 ± 0.06 (3.50)	0.26 ± 0.06 (4.69)	0.19 ± 0.07 (3.48)	0.34 ± 0.10 (6.14)		0.26 ± 0.08 (4.64)	0.19 ± 0.07 (3.34)	0.30 ± 0.12 (5.42)	0.46 ± 0.11 (8.30)	0.25 ± 0.09 (4.54)
J	0.13 ± 0.04 (2.86)	0.09 ± 0.04 (2.01)	0.16 ± 0.05 (3.44)	0.14 ± 0.03 (3.07)	0.15 ± 0.06 (3.22)		0.16 ± 0.03 (3.35)	0.09 ± 0.03 (2.00)	0.17 ± 0.04 (3.64)	0.17 ± 0.04 (3.66)	0.13 ± 0.03 (2.80)
K	0.38 ± 0.23 (1.90)	0.30 ± 0.08 (1.54)	0.58 ± 0.09 (2.91)	0.43 ± 0.11 (2.17)	0.71 ± 0.15 (3.62)		0.23 ± 0.05 (1.17)	0.29 ± 0.08 (1.48)	0.39 ± 0.11 (1.98)	0.41 ± 0.14 (2.09)	0.38 ± 0.09 (1.91)
n	6	6	6	7	7		7	7	7	7	7

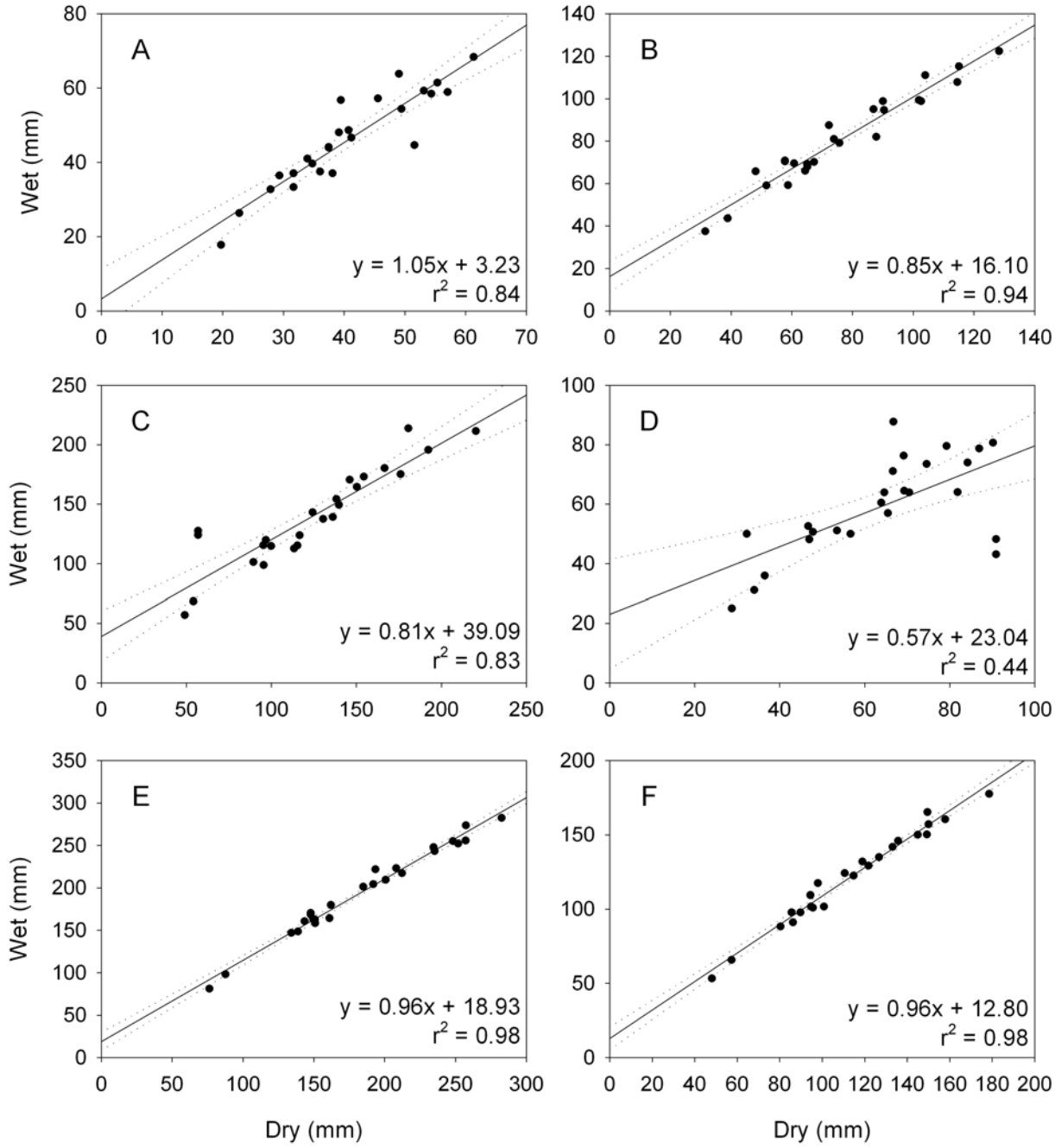


Figure 2.12 Relationship between wet and dry values (mm) for each pectoral fin measurement A–U (n = 26 specimens). Regression lines are included when significant ($P \leq 0.05$). Dotted lines show 95% confidence intervals for the regression equation.

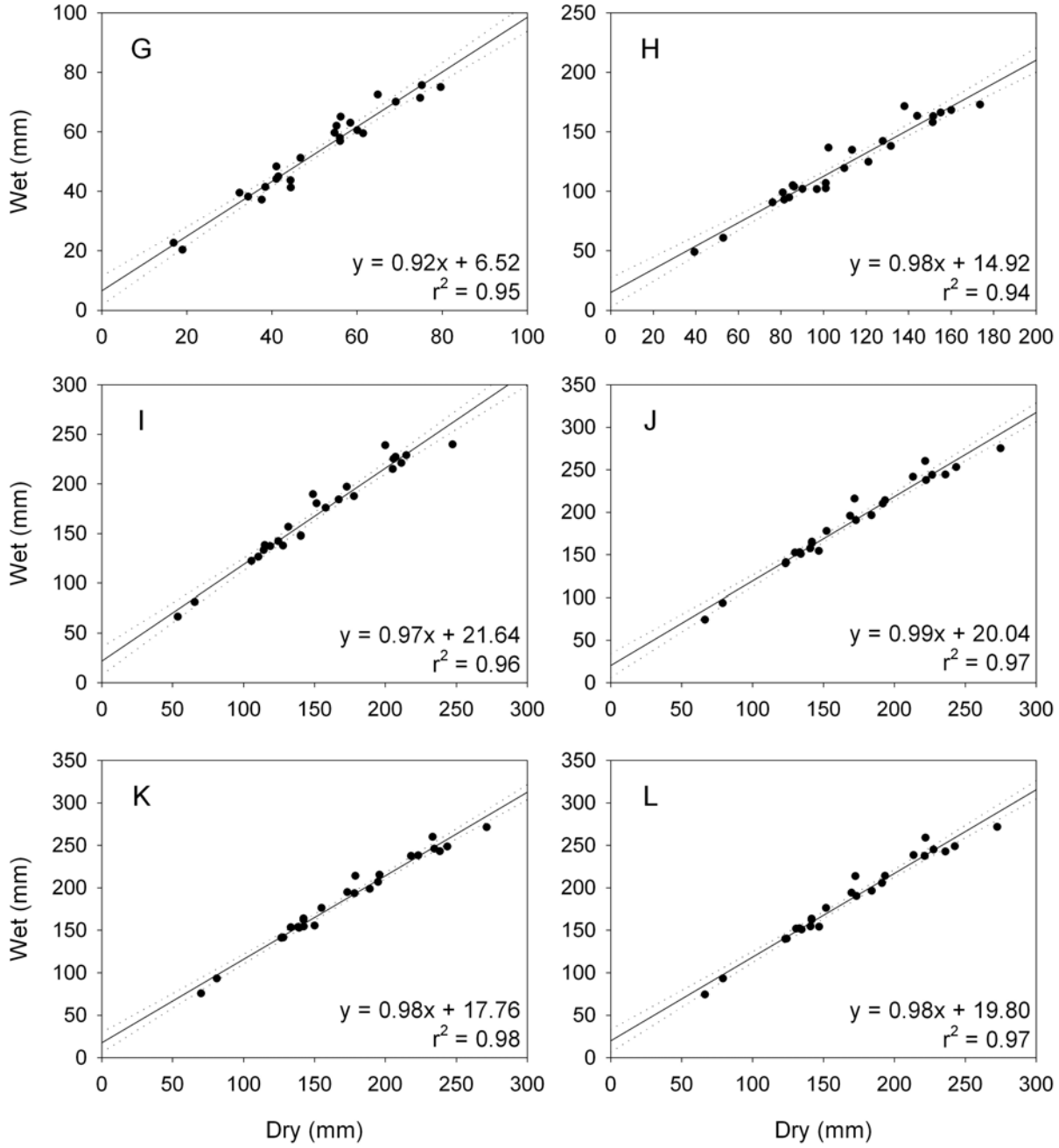


Figure 2.12 Continued.

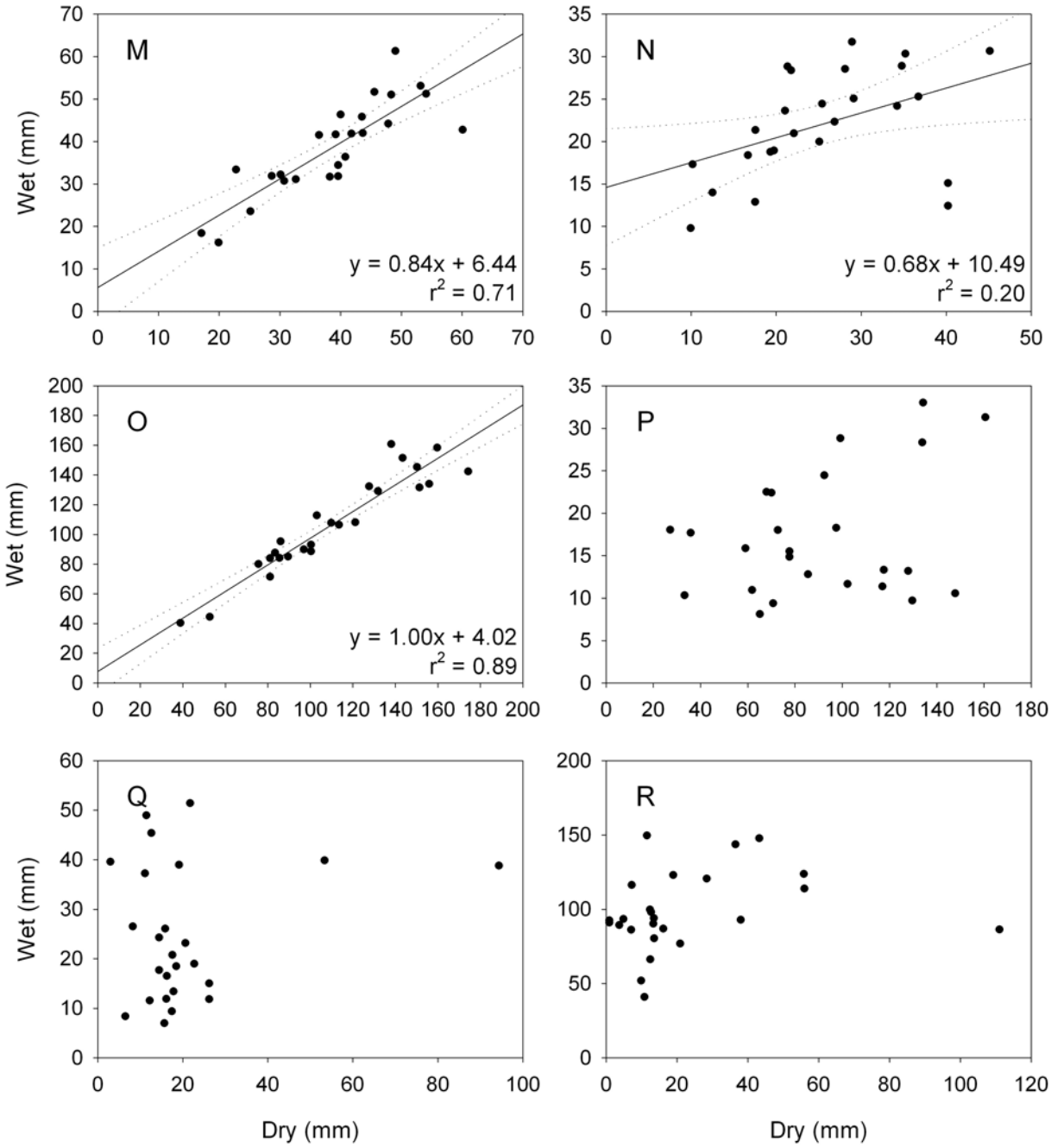


Figure 2.12 Continued.

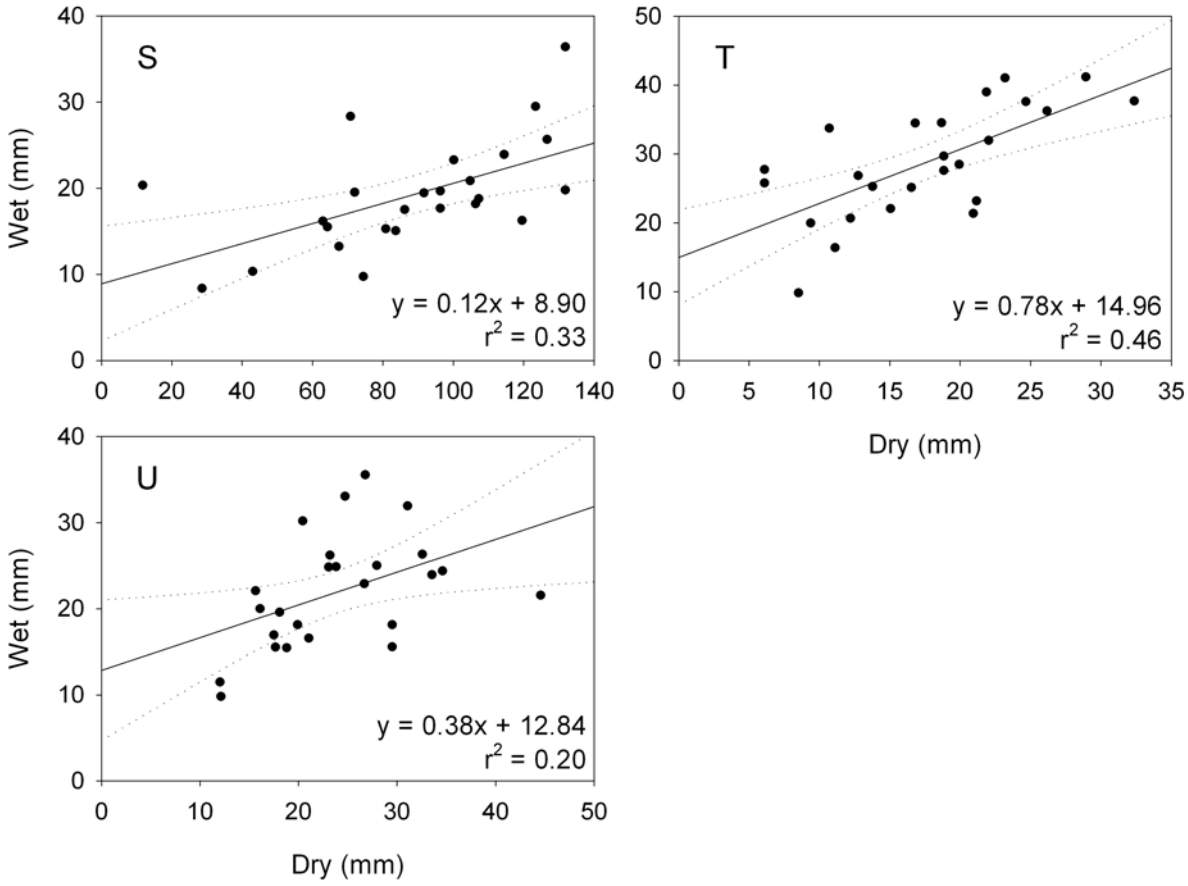


Figure 2.12 Continued.

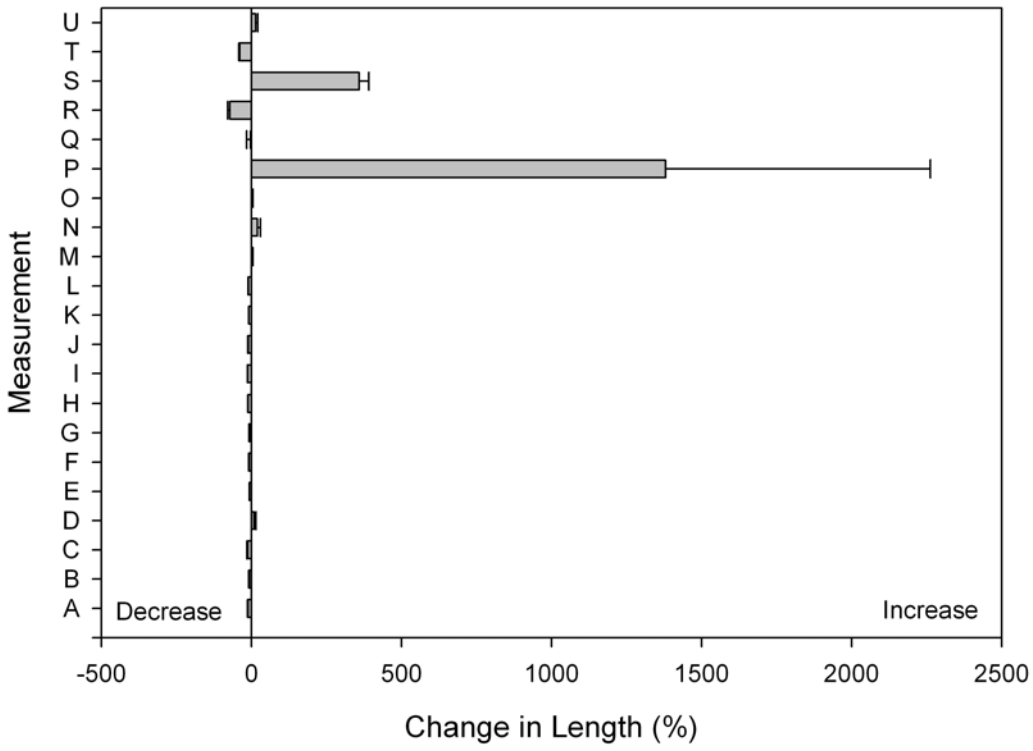


Figure 2.13 The mean change in length after drying for each of the 21 measurements (Figure 2.6) taken on 26 pectoral fins.

Most (91.35%) of the dorsal fins from the sample of fins from the IUU catch in northern Australia were in a fully wet state. Indonesian-caught fins were generally more desiccated than Taiwanese-caught fins, however the majority of Indonesian-caught fins were still in a wet (60.3%) or wet to partially dry (15.7%) state (Table 2.7).

Table 2.7 Number of dorsal fin samples from foreign fishing vessels by degree of desiccation and vessel type.

	Vessel Type		
State of Drying	Indonesian	Taiwanese	Total
Dry	2 (0.9%)		2 (0.19%)
Partially Dry to Dry	30 (13.1%)		30 (2.85%)
Partially Dry	23 (10%)		23 (2.19%)
Wet to Partially Dry	36 (15.7%)		36 (3.42%)
Wet	138 (60.3%)	823 (100%)	961 (91.35%)
	229	823	1052

2.4 Discussion

The aim of this chapter was to describe and justify the core methodologies used in this thesis, and to demonstrate that sources of bias were considered when designing the methodology. As digital images are used subsequently to investigate the different aspects of shark fin morphology, particular attention was paid to investigating sources of bias associated with this method. Three major concerns were addressed with respect to the ability to use of digital images of fins to identify sharks to species; 1) using a handheld camera for capturing images, 2) the effect of fin cut on the fin shape, and 3) the effect of drying on the fin shape.

If the methods developed in this thesis are to be an effective tool for contributing to the conservation of shark species, regional fisheries management authorities must actually use them. For this reason, the development of robust, field-friendly methods is imperative. The likelihood of a fisheries officer using a handheld digital camera to photograph illegal catch is far higher than if sophisticated stabilising equipment (*e.g.* a tripod) or lighting is needed. This study found that substantial changes in camera angle (from 0–20°) did not significantly affect any of the measurements examined. Most importantly, this means that photographing the subject with a hand held camera from directly above the sample is an acceptable method of image capture.

All of the measurements that are proposed for identifying shark species from digital images of their fins are dependant on the ability to locate two points on the fin, the origin and the insertion. Therefore, a major concern was how frequently these points could be encountered, as this is subject to the way illegal fishermen remove the fins from the shark. This study found that a very high proportion of fins in the illegal catch (98%) were cut in a manner that preserved the fin origin and insertion. This high frequency meant that the required measurements could be derived on most of the fins sourced from the illegal catch. The reason that these points were so readily preserved on the fins present in the IUU catch may be due to the high price by weight of fin, persuading fishers to leave more flesh on excised fins.

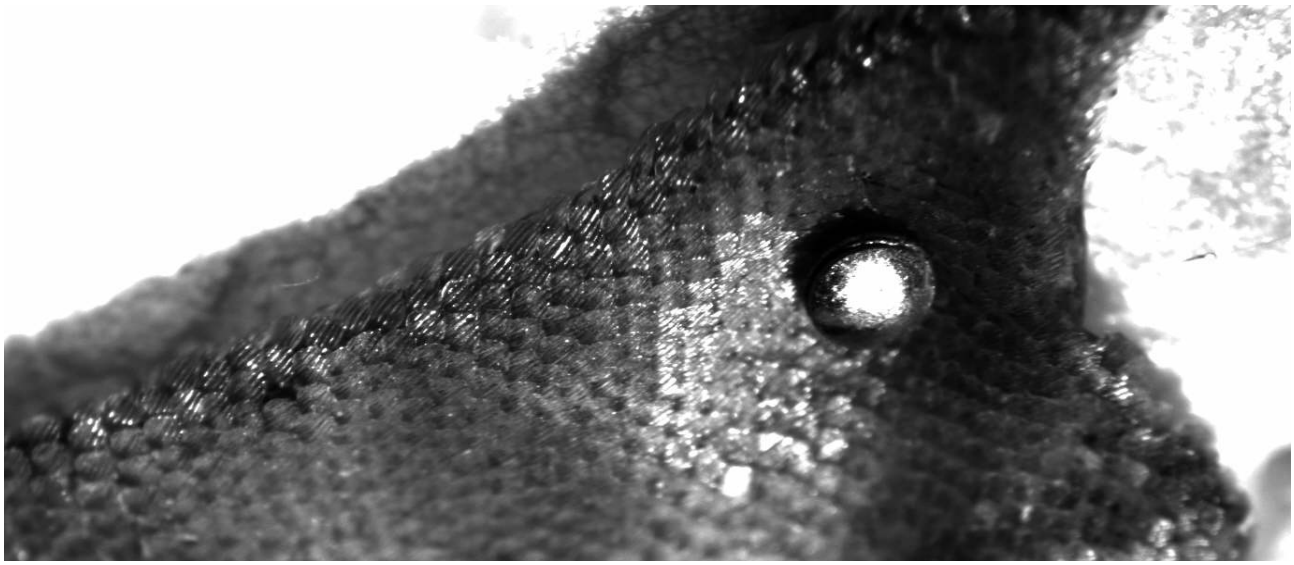
An important part of the preparation process of shark fins for their use in shark fin soup involves drying of the fin (see Chapter 1). Also, most Indonesian fishing vessels do not have equipment such as freezers to store their catch, and dry shark fin on the deck as a preservation method. As such, it was essential to understand how drying would affect the proposed measurements to be used for identifying shark species. Some measurements were affected by drying more than others. For example, when comparing the wet and dry values, the measurement, P, showed no significant correlation between these values. As P is a tertiary measurement, this reandom change in values between wet and dry measurements is likely due to the change in the ability to locate this point because of the change in the location of the secondary landmarks. It was therefore concluded that primary measurements were more robust than secondary and tertiary measurements, respectively. Pectoral fins were arbitrarily chosen to investigate the effect of drying on fin shape; however, it is expected that dorsal fins (used to develop the morphological ID protocols in Chapter 4) will behave similarly. As fins in the FFV catch are confiscated in varied stages of drying (Table 2.7), it is difficult to predict the exact degree of change in measurements based on the exact stage of drying. Our drying methods may not have represented the actual level of desiccation of fins found in FFV collections, as the IUU catch had a very high percentage (91.35%) of wet fin. Of the five categories listed, ‘wet’ to ‘dry’, our laboratory-dried fins would most closely correspond to those in the ‘Dry’ desiccation category, which represented only 0.9% from actual foreign fishing vessels. Because of this high prevalence of ‘wet’ fin, combined with the limited degree of drying observed within the FFV catch, identification protocols were therefore developed using ‘wet’ fins (Chapter 4).

The effect of foreign fishing on the composition of shark and ray fauna in northern Australia cannot be quantified without also examining baseline data from which to gauge the level of change. A fast, easy, and cost-effective method of collecting a vast amount of baseline data on species composition is urgently needed. Digital photography fulfils these criteria as a method of collecting such data. This study has ratified some of the main practical considerations that may hinder the use

of digital images as a tool to identify shark species from their isolated dorsal fins, demonstrating that the methods used in this thesis have been developed with no major biases.

3

Shark Fin Dermal Denticles: species discrimination and hydrodynamics



3.1 Introduction

In the last ten years, the demand for shark fin products has fuelled high levels of exploitation resulting in significant declines in many shark stocks. These declines have occurred in both regulated and unregulated commercial fisheries and target and non-target shark fisheries (Barker & Schluessel 2005, Dulvy, *et al.* 2008, Lack & Sant 2009). Within these fisheries a major hindrance to the management of shark stocks is the paucity of species-specific catch data, as most sharks are difficult to identify to species level (Lack & Sant 2009). This problem is confounded when sharks

are landed or traded as fins only, which is the case in many shark fisheries. Illegal Unreported and Unregulated (IUU) shark fishing in northern Australian waters is a typical example of how large amounts of unregulated and unquantified shark-finning has resulted in fisheries managers being unable to make accurate risk assessments for otherwise closely-managed commercial shark fisheries (Salini, *et al.* 2007b). Furthermore, deficiencies in data collection in countries that target sharks and an ongoing failure to meet international responsibilities to provide accurate and comprehensive catch and trade data to the Food and Agriculture Organization (FAO) or to Regional Fisheries Management Organisations (RFMOs), is a significant challenge to global shark management (Lack & Sant 2009). As such, more accurate and affordable means of identifying sharks are needed to facilitate an improvement in data quality.

Dermal denticles, or placoid scales, have been used as a tool for species identification of whole sharks in many shark taxonomic studies and species guides (Compagno 1977, Compagno & Stevens 1993a, Compagno & Stevens 1993b, Last, *et al.* 2007, Yano, *et al.* 2004). Denticles are minute tooth-like structures which cover the body and fins of sharks, protecting the epidermis (Kemp 1999). Rays and chimaerids, however, have fewer scales than sharks and gain their protection from a slimy mucous which covers the scale's cuticle (Kemp 1999). Published studies on shark denticles mainly illustrate their use in systematics or describe their morphology and protective and hydrodynamic functions. However, very few studies address the use of denticles for species identification of shark fins, particularly in relation to the shark fin trade (Matsunaga, *et al.* 1998, SEAFDEC 2006, Tanaka, *et al.* 2002, Wagner 1996). These studies are based on qualitative descriptions of fin denticles from either an unspecified fin location using a compound microscope (SEAFDEC 2006), or the centre or base of the fin using a scanning electron microscope (Tanaka, *et al.* 2002, Wagner 2001). Such methodologies can be misleading as denticle morphology can vary considerably with location on the fin – perhaps related to the hydrodynamic requirements of swimming (Raschi & Tabit 1992). A more methodical and comparative approach is needed in order to reliably assimilate inter-species variability in denticle shape over the fin surface (Chernyshev &

Zayets 1971, Zayets 1973). Therefore, although denticles are a proven character for discriminating species, in order to facilitate their use as a species identification tool for shark fins in the northern Australian IUU catch a more quantitative, region-specific and user-friendly approach is needed.

3.1.1 Denticles and Taxonomy

Lateral trunk denticles have long been used in shark systematics (Compagno 1977, Compagno & Stevens 1993a, Compagno & Stevens 1993b, Last, *et al.* 2007, Yano, *et al.* 2004). Patches of skin from the lateral trunk below the first dorsal fin are usually removed, dried and fixed to a glass slide. The dried denticles are examined with a dissecting microscope and representative samples photographed under a scanning electron microscope (Compagno 1988). As denticle shape varies greatly on different parts of the body, for systematic purposes, denticles on the lateral trunk are typically used to differentiate between species (Bigelow & Schroeder 1948, Compagno 1988, Radcliffe 1916). While interspecific variation in denticle shape usually exists, Applegate (1967) noted that denticles on some regions of the body, such as the snout edges and the leading edges of the fins, are very similar in a wide range of species. These similarities in denticle shape or design are most likely due to hydrodynamic requirements.

Studies by Radcliffe (1916), Ford (1921), Garrick (1960), Applegate (1967) and Reif (1973, 1974, 1985b) have demonstrated ontogenetic changes in denticle shape, through the replacement of denticles, as individual sharks increase in size. Reif (1974) also found that during growth, denticles often become increasingly differentiated between regions of the body. Ontogenetic changes in the shape of carcharhinid denticles primarily occur through increases in the width of the crown (relative to its length), size of the crown, and in the size and number of lateral elements of the crown (ridges and cusps, when present), and through a decrease in the size of medial elements relative to the lateral elements (Raschi & Tabit 1992). Raschi & Tabit (1992) found no observable ontogenetic relationship between ridge height and spacing, with the exception of the Zebra Shark, *Stegostoma fasciatum*.

3.1.2 Crown Variation and Denticle Terminology

The denticles and teeth of sharks are very similar in form; having a pulp cavity, dentine structure and enameloid crown (Applegate 1967, Kemp 1999). Each denticle has three structural features: a single basal plate (attaching the denticle to the dermis), a pedicel (the connection between the basal plate and crown), and a crown (the exposed 'top' of the denticle) (Applegate 1967, Bargar & Thorson 1995, Compagno 1988, Kemp 1999, Raschi & Elsom 1986, Reif 1979). This study concentrates on the morphological features of the crown, the viewable surface of a denticle.

Denticle crowns exhibit a wide variety of structural shapes and variations (Wagner 2001). The most noticeable surface features are longitudinal ridges, trailing edge cusps, and microrelief (Bargar & Thorson 1995, Kemp 1999, Wagner 2001). These three features – which are used to describe the crown morphology of the denticles investigated in this chapter – are described below.

Ridges

The majority of denticles have a primary ridge that stretches in the anterior-posterior direction, from the anterior edge of the pedicel to the trailing edge of the crown surface (Bargar & Thorson 1995, Raschi & Tabit 1992, Wagner 2001). Commonly, there is further ridging of the crown surface that usually occurs in pairs on either side of the primary ridge, and are named as they progress outwards (*e.g.* secondary ridges, tertiary ridges, quaternary ridges, *etc.* see Figure 3.1a) (Wagner 2001). Variations in ridge structure can be considerable, both between species and between regions on the body of an individual. Differences in ridge structure can include the size and shape of the ridge crests (Figure 3.2a), the depth of valleys between ridges, and the length that the ridge extends along the cusp (Figure 3.1c). The shape of the ridge crests can vary – from fine crests with sharp edges, to wide crests with rounded tops, to broad, flattened plateaus (Wagner 2001). Occasionally, the primary ridge can be split into two paired crests (Figure 3.2a) that rejoin at some point towards the posterior margin – a feature that is appropriately termed 'bi-crested' (Wagner 2001). Bi-cresting of the primary ridge is thought to be a hydrodynamic adaptation that produces mixing vortices in areas

of adverse pressure gradients, reducing drag by increasing turbulence close to the boundary layer (Raschi & Tabit 1992, Wagner 2001).

Cusps

Cusps are not always as conspicuous as ridges (Figure 3.1a). They are usually formed when a ridge extends beyond the posterior margin of the crown (Bargar & Thorson 1995, Raschi & Tabit 1992, Wagner 2001). When present, the shape and size of the cusps can exhibit considerable variation within and between species. Cusps primarily vary in length and tip shape, which can be rounded to sharply pointed (Figure 3.2b). The shape of the cusp edges can also vary from straight to recurved (Figure 3.2b). Some cusps are reduced or 'vestigial' and form shoulders along the posterior margin of the cuspp. 'Micro-cusps' (Figure 3.2b) are present when cusps are not associated with the trailing edge tips of ridges (Wagner 2001).

Microrelief

Microrelief is dimpling or 'honeycombing' of the crown surface. It is thought to be a hydrodynamic and structural adaptation whereby the dimpled surface adds strength to the crown, allowing the crown to become thinner and lighter which reduces the overall weight of the integument (Raschi & Elsom 1986, Raschi & Tabit 1992). Microrelief occurs in two forms, honeycomb-type and scale-type (Raschi & Tabit 1992); honeycomb-type appears as a tessellated hexagonal pattern on the crown surface and is commonly associated with the anterior region of the crown, whereas scale-type microrelief takes the form of overlapping scale-like structures and is commonly associated with the sides of ridge crests. Occasionally, both types can be found on the same denticle crowns.

These three morphological features (ridges, cusps, and microrelief) will be used to describe the difference in shape between the denticle crowns of each species.

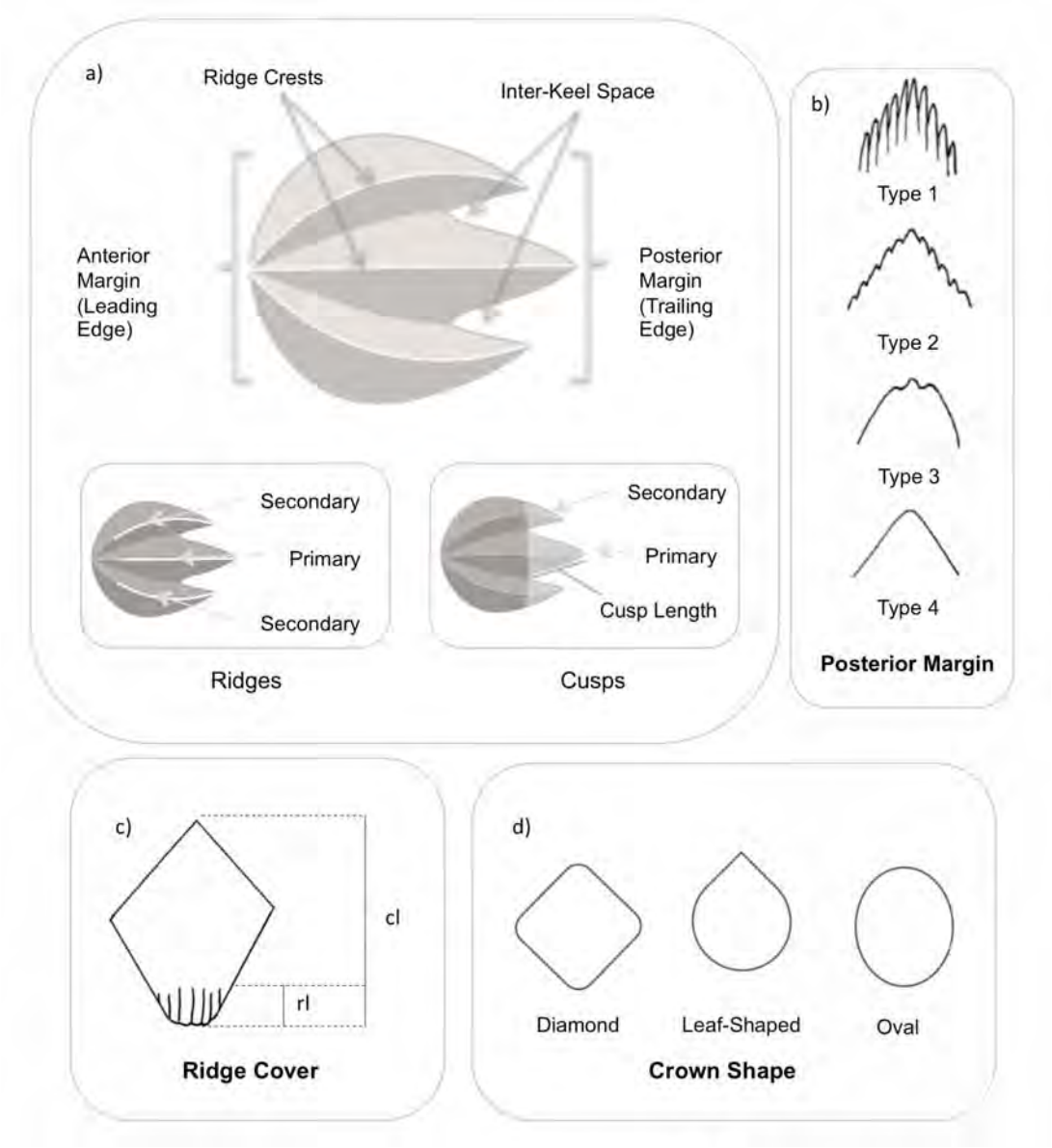


Figure 3.1 Schematic diagrams representing a) denticle crown ridges, cusps, inter ridge spaces, ridge crests and the position of primary and secondary ridge pairs; b) the four crown posterior margin types used to describe the crown posterior margins; c) percent ridge cover is described as the ridge length (rl) as a percentage of the crown length (cl), and; d) the three crown shapes used to describe the overall shape of the denticle crowns.

3.1.3 Denticle Function

The underlying premise of this study is that the denticle crowns of shark species will exhibit a difference in shape. Furthermore, within each species, denticle crown shape is expected to vary with respect to its position on the fin surface. This is because the shape of the denticle will influence its function. Therefore, to understand why these variations may occur, conclusions must be drawn with respect to denticle shape and denticle function.

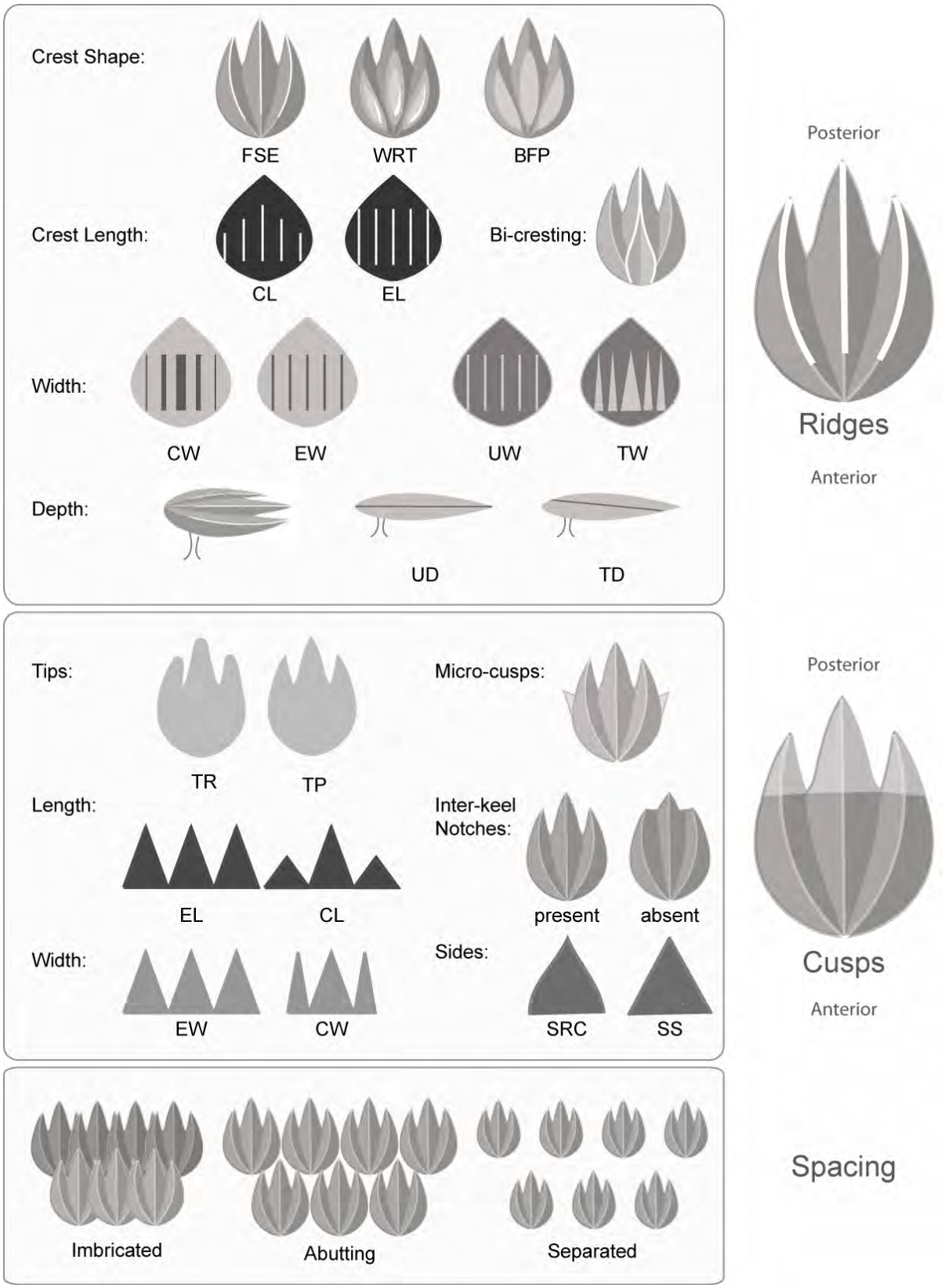


Figure 3.2 Schematic diagrams representing the summary of denticle characteristics and abbreviations used to describe the crown morphology of the denticles from each specimen. Abbreviations are explained as follows, a) **Ridges.** Crest Shape: fine, sharp-edged (FSE), wide, rounded tops (WRT), broad, flattened plateaus (BFP); Crest Length: cascading length (CL), even length (EL); Width: cascading width (CW), even width (EW), uniform width (UW) tapering width (TW); Depth: uniform depth (UD), tapering depth (TD); Bi-cresting Present: (BC). b) **Cusps.** Tips: rounded (TR), pointed (TP); Sides: recurved (SRC), straight (SS); Micro-cusps Present: (MC); Length: even length (EL), cascading length (CL); Width: even width (EW), cascading width (CW); Inter-keel Notches Present: (IKN). c) **Spacing.** Imbricated, abutting or separated.

The function of dermal denticles – their hydrodynamic aspects in particular – have been described by Wainwright *et al.* (1978), Raschi & Elsom (1986), Raschi & Musick (1986), Raschi & Tabit (1992), Bargar & Thorson (1995), Koeltzsch *et al.* (2002) and Reif (1978, 1982, 1985a, b). Denticles have become modified along several functional lines such as to allow for protection from predators and ectoparastites, to reduce mechanical abrasion, to accommodate bioluminescent and sensory organs, for feeding, and to reduce frictional drag (Raschi & Tabit 1992). According to Raschi & Tabit (1992) each of the aforementioned functions selects for a unique morphology of the denticle and denticle crown, which ranges in a continuum – from primarily protection to primarily drag reduction. The range in denticle shape within and among species reflects this continuum (Raschi & Tabit 1992).

At the protection end of the spectrum, denticles tend to be heavier and have more surface area (Raschi & Tabit 1992). Thickened, knob-like crowns that are highly sculpted are greatly modified for abrasion resistance. This type of denticle morphology is found on benthic species such as horn sharks (Heterodontidae), which frequently rub against hard abrasive rocky substrates (Raschi & Tabit 1992). Other benthic shark species, such as nurse sharks (*i.e. Ginglymostoma*), wobbegongs (*i.e. Orectolobus*) and zebra sharks (*i.e. Stegostoma*), exhibit less modified abrasion type scales with smaller, smoother crowns and widely separated ridges (Tabit 1985). This hypothesis is supported by Raschi & Tabit (1992) when they noted that demersal species often exhibit widely spaced denticles. Applegate (1967) suggested that the thickened, smooth scales on the belly of the angel shark (*Squatina*) formed a hard, protective resting surface for this benthic species.

In contrast to more sluggish and/or benthic species, denticles from faster pelagic sharks are noticeably smaller and lighter (Raschi & Elsom 1986). The reduction in the weight of these scales is accomplished mainly through a decrease in crown thickness. Additional reductions are also achieved through microrelief, as previously mentioned (Raschi & Elsom 1986, Raschi & Tabit

1992). Bechert *et al.* (1985) hypothesised that a decrease in the overall thickness of the crown allows for drag reduction through a process called ‘streak cancellation’ whereby cross flow from beneath the crown (injected downstream) might compensate for pressure distortions within the boundary layer by equalizing subscale pressure differences.

Crown ridging is thought to be an adaptation to reduce overall drag in adverse pressure gradients by increasing denticle, and consequently skin, friction. This forces the boundary layer (the hydrodynamic layer closest to the skin) to become turbulent, resulting in more efficient mixing in that layer. Boundary layer thickness is subsequently reduced and delays or prevents the separation of this layer (boundary layer separation results in increased drag) (Burdack 1973, Bushnell & Moore 1991, Raschi & Elsom 1986). Optimal values for ridge height and spacing were observed for both ‘normal-voluntary’ and ‘burst’ swimming speeds (Raschi & Elsom 1986). For ‘drag reduction’ type species, compared to more sluggish species, it was found that these values were conserved despite an ontogenetic increase in scale size (Raschi & Elsom 1986). Ridge involvement in overall drag reduction requires a continuous surface, which results in scales being densely packed and overlapping (imbricated) (Raschi & Tabit 1992). Increased swimming efficiency is gained as a product of this drag reduction, but not at the expense of increased integument weight due to greater denticle densities (Raschi & Elsom 1986).

3.1.4 Objectives

This study will use qualitative criteria to describe denticle crown variation at four specific locations on the dorsal and pectoral fins of 13 species of shark common to northern Australian waters. This study aims to assess the usefulness of these characters for discriminating between species and identifies which characters are most useful for this purpose. Additionally, this study will investigate how denticle crown morphology varies between species and between location on the fin with respect to functional requirement, such as protection or hydrodynamic function.

3.2 Methods

Skin samples from the dorsal and pectoral fins from a total of 56 individuals from 13 species of sharks were examined (Table 3.1). These skin samples were taken from specimens collected from the eastern Gulf of Carpentaria in northern Queensland, and from the Kimberly region of north Western Australia as part of the first phase of a corresponding preliminary project (Salini, *et al.* 2007a).

A preliminary study of the fin denticles of eight shark species from northern Australian waters, revealed an ontogenetic change in denticle crown patterns (Marshall, *et al.* 2007). The most relevant difference between small and large individuals was that, for smaller specimens, denticles were uneven in size across the skin surface and that after a certain total length threshold, denticle size became constant (Marshall, *et al.* 2007). Based on these preliminary findings, only larger, adult specimens were used in this study.

Previous studies have found that there is large variation in denticle pattern and shape across the fin (Chernyshev & Zayets 1971, Raschi & Tabit 1992, Zayets 1973). Preliminary investigations into denticle morphology of northern Australian sharks, suggested that four areas on the dorsal fin are most useful for discriminating species (Marshall, *et al.* 2007). These four areas (D, C, E, and H) are investigated in this study (Figure 3.3).

Skin patches (1 cm^2) were removed from four areas on a) the left side of the dorsal fin and, b) the dorsal side of the right pectoral fin (Figure 3.3), from each specimen, and mounted on a glass slide. The denticles were both investigated and photographed using a Leica DM LS compound microscope with camera attachment (Leica Microsystems, Wetzlar, GmBH). The denticles were then described using a qualitative set of criteria (Figure 3.1, Figure 3.2, and Table 3.2). Analysis was carried out by direct comparison of the resulting denticle descriptions. The term ‘cusping’ is used to describe the extent of formation of cusps on the posterior margin of the denticle crown. The term ‘ridging’ is used to describe the extent of ridge formation.

Table 3.1 Summary of all shark specimens for which the denticles of the left side of the dorsal fin and the dorsal side of the right pectoral fin, at areas C, D, E and H (see Figure 3.3), were examined. For all species investigated, total length range (cm) and total number (n) is given.

	Species	TL (cm) Min	TL (cm) Max	*n*
 CSIRO Marine and Atmospheric Research	*Carcharhinus amblyrhynchoides* (Graceful Shark)	114.5	144	5
	*Carcharhinus amblyrhynchos* (Grey Reef Shark)	110.5	167	5
	*Carcharhinus amboinensis* (Pigeye Shark)	136.2	186	5
	*Carcharhinus cautus* (Nervous Shark)	89	141.5	6
	*Carcharhinus falciformis* (Silky Shark)	242	242	1
	*Carcharhinus leucas* (Bull Shark)	183	285	5
	*Carcharhinus limbatus* (Common Black-tip Shark)	150.5	192	5
	*Carcharhinus plumbeus* (Sandbar Shark)	110	165	2
	*Carcharhinus sorrah* (Spot-tail Shark)	103.8	121	5
 CSIRO Marine and Atmospheric Research	*Carcharhinus tilstoni* (Australian Black-tip Shark)	124	164.5	5
	*Galeocerdo cuvier* (Tiger Shark)	204	380	5
	*Sphyrna lewini* (Scalloped Hammerhead)	71.6	178.5	5
 CSIRO Marine and Atmospheric Research	*Triaenodon obesus* (White-tip Reef Shark)	123	128	2

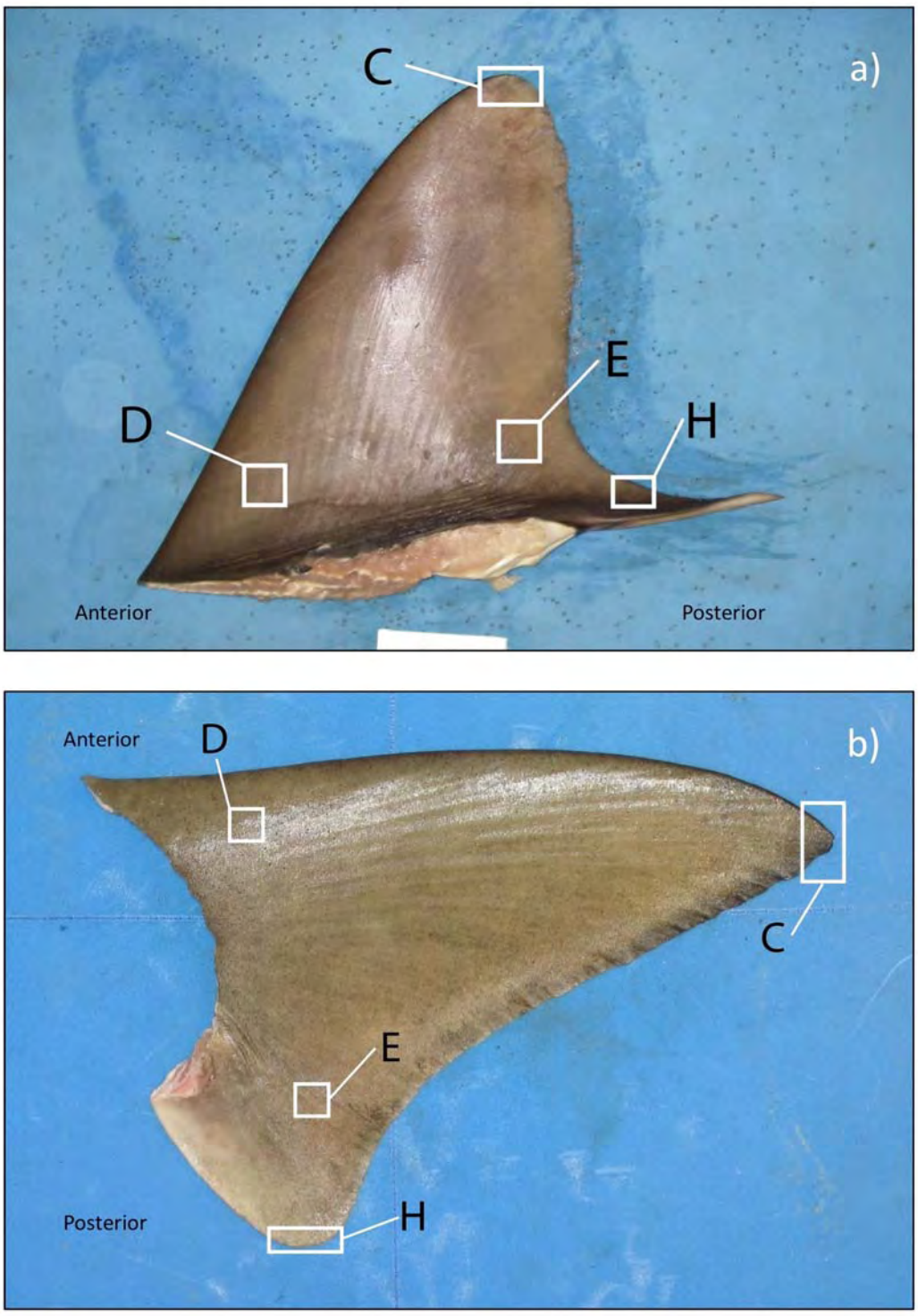


Figure 3.3 Photographs representing areas from where skin patches were taken for denticle examination from the a) left side of the dorsal fin and b) dorsal side of the pectoral fin. Each photograph shows anterior and posterior orientation of each fin. C = area C (fin tip), D = area D (anterior margin), E = area E (posterior margin) and H = area H (free rear tip).

Table 3.2 The characters used to describe each crown morphology feature on the denticles at areas C, D, E and F, on both dorsal and pectoral fins.

Feature	Category	Category Description
Ridges	Number	Highest number of ridge pairs observed. Primary (1˚), secondary (2˚), tertiary (3˚), *etc.* Figure 3.1a.
	Length	Percent cover of the crown (Figure 3.1 c). Length of ridges: Cascading length (CL), even length (EL). Figure 3.2a.
	Crests	**Crest Shape.** Fine, sharp-edged (FSE). Wide, rounded tops (WRT). Broad, flattened plateaus (BFP). **Width of crests**. Cascading width (CW) even width (EW). **Crest Spacing.** Uniform width (UW), tapering width (TW). Depth of crests. Uniform depth (UD), tapering depth (TD). Figure 3.2a and Figure 3.2a.
	Bi-cresting	Present or absent (BC). Figure 3.2a.
Cusps	Tips	Rounded (TR). Pointed (TP). Figure 3.2b.
	Sides	Recurved (SRC). Straight (SS). Figure 3.2b.
	Micro-cusps	Present or absent (MC). Figure 3.2b.
	Size	**Length and width.** Even length (EL), cascading length (CL), even width (EW), cascading width (CW). Figure 3.2b.
	Inter-keel notches	Present or absent (IKN). Depth. Figure 3.2b.
Microrelief	Presence	Present or absent. Coverage.
	Type	Honeycomb and/or scale-like.
Overall shape	Shape	Diamond. Leaf-shaped. Oval. Figure 3.2a.
	Width	Wide. Medium. Narrow.
Spacing	Type	Imbricated (overlapping). Abutting (tightly adjacent). Separated (gaps between denticles). Figure 3.2c.
	Level	High. Medium. Low.

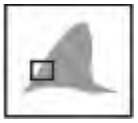
3.3 Results

3.3.1 Denticle Characteristics

The major crown features that distinguished species, or groups of species, are summarized below by skin patch area, for both dorsal and pectoral fins.

Dorsal Fins

Area C (Table 3.3) *Galeocerdo cuvier* (Figure 3.4k) was differentiated from all other species at area C – and all other areas on both the dorsal and pectoral fins – by the presence of a large, bi-crested, raised primary ridge, with deep grooves between the primary and secondary ridges. Additionally, it was the only species to have space between denticles in area C. *Carcharhinus plumbeus* (Figure 3.4h) could be differentiated from all other species by the presence of a bi-crested primary ridge that was larger than the other ridges and a sharply pointed, elongated primary cusp. The remaining species were split into three groups. The first had crowns that were smooth and leaf-shaped with no conspicuous ridges, *i.e. C. amblyrhynchoides* (Figure 3.4a), *C. limbatus* (Figure 3.4g), *C. sorrah* (Figure 3.4i), *C. tilstoni* (Figure 3.4j), and *Triaenodon obesus* (Figure 3.4m). The second group had crowns similar to group one, but had a conspicuous primary ridge that covered the length of the crown, *i.e. C. amboinensis* (Figure 3.4c) and *C. leucas* (Figure 3.4f). The third group had crowns with conspicuous, sharp parallel ridges that covered the length of the crown, *i.e. C. amblyrhynchos* (Figure 3.4b), *C. cautus* (Figure 3.4d), *C. falciformis* (Figure 3.4e), and *Sphyrna lewini* (Figure 3.4l). *Sphyrna lewini* was further separated from group three by visible, scale-like microrelief at high magnification (Figure 3.4l).



Area D (Table 3.4) *Galeocerdo cuvier* was differentiated from all other species by the same characters described for area C (Figure 3.5k), and by large spaces between denticles in area D. *Carcharhinus amboinensis* (Figure 3.5c) and *C. leucas* (Figure 3.5f) were differentiated from the remaining species by the presence of highly overlapping (imbricated) denticles with comparatively large primary ridges. Of the remaining species, all had tightly abutting

denticles with the exception of *S. lewini* (Figure 3.5l). Furthermore, when compared to the remaining species, *C. amblyrhynchos* (Figure 3.5b), *C. cautus* (Figure 3.5d), *C. falciformis* (Figure 3.5d), and *S. lewini* (Figure 3.5l) had easily discernible ridges. These ridges covered most of the crown surface, were thin, and uniform in thickness. All other species had denticles that appeared smooth throughout most of the crown.

Area E (Table 3.5) *Galeocerdo cuvier* was differentiated from all other species by the same characters described for area C (Figure 3.6k). *Carcharhinus amboinensis* (Figure 3.6c) and *C. leucas* (Figure 3.6f) were distinguished from the remaining species by the presence of highly imbricated denticles, low spacing (uneven spacing), and obvious, un-even cusps with inter-keel notches. *Carcharhinus leucas* was further differentiated by the presence of honeycomb microrelief over the entire crown surface at high magnification (Figure 3.6f). *Carcharhinus falciformis* (Figure 3.6e) and *S. lewini* (Figure 3.6l) were differentiated from all other species by visible scale like micro-relief on the crown surface at high magnification. The remaining species could not be differentiated.

Area H (Table 3.6) *Galeocerdo cuvier* was differentiated from all other species by the same characters described for area C (Figure 3.7k). *Triaenodon obesus* was distinguished by round, leaf-shaped crowns with no cusps (smooth posterior margin) and very small ridges (crown appears smooth) (Figure 3.7m). *Carcharhinus leucas* was distinguished by highly overlapping, un-tessellated denticles with obvious, uneven cusps and inter-keel ridges (Figure 3.7f). The remaining species were divided into two groups. The first had a conspicuous primary ridge that was significantly longer and larger than subsequent ridges, *i.e. C. amboinensis* (Figure 3.7c), *C. cautus* (Figure 3.7d), *C. plumbeus* (Figure 3.7h), and *S. lewini* (Figure 3.7l). *Carcharhinus plumbeus* (Figure 3.7h), and *C. cautus* (Figure 3.7d) were further differentiated from group one by a bi-crested primary ridge and scale-like microrelief at high magnification (however, *C. plumbeus*

had a much larger primary cusp and more obvious bi-cresting of the primary ridge). *Sphyrna lewini* was further distinguished from group one by presence of scale-like microrelief at high magnification, with an absence of bi-cresting of the primary cusp (Figure 3.7l). The second group had crowns with parallel, relatively even ridges in length and size, *i.e. C. amblyrhynchoides* (Figure 3.7a), *C. amblyrhynchos* (Figure 3.7b), *C. falciformis* (Figure 3.7e), *C. limbatus* (Figure 3.7g), *C. sorrah* (Figure 3.7i), and *C. tilstoni* (Figure 3.7j). *Carcharhinus falciformis* and *C. sorrah* were further distinguished from the second group by discernible scale-like microrelief at high magnification.

Table 3.3 Summary of denticle characteristics for each species for skin patch area C (fin tip) on the dorsal fin. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

C (fin tip)	Dorsal Fin						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	–	–	–	–	–	Oval. PM4.	Imbricated. Medium.
Carcharhinus amblyrhynchos	4°	80%	Crests: FSE, CL. Width: EW, TW. Depth: shallow TD.	–	–	Wide diamond. PM4.	Imbricated. Low.
Carcharhinus amboinensis	2°	80%	Crests: FSE, CL. Width: EW, TW. Depth: shallow, TD.	Tips: TP. Micro-cusps: MC, 1˚ and 2˚. Length: EL, CL. Width: EW, CW. Inter-keel notches: shallow.	–	Leaf-shaped. PM3.	Imbricated. Medium.
Carcharhinus cautus	–	–	–	–	–	Oval. PM4.	Imbricated. Medium-high.
Carcharhinus falciformis	4°	80–100%	Crests: FSE, CL. Width: thin, TW, UW. Depth: moderate, UD.	–	–	Wide Diamond. PM4.	Imbricated. High.
Carcharhinus leucas	2°	50–100%	Crests: FSE, CL. Width: thin, CW, TW. Depth: shallow, TD.	Tips: TP. Length: short, CL. Width: wide, CW. Inter-keel notches: shallow.	Honeycomb (entire crown).	Circular. PM2.	Imbricated. High.
Carcharhinus limbatus	–	–	–	–	–	Oval. PM4.	Imbricated. Med.
Carcharhinus plumbeus	2-3°	100%	Crests: FSE. CL. Width: wide, CW, TW. Depth: Moderate. TD. BC 1˚.	Tips: TP. Length: CL. Width: CW. Inter-keel notches: deep.	Scale-type (entire crown).	Wide diamond. PM2.	Imbricated. High.
Carcharhinus sorrah	–	–	–	–	–	Oval. PM4.	Imbricated. High.
Carcharhinus tilstoni	–	–	–	–	–	Oval. PM4.	Imbricated. Medium.
Galeocerdo cuvier	2°	100%	Crests: WR, CL. Width: wide, CW. TW. Depth: very deep. BC.	–	–	Oval. Tip pointed.	Separated, Medium.
Sphyrna lewini	3°	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: deep, UD.	–	Scale-type.	Oval. PM4.	Imbricated. Medium-high.
Triaenodon obesus	–	–	–	–	–	Oval. PM4.	Imbricated. Low.

Table 3.4 Summary of denticle characteristics for each species for skin patch area D (anterior margin) on the dorsal fin. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.1.

D (anterior margin)	Dorsal Fin						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	3°	80%	Crests: FSE, CL. Width: thin, EW, TW. Depth: very shallow, TD.	–	–	Diamond. PM2.	Abutting.
Carcharhinus amboinensis	3°	20%	Crests: FSE, CL. Width: thin, EW, TW. Depth: moderate, TD.	–	Scale-type.	Diamond. PM2.	Abutting.
Carcharhinus cautus	3-4°	20-50%	Crests: FSE, CL. Width: EW, TW. Depth: moderate, TD.	Tips: TR. Length: Very short, EL. Width: EW. Inter-keel notches: very shallow.	–	Diamond. PM2.	Tightly abutting.
Carcharhinus falciformis	4°	80–100%	Crests: FSE, CL. Width: EW, TW. Depth: moderate, TD.	–	–	Tip bluntly pointed.	Abutting.
Carcharhinus limbatus	3-4°	50–100%	–	Tips: TR. Length: very short, EL. Width: EW. Inter-keel notches: very shallow.	–	Tip bluntly pointed.	Abutting.
Carcharhinus leucas	3°	100%	Crests: FSE, CL. Width: EW, TW. Depth: deep, TD.	Tips: TP. Length: short, CL. Width: CW. Inter-keel notches: shallow.	–	Oval. PM3	Imbricated. High.
Carcharhinus plumbeus	3°	80–100%	Crests: FSE, CL. Width: EW, TW. Depth: shallow, TD. BC.	–	–	Oval - Diamond. PM4.	Abutting.
Carcharhinus sorrah	3-4°	10–50%	Crests: FSE, CL. Width: EW, UW. Depth: moderate, UD.	–	–	Oval. PM4.	Abutting.
Carcharhinus tilstoni	3-4°	50–100%	Crests: FSE, CL. Width: EW, UW. Depth: moderate, UD.	Tips: TR. Length: Very short, EL. Width: EW. Inter-keel notches: very shallow.	–	Diamond.PM4.	Separated - abutting.
Galeocerdo cuvier	2°	100%	Crests: WRT, CL. Width: CW, marked-TW. Depth: very deep, UD. BC, 1˚ and 2˚.	–	–	Oval. PM4.	Separated. Moderate.
Sphyrna lewini	3°	100%	Crests: FSE, slight-CL. Width: EW, UW. Depth: deep, UD.	Tips: TP. Length: Very short, EL. Width: EW. Inter-keel notches: very shallow.	Scale-type.	Oval. PM2.	Imbricated. Medium-high.
Triaenodon obesus	–	20%	–	–	–	Diamond. PM2-4.	Abutting.

Table 3.5 Summary of denticle characteristics for each species for skin patch area E (posterior margin) on the dorsal fin. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

E (posterior margin)	Dorsal Fin						
Species	Ridge No.	Ridge Cover	Ridges	Cusps	Microrelief	Overall Shape	Spacing
Carcharhinus amblyrhynchoides	3°	100%	Crests: FSE, CL. Width: EW, UW. Depth: moderate, UD.	Tips: TP. Sides: RC. Length: CL. Width: CW. Inter-keel notches: Very Shallow.	–	Leaf Shaped. PM3.	Imbricated. Medium-high.
Carcharhinus amblyrhynchos	4°	100%	Crests: FSE, EL. Width: EW, UW. Depth: deep, UD. Bi-cresting Present or absent (BC).	Tips: TP. Sides: SS. Length: short, EL. Width: EW.	–	Diamond. PM1.	Abutting.
Carcharhinus amboinensis	3°	100%	Crests: FSE, CL. Width: CW, UW. Depth: deep, UD.	Tips: TP. Sides: RC. MC. Length: CL. Width: CW. Inter-keel notches: shallow.	–	Oval. PM1.	Imbricated. High.
Carcharhinus cautus	3°	100%	Crests: FSE, CL. Width: EW, UW. Depth: deep, TD.	Tips: TP. Sides: SRC. Length: CL. Width: CW. Inter-keel notches: very shallow.	–	Oval. PM2.	Imbricated. Medium.
Carcharhinus falciformis	4°	80–100%	Crests: FSE, EL. Width: EW, UW.. Depth: moderate, TD.	–	Scale-type.	Diamond. PM2.	Abutting-Imbricated.
Carcharhinus leucas	3°	100%	Crests: FSE, EL. Width: CW, TW. Depth: deep, UD.	Tips: TP. Sides: SS. Length: CL. Width: CW. Inter-keel notches: shallow.	Honeycomb.	Oval. PM1.	Imbricated. Moderate.
Carcharhinus plumbeus	4°	100%	Crests: FSE, CL. Width: EW, UW. Depth: deep, UD.	–	–	Diamond. PM2-4.	Imbricated. Low.
Carcharhinus sorrah	3°	80–100%	Crests: FSE, CL. Width: EW, UW. Depth: moderate, UD.	–	Scale-type.	Diamond-Oval. PM2.	Imbricated. Medium.
Carcharhinus tilstoni	3°	100%	Crests: FSE, CL. Width: EW, UW. Depth: moderate, UD.	–	–	Leaf Shaped. PM3.	Imbricated. Medium-high.
Galeocerdo cuvier	2°	100%	Crests: FSE, CL. Width: EW, sharp TW. Depth: very deep, UD. 1˚ BC.	–	–	Oval. PM4.	Separated. Large.
Sphyrna lewini	3°	100%	Crests: FSE, UL. Width: EW, UW. Depth: moderate-deep, UD.	Tips: TP. Sides: SS. Length: moderate, EL. Width: EW. Inter-keel notches: shallow.	Scale-type.	Oval. PM1-2.	Imbricated. High.
Triaenodon obesus	3°	100%	Crests: FSE, CL. Width: EW, TW. Depth: Moderate, UD. BC 1˚.	–	–	Leaf-shaped. PM4.	Imbricated. Medium.

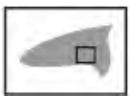
Table 3.6 Summary of denticle characteristics for each species for skin patch area H (free rear tip) on the dorsal fin. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

H (free rear tip)	Denticle Characters						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	3˚	100%	Crests: FSE, CL. Width: wide, EW, TW. Depth: medium, UD.	Tips: TP. Length: short, CL. Width: medium, CW. Inter-keel notches: very shallow.	–	Oval. PM3.	Imbricated. Medium-high.
Carcharhinus amblyrhynchos	4˚	100%	Crests: FSE, CL. Width: EW, UW. Depth: deep, UD.	Tips: TP. Length: short-medium, EL. Width: EW. Inter-keel notches: shallow.	–	Diamond. PM1.	Imbricated. Medium.
Carcharhinus amboinensis	4˚	100%	Crests: FSE, CL. Width: EW, UW. Depth: deep, UD.	Tips: TP. Length: long, CL. Width: wide, CW. Inter-keel notches: medium.	–	Oval. PM3.	Imbricated. High.
Carcharhinus cautus	3˚	100%	Crests: FSE, CL. Width: wide, EW, UW. Depth: deep, UD.	Tips: TP. Length: medium, CL. Width: wide, CW. Inter-keel notches: medium.	–	Oval. PM3.	Imbricated. High.
Carcharhinus falciformis	4˚	80–100%	Crests: FSE, EL. Width: thin, EW, UW. Depth: medium, UD.	–	Scale-type.	Oval. PM2.	Imbricated. Medium.
Carcharhinus leucas	2˚	100%	Crests: FSE, CL. Width: wide, CW, TW. Depth: deep, TD.	Tips: TR. Length: long, CL. Width: wide, CW. Inter-keel notches: shallow.	–	Oval. PM1.	Imbricated. Medium-high.
Carcharhinus limbatus	3˚	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: shallow, TD.	–	–	Leaf-Shaped. PM4.	Imbricated. Medium-high.
Carcharhinus plumbeus	3˚	100%	Crests: FSE, CL. Width: medium, CW, TW. Depth: deep, UD. BC.	Tips: TP. Length: long, CL. Width: wide, CW. Inter-keel notches: medium-deep.	Scale-type.	Leaf-Shaped. PM3.	Imbricated. High.
Carcharhinus sorrah	2˚	80–100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: moderate, TD.	–	Scale-type.	Diamond. PM2.	Imbricated. Medium.
Carcharhinus tilstoni	3˚	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: shallow, TD.	–	–	Leaf-Shaped. PM4.	Imbricated. Medium-high.
Galeocerdo cuvier	2°	100%	Crests: FSE, CL. Width: EW, sharp TW. Depth: very deep, UD. 1˚ BC.	–	–	Oval. PM4.	Separated. Large.
Sphyrna lewini	3˚	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: deep, TD.	Tips: TP. Length: medium, CL. Width: wide, CW. Inter-keel notches: deep.	Scale-type. Honeycomb.	Oval. PM3.	Imbricated. High.
Triaenodon obesus	3˚	30–50%	Crests: FSE, CL. Width: thin, CW, TW. Depth: shallow, TD.	–	–	Leaf-Shaped. PM4.	Imbricated. Low.

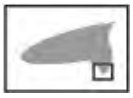
Pectoral Fins

Area C (Table 3.7) *Galeocerdo cuvier* was separated from all other species investigated by the presence of a large, bi-crested, raised primary ridge with deep grooves between the primary and secondary ridges (Figure 3.8k). It was also the only species to have space between denticles in area C. *Triaenodon obesus* was distinguished by a crowns that were rounded in shape and did not have ridges, cusps or inter-keel notches (Figure 3.8m). The remaining species were divided into two groups. The first had crowns with very large primary cusps, inter-keel notches and bi-crested primary ridges, *i.e. C. amblyrhynchoides* (Figure 3.8a), *C. amboinensis* (Figure 3.8c), *C. cautus* (Figure 3.8d), *C. plumbeus* (Figure 3.8h), *C. leucas* (Figure 3.8f), *C. limbatus* (Figure 3.8g), and *C. tilstoni* (Figure 3.8j). *Carcharhinus sorrah* had a large primary cusp, however there were no secondary cusps or inter-keel notches (Figure 3.8i). The second group possessed crowns that had similar sized ridges and cusps (where cusps were present), *i.e. C. amblyrhynchos* (Figure 3.8b), *C. falciformis* (Figure 3.8e) and *S. lewini* (Figure 3.8l).

Area D (Table 3.8) *Galeocerdo cuvier* was differentiated from all other species by the same characters described for area C (Figure 3.9k). *Carcharhinus leucas* was distinguished from all other species by the presence of larger spaces between crowns, low spacing, uneven cusps and inter-keel spaces (Figure 3.9f). *Carcharhinus amboinensis* (Figure 3.9c) and *S. lewini* (Figure 3.9l) were distinguished from other species by the presence of more imbricated denticles and inter-keel notches on the posterior margin. The remaining species were separated into two groups. The first group had crowns with conspicuous ridges that cover the entire crown, *i.e. C. amblyrhynchos* (Figure 3.9b), *C. falciformis* (Figure 3.9e), *C. plumbeus* (Figure 3.9h), and *C. sorrah* (Figure 3.9i) – although the ridges were less distinct for *C. sorrah*. The second group had crowns that appeared mostly smooth, *i.e. C. amblyrhynchoides* (Figure 3.9a), *C. cautus* (Figure 3.9d), *C. limbatus* (Figure 3.9g), *C. tilstoni* (Figure 3.9j), and *T. obesus* (Figure 3.9m).



Area E (Table 3.9) *Galeocerdo cuvier* was differentiated from all other species by the same characters described for area C (Figure 3.10k). *Carcharhinus plumbeus* was distinguished by the presence of a larger, and conspicuously bi-crested, primary ridge (Figure 3.10h). *Sphyrna lewini* was differentiated by conspicuous scale-like microrelief over the whole crown (Figure 3.10l). The remaining species were split into two groups. The first had crowns without conspicuous cusps on the posterior margin, *i.e. C. falciformis* (Figure 3.10e), *C. limbatus* (Figure 3.10g), *C. sorrah* (Figure 3.10i), *C. tilstoni* (Figure 3.10j), and *T. obesus* (Figure 3.10m). *Carcharhinus falciformis* was further separated from this group by the presence of overtly wide denticle crowns. The second group were typified by the presence of crowns that had conspicuous cusps on the posterior margin *i.e. C. amblyrhynchoides* (Figure 3.10a), *C. amblyrhynchos* (Figure 3.10b), *C. amboinensis* (Figure 3.10c), *C. cautus* (Figure 3.10d), and *C. leucas* (Figure 3.10f). *Carcharhinus amboinensis* and *C. leucas* could be further separated from this group (but not from each other) by the arrangement of the crowns that were un-evenly spaced and shaped.



Area H (Table 3.10) *Galeocerdo cuvier* was differentiated from all other species by the same characters described for area C (Figure 3.11k). The remaining species were split into two groups. Group one comprised those species that had a flat, wide primary ridge that covered 100% of the crown and a Type 3 posterior margin (Figure 3.1b), *i.e. Carcharhinus amblyrhynchoides* (Figure 3.11a), *C. amboinensis* (Figure 3.11c), and *C. leucas* (Figure 3.11f). The second group had oval shaped denticles with no ridges and a smooth posterior margin. From the second group, *T. obesus* was further distinguished by a bluntly pointed posterior margin (Figure 3.11m).

Table 3.7 A summary of the characteristics of the crown morphology of denticles from skin patch area C (fin tip) taken from the dorsal side of the right pectoral fin for each species. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

C (fin tip)	Pectoral Fin						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	3˚	100%	Crests: FSE, CL. Width: CW, TW. Depth: Deep, TD. BC.	Tips: TP. Sides: SRC. Length: long, CL. Width: CW. Inter-keel notches: IKN, moderate.	–	Leaf-shaped. PM1.	Imbricated. Medium-high.
Carcharhinus amblyrhynchos	4˚	100%	Crests: FSE, CL. Width: EW, UW. Depth: deep, UD.	Tips: TR. Sides: SS. Length: short, EL. Width: EW. Inter-keel notches: very shallow when present.	–	Diamond. PM2.	Abutting-imbricated.
Carcharhinus amboinensis	3˚	100%	Crests: FSE, CL. Width: CW, TW. Depth: deep. TD. BC.	Tips: TP. Sides: SRC. Micro-cusps: MC. Length: CL. Width: CW. Inter-keel notches: deep.	Scale-type.	Oval. PM1.	Imbricated. High.
Carcharhinus cautus	2-3˚	100%	Crests: FSE, CL. Width: Thin. CW, UW. Depth: shallow. TD. BC.	Tips: TP Sides: SRC. Length: long, CL. Width: CW. Inter-keel notches: deep.	Honeycomb.	Leaf-shaped. PM4.	Imbricated. High.
Carcharhinus falciformis	4˚	100%	Crests: FSE, CL. Width: EW, TW. Depth: moderate. TD.	–	–	Diamond. PM2-4.	Imbricated. High.
Carcharhinus leucas	2˚	100%	Crests: FSE, CL. Width: Thin, CW, TW. Depth: deep, TD. BC.	Tips: TP. Sides: SRC. Length: CL Width: CW. Inter-keel notches: deep.	–	Oval. PM3.	Imbricated. High.
Carcharhinus limbatus	3˚	100%	Crests: FSE, CL. Width: CW, TW. Depth: deep, TD. BC.	Tips: TP. Sides: SRC. Length: CL. Width: CW. Inter-keel notches: moderate.	–	Oval. PM3.	Imbricated. Med-high.
Carcharhinus plumbeus	2˚	100%	Crests: FSE, CL. Width: CW, TW. Depth: moderate. TD. BC.	Tips: TP. Length: CL. Width: CW. Inter-keel notches: deep.	Scale-type.	Leaf-shaped. PM3.	Imbricated. High.
Carcharhinus sorrah	–	–	–	–	–	Leaf-shaped. PM4.	Imbricated. High.
Carcharhinus tilstoni	3˚	100%	Crests: FSE, CL. Width: thin, CW, TW. Depth: deep, TD. BC.	Tips: TP. Length: long, CL. Width: CW. Inter-keel notches: deep.	–	Oval. PM3.	Imbricated. Med-high.
Galeocerdo cuvier	2˚	100%	Crests: WRT CL. Width: wide, CW, TW. Depth: very deep, UD. BC.	–	–	Oval. PM3.	Separated.
Sphyrna lewini	3˚	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: moderate, TD.	Tips: TP. Length: short, EL. Width: EW Inter-keel notches: very shallow.	Scale-type.	Diamond. PM2.	Imbricated. Med-high.
Triaenodon obesus	–	–	–	–	–	Oval. PM4.	Imbricated. Low.

Table 3.8 A summary of the characteristics of the crown morphology of denticles from skin patch area D (anterior margin) taken from the dorsal side of the right pectoral fin for each species. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

D (leading edge)	Pectoral Fin						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	3-4˚	50–100%	–	–	–	Diamond. PM2.	Abutting.
Carcharhinus amblyrhynchos	4˚	80–100%	Crests: FSE, CL. Width: thin, EW, TW. Depth: shallow, TD.	–	–	Diamond. PM4.	Abutting.
Carcharhinus amboinensis	3˚	100%	Crests: FSE, CL. Width: thin, EW, TW. Depth: moderate, TD.	Tips: TP. Length: CL. Width: CW. Inter-keel notches: moderate.	–	Oval. PM1.	Imbricated. Med.
Carcharhinus cautus	3-4˚	20–50%	Crests: FSE, CL. Width: thin, EW, TW. Depth: shallow, TD.	–	–	Oval. PM2.	Abutting.
Carcharhinus falciformis	4˚	80–100%	Crests: FSE, CL. Width: thin, EW, TW. Depth: shallow-moderate, TD.	–	–	Diamond. PM4.	Imbricated.
Carcharhinus leucas	3˚	80–100%	Crests: FSE, EL. Width: thin, EW, TW. Depth: moderate, TD.	Tips: TP. Length: long, EL, CL. Width: CW. Inter-keel notches: moderate.	Scale-type.	Diamond. PM3.	Separated. Moderate.
Carcharhinus limbatus	3-4˚	50–100%	–	–	–	Diamond. PM2.	Abutting.
Carcharhinus plumbeus	4˚	80–100%	Crests: FSE, CL. Width: thin, EW, TW. Depth: moderate, TD. BC.	–	–	Diamond-oval. PM4.	Spaced. Small.
Carcharhinus sorrah	3˚	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: moderate-shallow, TD.	–	–	Diamond-oval. PM4.	Imbricated. Low.
Carcharhinus tilstoni	3-4˚	50–100%	–	–	–	Diamond. PM2.	Abutting.
Galeocerdo cuvier	2˚		Crests: RT, CL. Width: wide, EW, TW. Depth: very deep, UD. BC (1-2°).	–	–	Oval. PM4.	Separated. Large.
Sphyrna lewini	3˚	1	Crests: FSE, EL. Width: thin, EW, UW. Depth: deep, TD.	–	Scale-type. Honeycomb.	Oval. PM2.	Imbricated. Medium.
Triaenodon obesus	3˚	20%	–	–	–	Oval. PM4.	Abutting.

Table 3.9 A summary of the characteristics of the crown morphology of denticles from skin patch area E (posterior margin) taken from the dorsal side of the right pectoral fin for each species. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

E (trailing edge)	Pectoral Fin						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	3˚	100%	Crests: FSE, CW. Width: moderate, EW, UW. Depth: moderate, UD.	Tips: TP. Sides: Length: long, CL. Width: wide, CW. Inter-keel notches: moderate-deep.	–	Oval. PM3.	Imbricated. High.
Carcharhinus amblyrhynchos	4˚	100%	Crests: FSE, CL. Width: thin, EW, UW. Depth: deep, UD.	Tips: TP. Length: short, EL, EW. Inter-keel notches: very shallow.	–	Diamond. PM2.	Imbricated. Medium.
Carcharhinus amboinensis	3˚	100%	Crests: FSE, CL. Width: wide, CW, UW. Depth: shallow-moderate, UD.	Tips: TP. Length: moderate, CL. Width: wide, CW. Inter-keel notches: medium.	–	Oval. PM3.	Imbricated. High.
Carcharhinus cautus	3˚	100%	Crests: FSE, CL. Width: medium, EW, UW. Depth: medium, TD. BC.	Tips: TP. Length: short-medium, CL, EW. Inter-keel notches: very shallow.	Honeycomb.	Diamond. PM3.	Imbricated. High.
Carcharhinus falciformis	4˚	100%	Crests: FSE, EL. Width: thin, EW, UW. Depth: medium, TD. BC.	–	Scale-type.	Diamond. PM3.	Imbricated, Low.
Carcharhinus leucas	3˚	100%	Crests: FSE, EL. Width: wide, CW, TW. Depth: medium, TD.	Tips: TP. Length: long, CL. Width: wide, CW. Inter-keel notches: deep.	–	Diamond. PM3.	Imbricated, Moderate.
Carcharhinus limbatus	4˚	100%	Crests: FST, CL. Width: medium, EW, UW. Depth: medium, UD.	–	–	Diamond. PM3.	Imbricated. Low.
Carcharhinus plumbeus	2-3˚	100%	Crests: FSE, CL. Width: medium, CW, TW. Depth: medium, TD. BC.	Tips: TP. Length: long, CL. Width: medium, CW. Inter-keel notches: shallow.	–	Leaf-shaped. PM3.	Imbricated. Medium.
Carcharhinus sorrah	3˚	80–100%	Crests: FSE, CL. Width: medium, EW, TW. Depth: medium, TD.	–	Scale-type.	Diamond. PM4.	Imbricated. Medium.
Carcharhinus tilstoni	4˚	100%	Crests: FST, CL. Width: medium, EW, UW. Depth: medium, UD.	–	–	Diamond. PM3.	Imbricated. Low.
Galeocerdo cuvier	3˚	100%	Crests: WFP to FSE. Width: wide, CW, TW. Depth: very deep, UD. BC.	Tips: TP. Length: short, EL. Width: EW. Inter-keel notches: shallow.	–	Oval. PM3.	Separated. Large.
Sphyrna lewini	3˚	100%	Crests: FSE, CL. Width: EW, TW. Depth: moderate, UD.	Tips: TP. Length: medium, CL. Width: medium, CW. Inter-keel notches: medium.	Scale-type. Honeycomb.	Diamond. PM1.	Imbricated. High.
Triaenodon obesus	3˚	100%	Crests: FSE, CL. Width: medium, EW, TW. Depth: shallow, TD. BC.	–	–	Leaf-shaped. PM4.	Imbricated. Medium.

Table 3.10 A summary of the characteristics of the crown morphology of denticles from skin patch area H (free rear tip) taken from the dorsal side of the right pectoral fin for each species. Abbreviations and terms are described in Figure 3.1 and Figure 3.2 and Table 3.2.

Area H (free rear tip)	Pectoral fins						
Species	**Ridge No.**	**Ridge Cover**	**Ridges**	**Cusps**	**Microrelief**	**Overall Shape**	**Spacing**
Carcharhinus amblyrhynchoides	2˚	100%	Crests: FSE, CL. Width: very wide, EW, UW. Depth: very shallow, TD.	Tips: TP. Length: short, CL. Width: CW. Inter-keel notches: shallow.	–	Oval. PM3.	Imbricated. Medium.
Carcharhinus amblyrhynchos	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Carcharhinus amboinensis	2˚	100%	Crests: FSE, CL. Width: very wide, EW, UW. Depth: very shallow, TD.	Tips: TP. Length: short, CL. Width: CW. Inter-keel notches: shallow.	–	Oval. PM3.	Imbricated. Medium.
Carcharhinus cautus		–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Carcharhinus falciformis	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Carcharhinus leucas	2˚	100%	Crests: FSE, CL. Width: very wide, EW, UW. Depth: very shallow, TD.	Tips: TP. Length: short, CL. Width: CW. Inter-keel notches: shallow.	–	Oval. PM3.	Imbricated. Medium.
Carcharhinus limbatus	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Carcharhinus plumbeus	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Carcharhinus sorrah	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Carcharhinus tilstoni	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.
Galeocerdo cuvier	2˚	100%	Crests: WFP to FSE. Width: wide, CW, TW. Depth: very deep, UD. BC.	–	–	Oval. PM3.	Separated. Large.
Sphyrna lewini	Denticles in this region are very thin, translucent and hard to distinguish, and are therefore not useful for distinguishing this species.						
Triaenodon obesus	–	–	–	–	–	Oval. PM4.	Imbricated. Med-high.

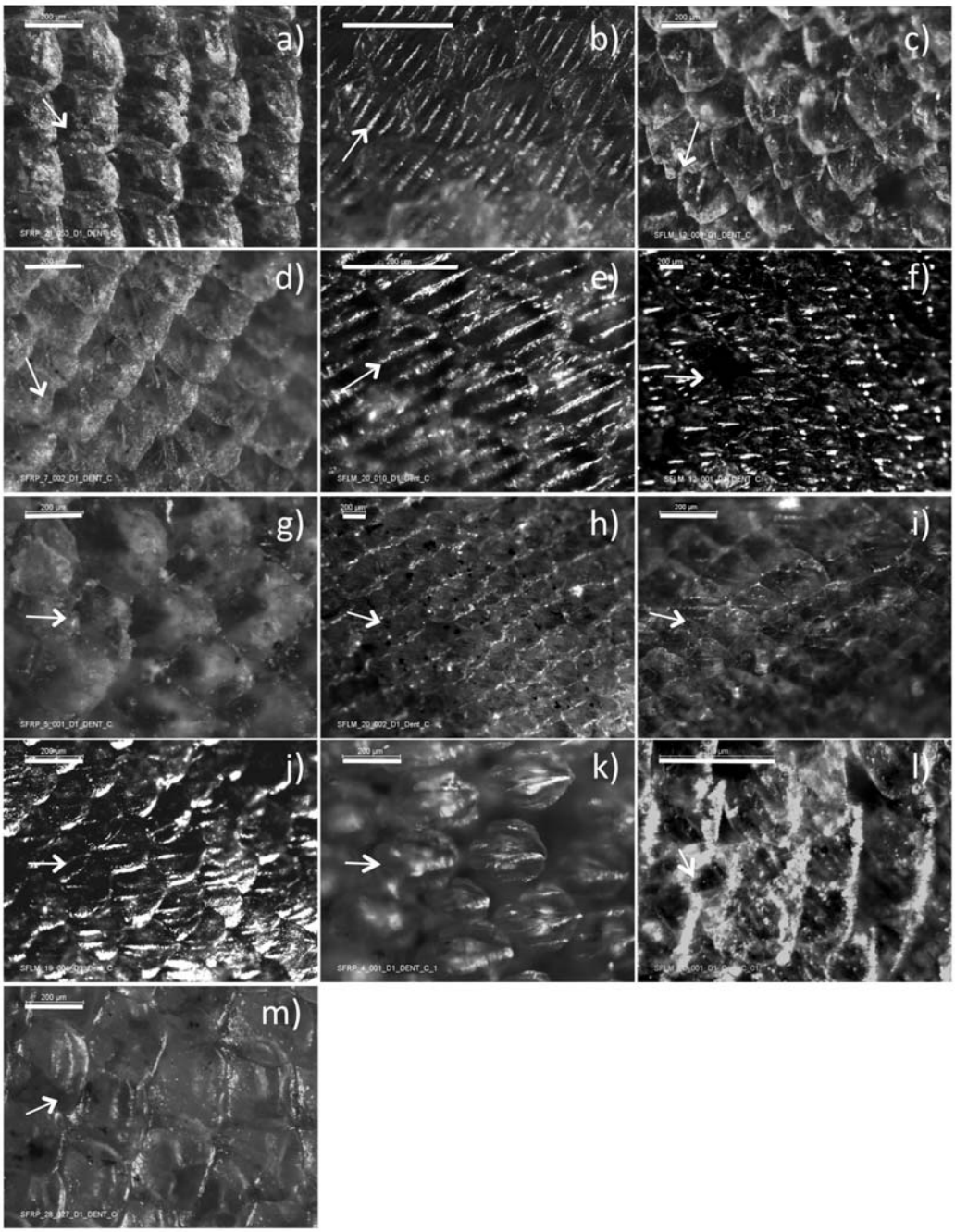


Figure 3.4 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area C on the dorsal fin. Scale bars represent 200 μm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL c) *Carcharhinus amboinensis*, female, 152 cm TL ; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

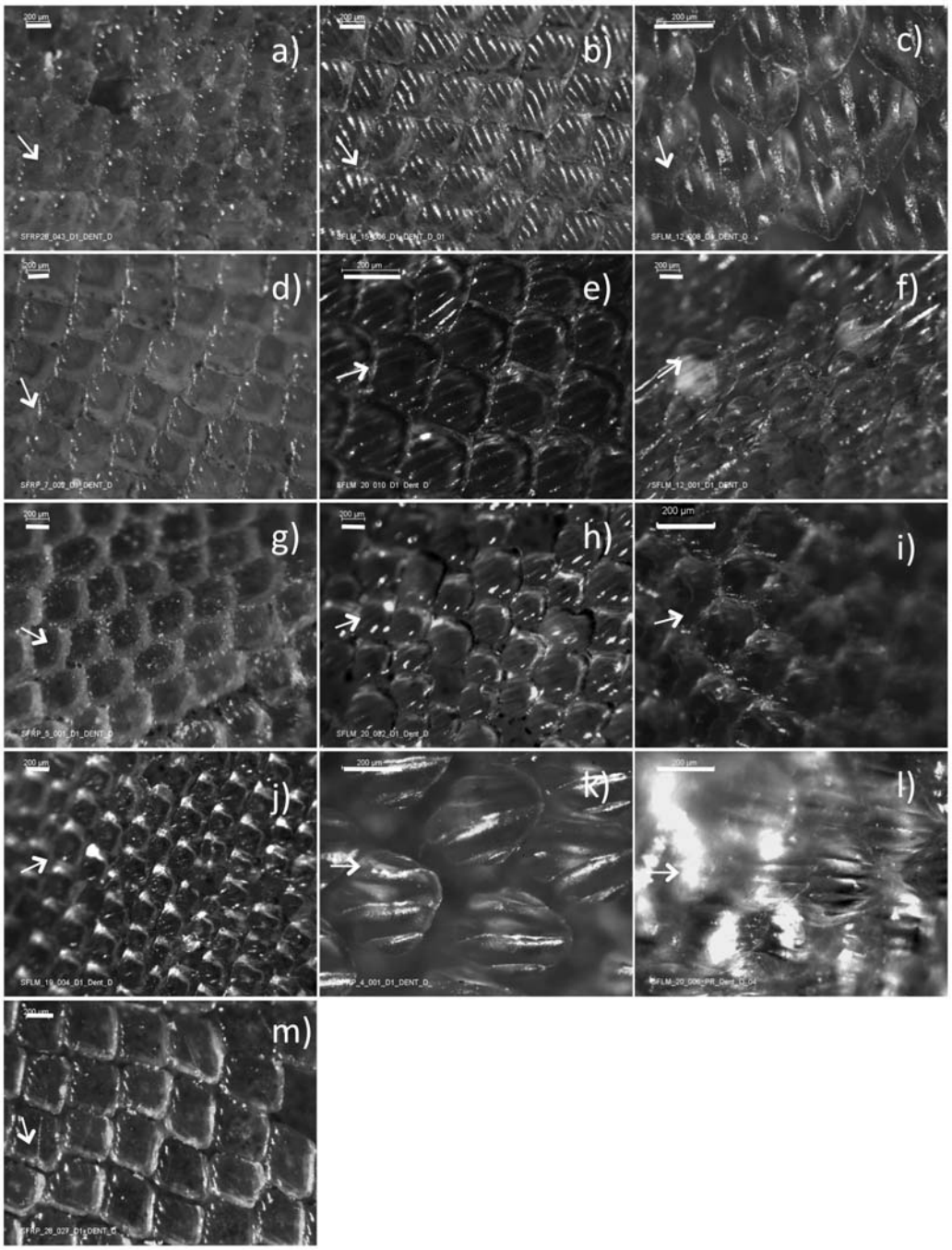


Figure 3.5 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area D on the dorsal fin. Scale bars represent 200 μm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

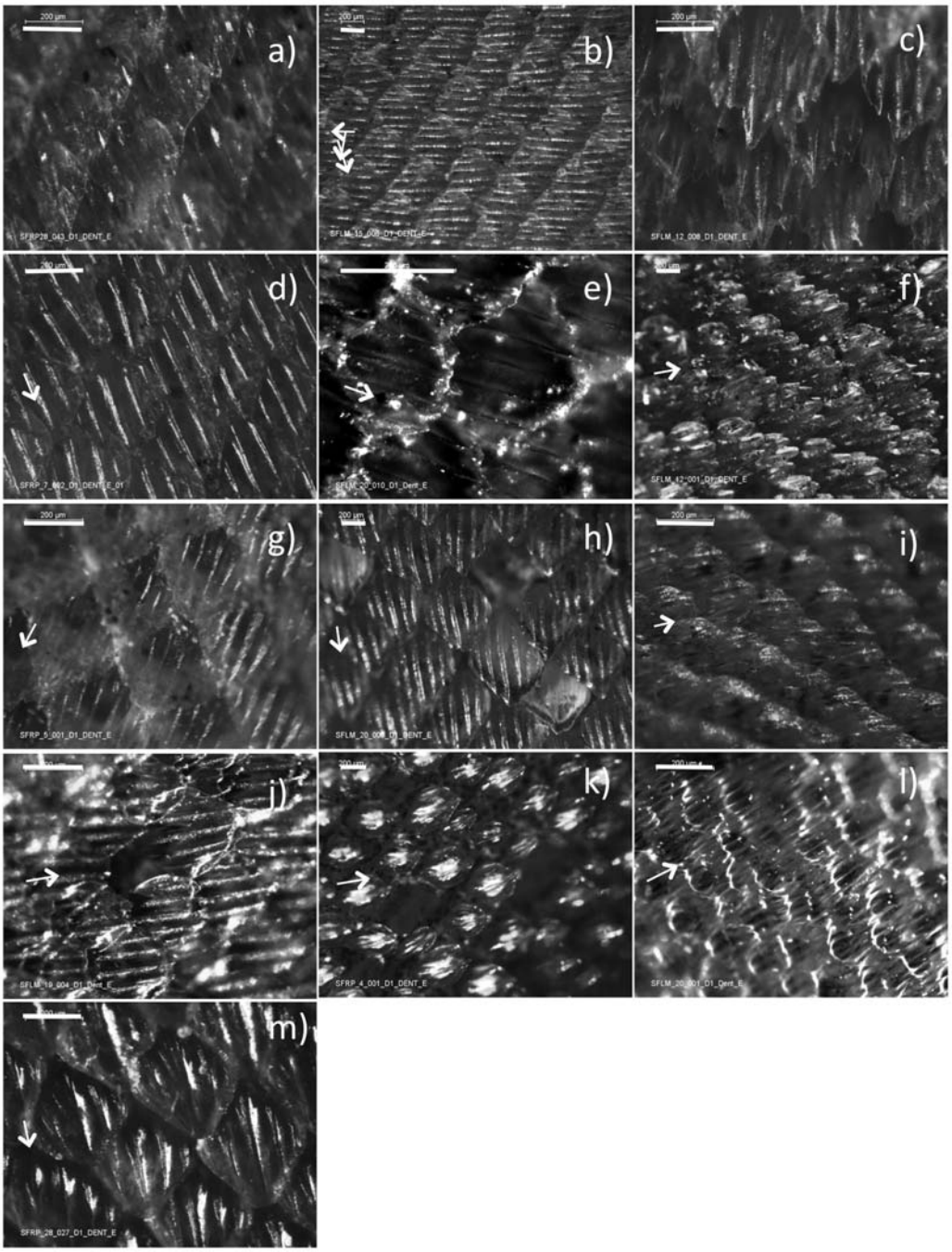


Figure 3.6 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area E on the dorsal fin. Scale bars represent 200 µm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

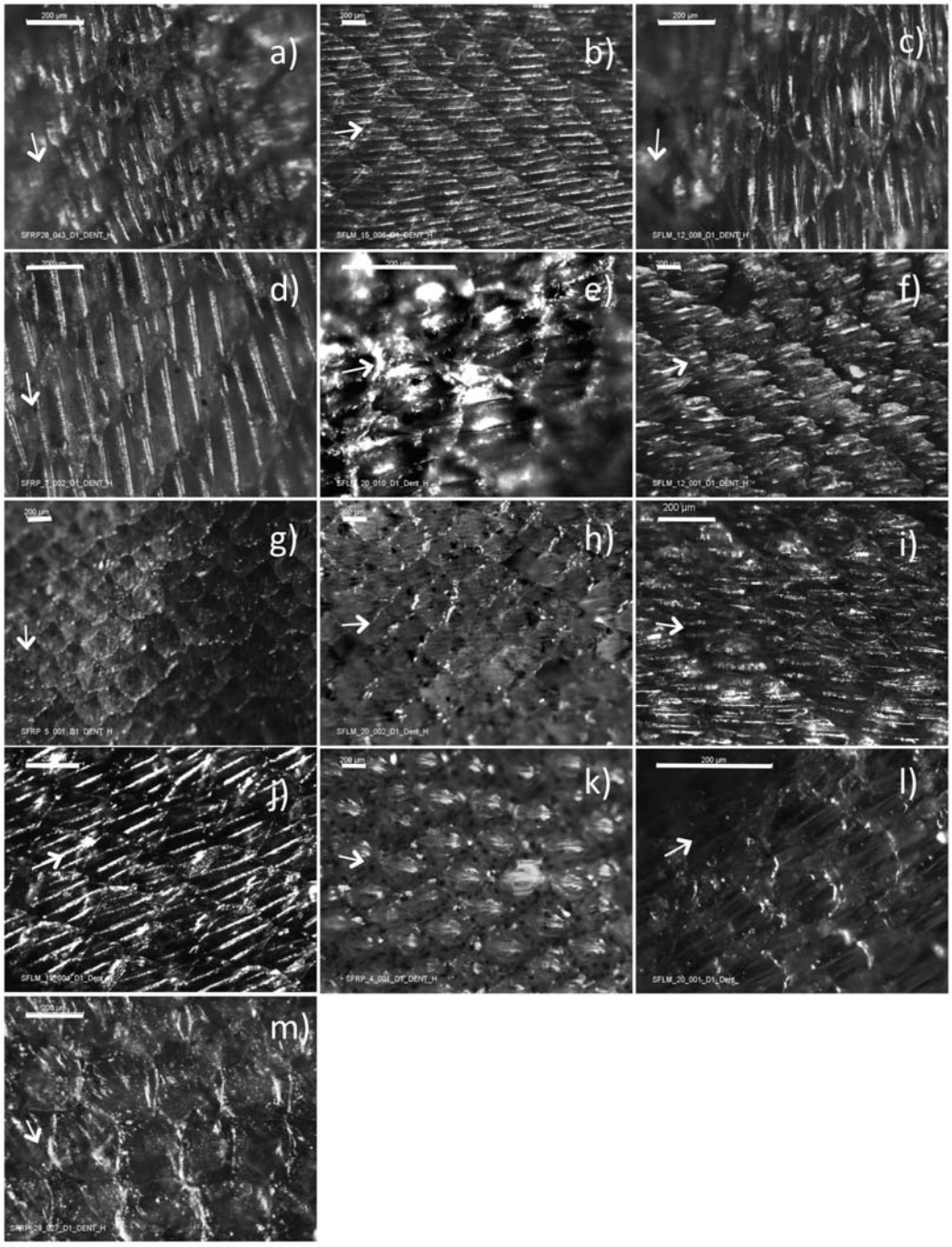


Figure 3.7 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area H on the dorsal fin. Scale bars represent 200 μm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

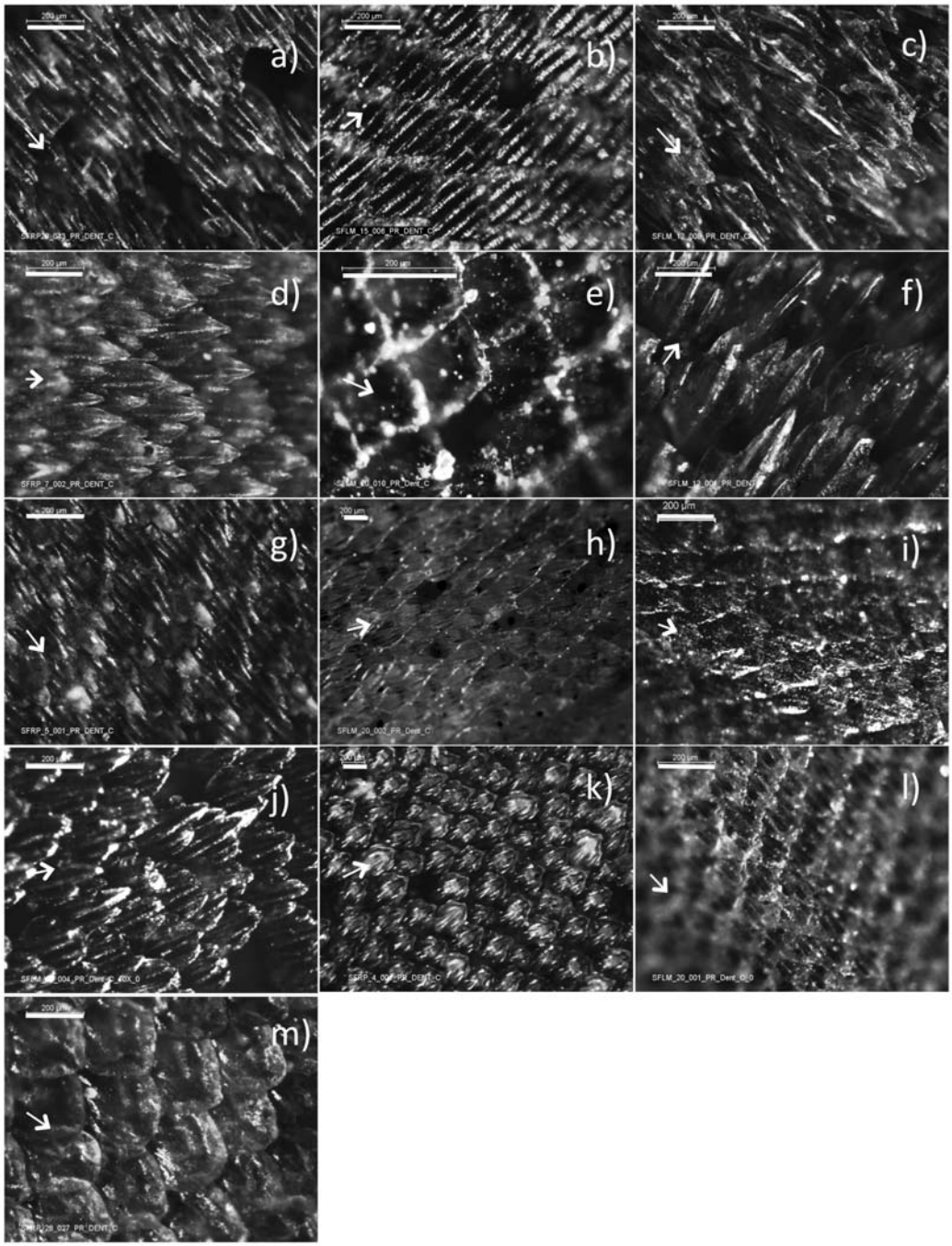


Figure 3.8 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area C on the dorsal side of the right pectoral fin. Scale bars represent 200 μm. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

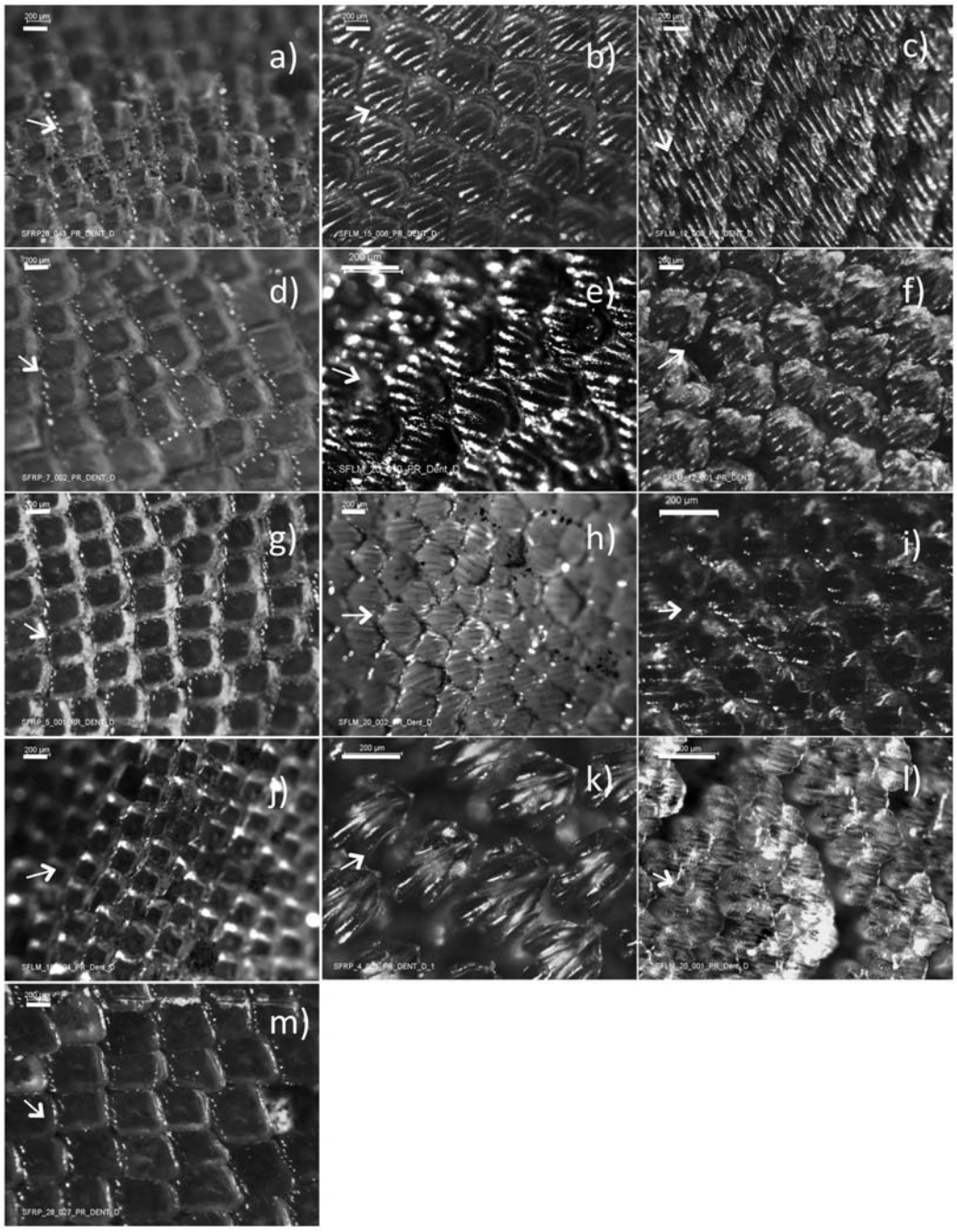


Figure 3.9 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area D on the dorsal side of the right pectoral fin. Scale bars represent 200 μm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL ; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

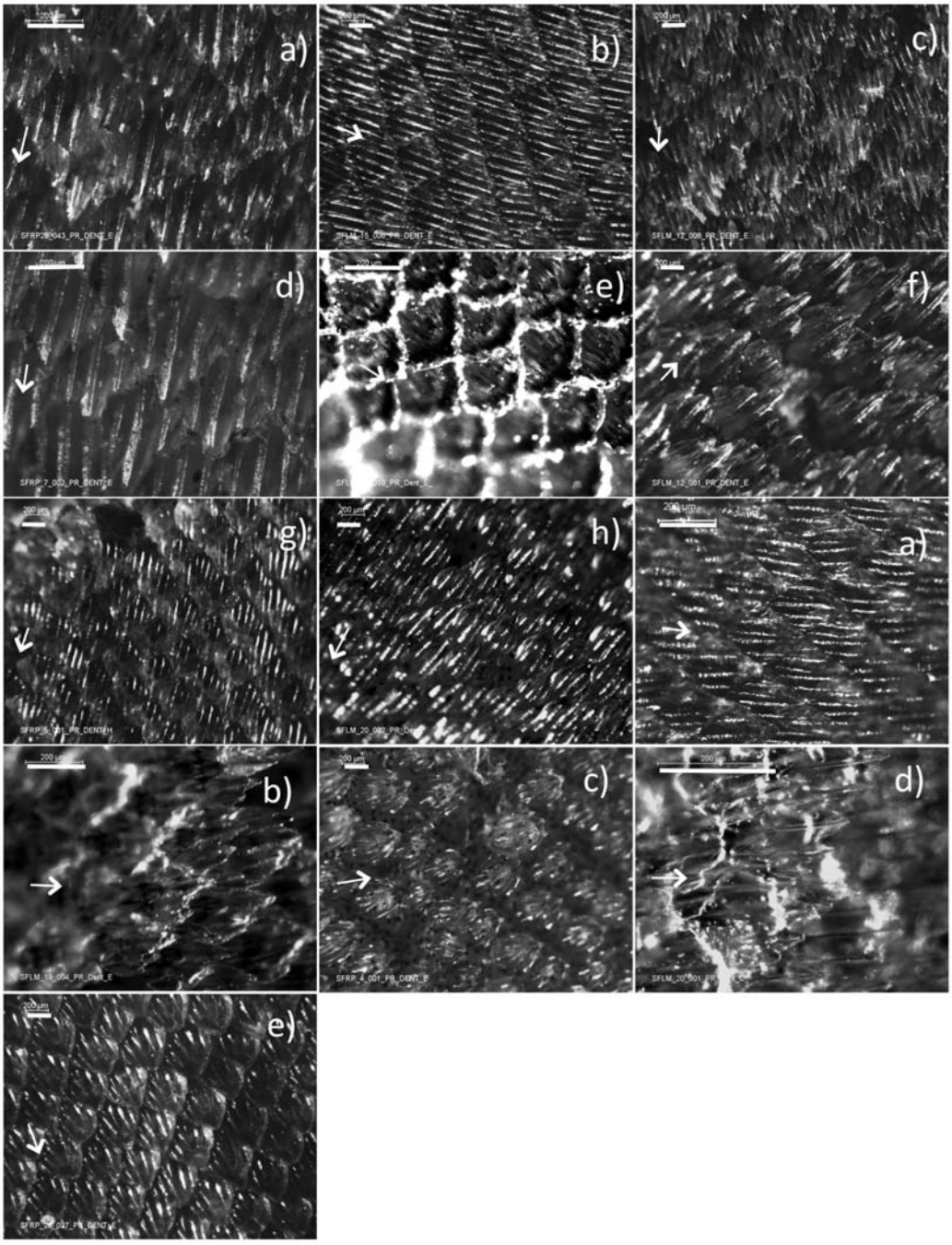


Figure 3.10 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area E on the dorsal side of the right pectoral fin. Scale bars represent 200 μm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

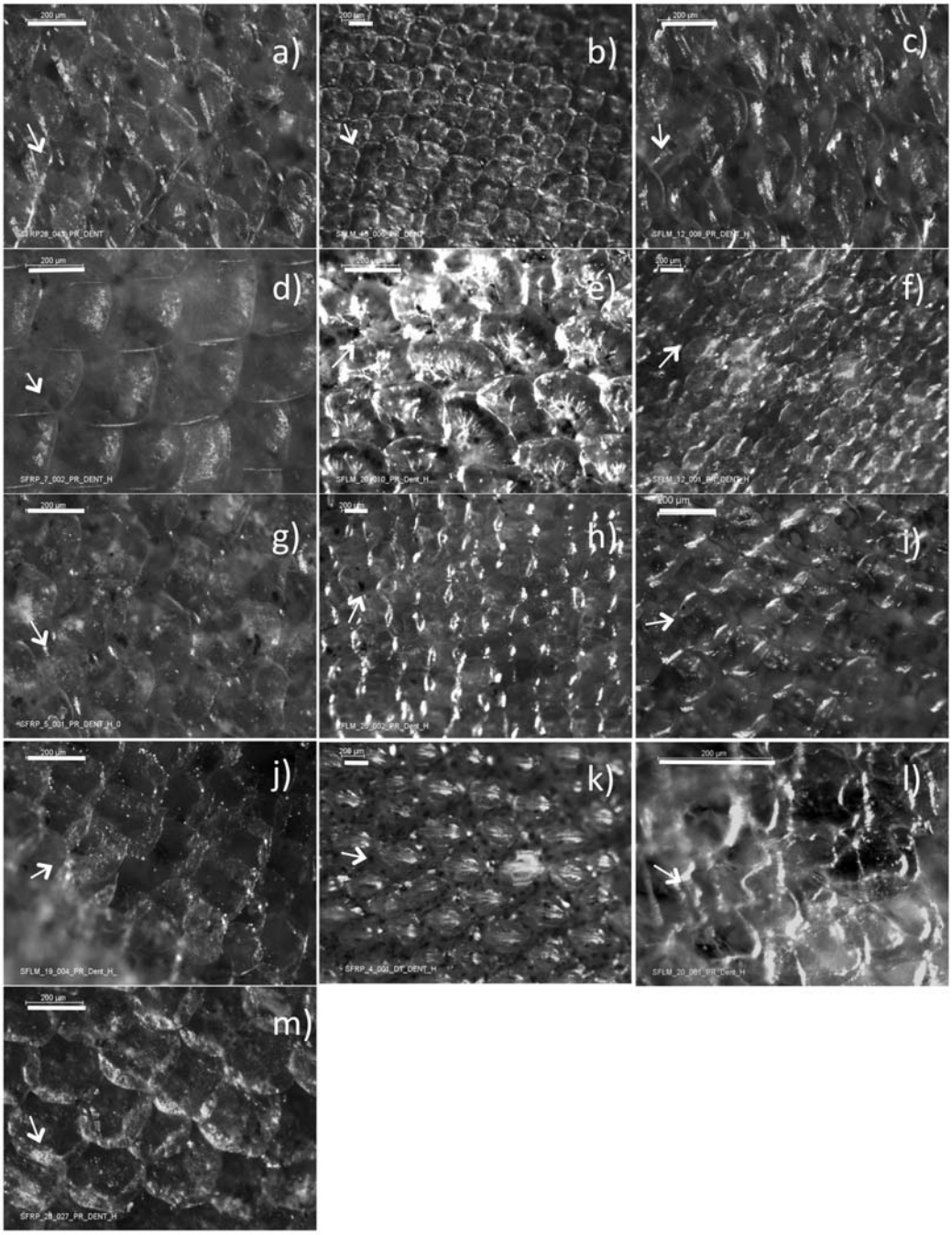


Figure 3.11 Photographs taken under light microscope (4-20x magnification) highlighting the different denticle morphologies of all species at area H on the dorsal side of the right pectoral fin. Scale bars represent 200 μm. Arrows indicate the direction of anterior to posterior. a) *Carcharhinus amblyrhynchoides*, female, 114 cm TL; b) *Carcharhinus amblyrhynchos*, female, 167 cm TL; c) *Carcharhinus amboinensis*, female, 152 cm TL; d) *Carcharhinus cautus*, female, 114 cm TL; e) *Carcharhinus falciformis*, male, 242 cm TL; f) *Carcharhinus leucas*, male, 197.8 cm TL; g) *Carcharhinus limbatus*, male, 192 cm TL; h) *Carcharhinus plumbeus*, female, 110 cm TL; i) *Carcharhinus sorrah*, male, 103.8 cm TL; j) *Carcharhinus tilstoni*, female, 124 cm TL; k) *Galeocerdo cuvier*, female, 240 cm TL; l) *Sphyrna lewini*, female, 173.5 cm TL; m) *Triaenodon obesus*, male, 123 cm TL.

3.3.2 Species Discrimination at Each Area Using Dermal Denticles

All but three (*Carcharhinus amblyrhynchoides, C. limbatus and C. tilstoni*) of the 13 species could be distinguished from all other species investigated by the denticles at one or more areas using dorsal fins (Table 3.11), and all but two (*C. limbatus* and *C. tilstoni*) using pectoral fins (Table 3.12). *Galeocerdo cuvier* could be distinguished from all other species investigated at all areas on both dorsal and pectoral fins.

Table 3.11 A summary of the areas on the dorsal fin which can be used to differentiate between the 13 shark species studied, using denticle characters. For each species pair, the area on the fin where denticle morphology differs between those species is given.

Dorsal Fin	CA	AC	AS	CC	CF	LC	CL	CP	CS	CT	GC	SL	TO
***Carcharhinus amblyrhynchoides* (CA)**													
***Carcharhinus amblyrhynchos* (AC)**	C, D												
***Carcharhinus amboinensis* (AS)**	All areas	All areas											
***Carcharhinus cautus* (CC)**	C, D, H	H	All areas										
***Carcharhinus falciformis* (CF)**	All areas	E, H	All areas	E, H									
***Carcharhinus leucas* (LC)**	C, D, H	C, D, H	E, H	C, D, H	All areas								
***Carcharhinus limbatus* (CL)**	–	C, D	All areas	C, D, H	All areas	C, D, H							
***Carcharhinus plumbeus* (CP)**	C, H	C, D, H	All areas	C, D	All areas	C, D, H	C, H						
***Carcharhinus sorrah* (CS)**	H	C, D, H	All areas	C, D, H	C, D, E	C, D, H	H	C, H					
***Carcharhinus tilstoni* (CT)**	–	C, D	C, D, E	C, D, H	All areas	C, D, H	–	C, H	H				
***Galeocerdo cuvier* (GC)**	All areas	All areas	All areas	All areas	All areas	All areas	All areas	All areas	All areas	All areas			
***Sphyrna lewini* (SL)**	C, D, H	C, D, H	All areas	C, D, H	C, D, H	C, D, H	C, D, H	C, D, H	C, D, H	C, D, H	All areas		
***Triaenodon obesus* (TO)**	H	C, D, H	All areas	C, D, H	All areas	C, D, H	H	C, H	H	H	All areas	C, D, H	

The most useful identification area for dorsal fins, in terms of percentage of species pairs distinguished (the proportion of all species pair combinations that could be differentiated), was area H (88%), followed by area C (82%), area D (76%) and area E (41%). Furthermore, eight of the 78 species pairs were only distinguishable using area H.

Table 3.12 A summary of the areas on the dorsal side of the right pectoral fin which can be used to differentiate between the 13 shark species studied using denticle characters. For each species pair, the area on the fin where denticle morphology differs between those species is given.

Pectoral Fin	CA	AC	AS	CC	CF	LC	CL	CP	CS	CT	GC	SL	TO
***Carcharhinus amblyrhynchoides* (CA)**													
***Carcharhinus amblyrhynchos* (AC)**	C, D, H												
***Carcharhinus amboinensis* (AS)**	D, E	All areas.											
***Carcharhinus cautus* (CC)**	H	C, D	D, E, H										
***Carcharhinus falciformis* (CF)**	All areas	E	All areas	C, D, E									
***Carcharhinus leucas* (LC)**	D, E	All areas	D	D, E, H	All areas								
***Carcharhinus limbatus* (CL)**	E, H	C, D, E	D, E, H	E	C, D, E	D, E, H							
***Carcharhinus plumbeus* (CP)**	D, E, H	C, E	D, E, H	D, E	C, E	D, E, H	D, E						
***Carcharhinus sorrah* (CS)**	All areas	C, E	All areas	C, D, E	C, E	All areas	C, D	C, E					
***Carcharhinus tilstoni* (CT)**	E, H	C, D, E	D, E, H	E	C, D, E	D, E, H	–	D, E	C				
***Galeocerdo cuvier* (GC)**	All areas	All areas	All areas	All areas	All areas	All areas	All areas	All areas	All areas	All areas			
***Sphyrna lewini* (SL)**	C, E, H	D, E	C, E, H	C, E	D, E	All areas	C, E	C, D, E	C, D, E	C, E	C, E		
***Triaenodon obesus* (TO)**	C, E, H	All areas	All areas	C, E, H	All areas	All areas	C, H	All areas	C, D, H	C, H	C, H	C, E, H	

For pectoral fins, the most useful identification area in terms of percentage of species pairs distinguished, was area E (86%), followed by area C (69%), area D (68%) and area H (59%). Three

of the 78 species pairs were only distinguishable using area E, and one pair was distinguishable for each of the areas C, D, and H.

3.4 Discussion

This study has revealed variations in denticle crown morphology between both the location on the fin surface, and at the same location between different species. Most of the shark species investigated could be distinguished using denticle characters on both the dorsal and pectoral fins. To this effect, pectoral fins were the most successful, as 11 of the 13 species could be distinguished; however, denticle characteristics from dorsal fins were also very useful, distinguishing ten of the 13 species. On the pectoral fin, area E was most useful for distinguishing species, while H was the most useful area on the dorsal fin. The difference in denticle crown morphology between location on the fin and between species (at the same location) is likely related to their hydrodynamic and/or defensive function.

3.4.1 Functional Characters of Denticles at Different Regions on The Fin

The crown morphology of the denticles at the fin tip (area C), the anterior margin (area D), the posterior margin (area E), and the free rear tip (area H) were found to differ markedly. This is likely to be associated with the varying hydrodynamic forces acting on the fin during swimming.

The fin tips (area C) of both dorsal and pectoral fins are characterised by highly overlapping denticles, with more extensive ridging occurring in some species. For pectoral fins, both bi-cresting of the primary ridge and the prominence of denticles with a large primary ridge is a common feature in this region. Bi-crested ridges are hypothesized to be a hydrodynamic adaptation that produces mixing vortexes in areas of adverse pressure gradients, thus reducing drag (Raschi & Tabit 1992, Wagner 1996). Furthermore, turbulent flow is strongest at the distal tips of wings, called a ‘wing-tip’ or ‘fin-tip’ vortex. This phenomenon creates increased drag at the fin tip, which increases with speed (Anderson 2007). Thus, because of strong drag forces experienced at the fin tips during

swimming the denticles in this area show modifications for drag reduction such as imbrication, increased ridging, and bi-crested primary ridges (*e.g. Carcharhinus plumbeus*).

The leading edge (area D) of both dorsal and pectoral fins is characterised by thicker, abutting (closely associated) denticles and denticle crowns with greatly reduced ridges and cusps. The boundary layer, created by the flow of water across the fin during swimming, is thinnest at the leading edge of the fin. Consequently, there is less drag in this area and modifications that reduce frictional drag, such as ridges and cusps, are reduced (Raschi & Tabit 1992). Crown smoothness is also attributed to protective-type denticle morphology (Raschi & Tabit 1992). As the leading edge of the fin would be subject to higher mechanical wear, the need for protection at this area would also influence crown morphology.

The trailing edge of the fin (area E) of both dorsal and pectoral fins is characterised by highly imbricated (overlapping) denticles and the prevalence of denticle crowns with extensive ridging, obvious cusps, and microrelief. This area is subject to increased drag resulting from boundary layer separation effects (Moore 1953). To combat drag in this area the denticle crowns have more developed ridges and cusps that increase surface area and, consequently, increase surface turbulence close to the skin. This results in highly efficient mixing in the boundary layer (close to the skin), reducing boundary layer thickness and preventing separation of the layer at the posterior edge of the fin (Burdack 1973, Bushnell & Moore 1991, Raschi & Elsom 1986). Cusps are structures that are susceptible to damage (*e.g.* breaking off from the crown) and the high amount of cusping, ridging, and crown overlap in this area suggests that crown morphology in the trailing edge of the fin is influenced more by hydrodynamic function than a requirement for protection.

The structure of the free rear tip (area H) differs considerably between dorsal and pectoral fins, which can be observed in the crown morphology of denticles at these areas. Denticles at the free rear tip of the dorsal fin are characterised by crowns with extensive ridging and prominent cusps, similar to the trailing edge of the dorsal fin (area E). Comparatively, the free rear tip of the pectoral fin is characterised by wide, rounded denticle crowns with absent (or very reduced) ridges

and cusps. The function of the free rear tip of the dorsal fin may act as a rudder during swimming and turning. When the shark turns, the free rear tip of the dorsal fin swings back and fourth, which may break up fin-tip vortices and reduce drag. This function is indicated by the prevalence of denticles with a crown morphology modified for drag-reduction. Conversely, the free rear tips of the pectoral fins are commonly tucked alongside the body, rubbing against the dorsal surface of the shark trunk. As such, denticles in this area require crown morphologies that are streamlined against snagging, and modified for protection against abrasion.

3.4.2 Functional Aspects of the Fin Denticles of Different Species

The requiem sharks (Carcharhinidae) and hammerhead sharks (Sphyrnidae) are among the faster swimming taxonomic groups of elasmobranchs (Compagno 1990). This is reflected in the crown morphologies of the fin denticles, which are specialised for hydrodynamic efficiency. Such specialisations include longitudinal ridging and highly overlapping, tessellated denticles. Despite the overall crown modifications for the functional requirement of fast swimming, the investigated species do not share identical life histories within their taxonomic group. Variations in denticle crown morphology may therefore correspond to a trade off between protection and hydrodynamic function, as described by Raschi & Tabit (1992).

The fastest swimming species investigated in this study are likely to be *Carcharhinus falciformis* (Silky Shark) and *Sphyrna lewini* (Scalloped Hammerhead) (Reif 1985a). These species exhibited crown characteristics that were highly modified for drag reduction such as extensive parallel ridging, microrelief, and high imbrication (Raschi & Elsom 1986, Raschi & Musick 1986, Raschi & Tabit 1992). Species that are also considered typically fast swimming, such as *Carcharhinus amblyrhynchoides* (Graceful Shark), *C. amblyrhynchos* (Grey Reef Shark), *C. cautus* (Nervous Shark), *C. limbatus* (Common Blacktip Shark), *C. plumbeus* (Sandbar Shark), *C. sorrah* (Spot-tail Shark), and *C. tilstoni* (Australian Blacktip Shark), exhibited the above characters to a lesser extent.

The crown morphologies of *Carcharhinus amboinensis* (Pigeye Shark) and *C. leucas* (Bull Shark) differ markedly from all other species investigated. These differences include uneven denticle spacing, and oblique ridges and cusps. Although the presence of both ridges and cusps is typically associated with hydrodynamic modification, the uneven ridges and cusps on the denticle crowns of the fins of these two species may indicate that during swimming these species do not require as much drag-reduction as other species investigated. This may be due to their life history patterns as both species are known to spend most of their life in and around estuaries and inshore environments, the Bull Shark being the only shark investigated that can live in both freshwater and seawater for extended periods (Last & Stevens 2009, Pillans & Franklin 2004). The diet of the Pigeye Shark consists of mostly benthic species including elasmobranchs, crustaceans, cephalopods, and other molluscs (Stevens & McLoughlin 1991), which could indicate a more benthic foraging lifestyle. Benthic sharks can be more susceptible to mechanical abrasion through increased likelihood of contact with the substrate and typically show denticle morphologies modified for protection (Raschi & Tabit 1992).

Carcharhinus plumbeus (Sandbar Shark) exhibits a crown morphology suited to both drag-reduction and protection. Denticles from the fins of this species possess drag-reduction characters such as thin, parallel ridges and a high prevalence of bi-crested ridges. Unlike other species however, the denticles are thicker and often exhibit characters associated with protective function such as reduced ridge depth and, in particular, the reduction or absence of cusps. The stronger denticles on the fins of this species may be indicative of a particular requirement for protection from predators, parasites, or mechanical abrasion due to a benthic foraging lifestyle. Adult *C. plumbeus*, like *C. amboinensis*, are also known to have a diet that includes a wide variety of mostly benthic species (*e.g.* benthic teleosts, elasmobranchs, and cephalopods) (McElroy, *et al.* 2006). However, unlike *C. amboinensis* and *C. leucas*, this species is known to undergo extensive seasonal migrations (Last & Stevens 2009). Thus, the denticle characteristics of the sandbar shark may show a trade off between both efficient swimming and protection by retaining crown qualities

indicative of hydrodynamic function (*e.g.* thin parallel ridges, bi-crested ridges and tessellated overlapping crowns) and protective modifications (*e.g.* thicker crowns and absent or reduced cusps). Furthermore, a higher prevalence of bi-crested ridges in the denticles of this species may compensate for reduced cusping by decreasing drag (see section 1.4.1 'area C'). The denticles of *C. amboinensis* and *C. leucas*, in contrast, show less parallel ridging and low spacing patterns but have extensive cusping. Indeed, bi-crested ridges may be a modification for greater drag-reduction while retaining thicker denticle crowns.

Exhibiting denticle crown morphology that is more adapted for protection is *Triaenodon obesus* (Whitetip Reef Shark). This species is typically associated with shallow reef flats and lives amongst rock and reef formations, showing a narrow home range and strong site fidelity (Robbins 2006). As such, this species would encounter abrasion from benthic structures and would therefore require morphological adaptations to offset these challenges. This was indeed the case with the denticle crown morphology of *T. obesus*. Cusps were absent on all denticles and the denticle crowns of this species displayed the least ridging of all species investigated.

The denticles of *Galeocerdo cuvier* (Tiger Shark) exhibited very distinct crown morphology and could easily be differentiated at all areas on both the dorsal and pectoral fins. This species has many characteristics that are atypical of the family Carcharhinidae, such as the presence of a caudal peduncle with lateral ridges, spiracles, and a reproductive mode of aplacental viviparity (Last & Stevens 2009). The taxonomy of this species is currently being revised to place it in its own monospecific family (Peter Last, pers com). Consequently, the marked difference in the crown morphology of the denticles of this species may be due to phylogeny, more so than function.

3.4.3 The Validity of Using Denticles for Species Identification

The need for high-resolution images in order to investigate denticle morphology poses a particular limitation for the use of dermal denticles as a tool for species identification. High-resolution images are obtained via a light microscope, which is usually impractical for field use. However, field

techniques are desirable for fisheries managers conducting *in situ* catch inspections. Hand lenses are a more field-friendly option that may be used to discriminate the more gross morphological features of the denticle crowns, but may not distinguish features such as microrelief. Marshall *et al.* (2007) demonstrated that the macro function on a digital camera could be used for inspecting denticles in the field, however the comparatively low resolution of a digital camera may not capture microscopic characters, such as microrelief, that are useful for species identification. Nevertheless, digital camera techniques are useful for discriminating species that have gross differences in denticle morphology (*e.g.* both *Carcharhinus leucas* and *C. amboinensis* can be discriminated from other carcharhinid species). If further advances in camera resolution occur, more denticle characters will become available for discriminating species in field situations.

A preliminary investigation found that juvenile specimens exhibited denticles that were uneven in size and shape across the fin. As the objective was to investigate the differences in denticle crown morphology between species, only adult specimens were used so as to reduce the number of variables in the analysis. As juvenile sharks are also caught by illegal fishing vessels, further studies should investigate whether the differences in crown morphology found in this study also hold true for juvenile specimens.

3.4.4 Conclusions

From this analysis it is clear that dorsal and pectoral fin denticle characteristics can be used for the discrimination of a number of shark species found in northern Australia, as nearly all species showed discernable differences in crown morphology. As the species in this study are known to have varied life history styles, differences in crown morphology are likely to be attributed to modifications along differing functional lines of drag-reduction versus protective function. Consequently, denticle crown characteristics appear to correspond to the functional requirements of each species. It is hypothesised that denticle cusps may be a feature that allow for reduced overall drag when protective function is not as acutely required, while bi-cresting may be an adaptation for

overall drag-reduction in denticles that have thicker crowns. As this study did not investigate the quantitative effect of denticle patterning on hydrodynamic flow, future studies should consider this to examine how flow effects differ between species.

Each individual fin showed large differences in denticle crown morphology at each area investigated, likely to be due to the varied hydrodynamic forces that act on the fin during swimming. Future studies of fin identification via denticles should incorporate these differences by specifying the area of the fin that is investigated, or by using a combination of areas to maximise the available characters for discrimination. Improvement of methods for identifying shark species, particularly from removed fins, is imperative for adequate species management. The ability to easily and reliably identify sharks to species, from both whole animals and shark parts, will enable fisheries managers to quantify catch composition and fishing mortality. These are fundamental data requirements for responsible fisheries management (see Chapters 1, and 5).

Despite the challenges of using this technique in the field, denticles can be considered a useful tool for identifying species of sharks from fins in such situations as 1) where confiscated catch is investigated in a lab, 2) when portable devices with high enough resolution to show distinguishing features are used (*e.g.* a handheld digital microscope), and 3) when used in conjunction with other characteristics such as fin shape and colour (discussed further in Chapter 4). In the latter case, denticle morphology can be used as supporting evidence to make a positive final identification from a list of possible species. Denticle morphology may particularly prove useful in cases where the fin shape is not conserved, such as when fins are damaged or acutely desiccated during processing.

Poor catch data collection in countries that target sharks and a failure to meet international responsibilities to provide accurate and comprehensive catch and trade data to the Food and Agriculture Organization (FAO) or to Regional Fisheries Management Organisations (RFMOs) is a significant challenge to global shark management (Lack & Sant 2009). The importance of validating and quantifying the use of characters such as dermal denticles to distinguish species,

particularly from fins alone, is vital in order to improve means of shark identification and improve data quality. The aim of this study was to investigate the validity of using denticle features to discriminate between common northern Australian shark species. As it was an investigative study, the sample size and range of species used was not comprehensive enough to develop stand-alone identification methods as yet, *e.g.* a binomial key. As denticle characteristic were found to be useful for the aforementioned purpose, future studies should focus on comparing both a wider range of size classes, to investigate interspecies variation in denticle patterns, and a wider range of species.

4

Shark Fin Morphology: identifying shark species using dorsal fins

4.1 Introduction

Species are the basic unit for the sustainable management and conservation of biodiversity (King 2007, Lindenmayer & Burgman 2005). Therefore, it is desirable that exploitation is monitored as close to a species-specific level as possible in order to assess the status of wild populations. Most

sharks are difficult to identify to species level, and a major hindrance to the management of shark stocks has been the lack of species-specific catch data (Barker & Schluessel 2005, Castro, *et al.* 1999, Lack & Sant 2009, Shotton 1999a). This problem of identification is confounded when whole sharks are reduced to severed fins for the shark fin trade. As fins represent one of the most traded parts, quantification of shark mortality represented by fins may help to give a more accurate representation of catch in the absence of more extensive and reliable species-specific statistics from commercial fisheries. For example, Clarke *et al.* (2006) estimated the shark biomass represented by the global fin trade is three to four times higher than shark catch figures reported in the FAO global data base. Therefore, clear benefits exist in efficiently examining trade data. Although the management priority for global shark fisheries is high, the resources available for the management of these fisheries are low. Given the issues of under-reporting and the general lack of species-specific data for global shark fisheries, a cost-effective tool is needed to collect species-specific catch data using shark fins.

Shark management in northern Australia illustrates this need. In recent years, northern Australian waters have seen a large increase in the amount of illegal foreign fishing targeting shark fin mainly by Indonesian fishers (Field, *et al.* 2009, Griffiths, *et al.* 2008, Salini, *et al.* 2007a, Salini, *et al.* 2007b). This activity peaked dramatically in 2005-2006 with 368 vessel apprehensions, and has steadily decreased to the present day (Griffiths, *et al.* 2008, Salini, *et al.* 2007c). Despite reduced FFV numbers there is still illegal fishing activity in the region, and the past and current impact of such fishing on shark stocks remains unknown. This is largely due to the inability to identify shark species from isolated fins, which form a major component of the illegal shark catch. As a result of this paucity of data, reliable risk assessments can not be made to effectively manage the legal fisheries in these waters (Salini, *et al.* 2007b).

To date, the most common approach for identification of excised fins has been molecular-based methods (Abercrombie, *et al.* 2005, Clarke, *et al.* 2006, Hernandez, *et al.* 2009, Hoelzel 2001, Holmes, *et al.* 2009, Smith & Benson 2001, Ward, *et al.* 2008, Wong, *et al.* 2009). Molecular

methods not only provide accurate species identifications, but defensible evidence for prosecution in the case of illegal fishing (Dawnay, *et al.* 2007). Molecular-based methods are particularly useful in later stages of processing when morphological traits are not conserved, and visual identification is not possible. Furthermore, they can potentially be used to identify stocks and trace the geographic origin of fins (Chapman, *et al.* 2009). Despite these benefits and applications, there are drawbacks to using molecular-based methods in catch quantification, including 1) analysis costs, 2) the time lag between gaining a sample and the subsequent identification, inhibiting use in the field, and 3) the inability to determine the size of the animal from which the fin was removed. As such, molecular methods, although useful, cannot be solely relied upon to provide catch data using shark fins.

Fewer studies have attempted to identify shark species from body parts using morphological methods, such as denticle analysis (Marshall, *et al.* 2007, SEAFDEC 2006, Tanaka, *et al.* 2002, Wagner 2001) and descriptive morphology (Hernandez, *et al.* 2009, Nakano & Kitamura 2000). These studies have been largely qualitative and, in the case of general morphology, have only compared a small number (> 11) of species. This is somewhat surprising, as morphological methods are the preferred technique for identifying whole sharks, *e.g.* Last & Stevens (2009).

The current lag in morphological identification techniques for shark fins is due to a lack of repeatable protocols, and techno-phile preference for molecular methods. In many cases, simpler morphological methods would be more appropriate. The development of morphology-based methods for identifying shark fins has potential advantages over molecular methods, such as 1) real-time identifications of shark species in the field, 2) the estimation of shark size based on fin size, and 3) cost-effectiveness, given the general lack of resources for the management of shark fisheries. Effective identification protocols would enable the collection of species-specific catch data, which can be used to accurately assess the catch of exploited species.

4.1.1 Objectives and Approach

The aims of this chapter were to 1) assess if morphological characters could be used to identify 35 species of shark found in northern Australian waters via morphometric analysis of their dorsal fins, 2) develop a protocol for identifying these species using dorsal fin morphology, 3) for each species, generate a mathematical relationship to estimate the size of the shark using the dorsal fin, and 3) assess the accuracy of the protocol by identifying a number of unknown dorsal fins, sourced from Foreign Fishing Vessels (FFVs), and compare the resulting morphological identification with the molecular species identification for each unknown sample.

4.2 Methods

4.2.1 Description of Specimens

When collecting specimens for the identification protocol the aim was to collect the maximum number of fin sets for a broad number of species groups, using limited funding resources. Therefore, specimen collection was opportunistic in nature and fin samples were obtained from a variety of sources, with varying levels of associated specimen data. The following section describes the specimens used in this chapter, as well as how ‘pseudo-species’ groups were created for analysis from a) the assembly of groups of similar species, or b) the division of similar fins from the same species. Lastly, the allocation of ‘known’ specimens to training and testing data for discriminant analysis is detailed.

Designation of ‘Pseudo-species’

This study ultimately aimed to identify fins to species, however, during a preliminary analysis there were cases where 1) similar species could not be distinguished and were grouped together, or 2) similar fins from a single species needed to be identified separately (species split into smaller groups). These artificially created groups were named ‘pseudo-species’ and were treated as a species variable for the purpose of analysis. For convenience, all pseudo-species are referred to

hereafter as a 'species'. The specific details and justifications of these pseudo-species designations are outlined below.

The Common Blacktip Shark (*Carcharhinus limbatus*) and the Australian Blacktip Shark (*C. tilstoni*) are morphologically very similar. Currently, whole specimens of these two species can only be separated by using pre-caudal vertebral counts or molecular methods (Last & Stevens 2009, Ovenden, *et al.* 2010). Therefore, both species were pooled for analysis and referred to as the pseudo-species '*Carcharhinus limb/tils*'.

At the commencement of this study the White-spotted Wedgefish (*Rhynchobatus australiae*) was the only recognised species from the genus *Rhynchobatus* in Australian waters. The taxonomy of the genus in Australia has since been revised, and two additional species are now known in Australia, the Smooth-nose Wedgefish (*Rhynchobatus laevis*), and the Eyebrow Wedgefish (*R. palpebratus*) (Last & Stevens 2009). Due to the ambiguity of the identity of many of the specimens in the data set collected previous to the revision, all specimens examined belonging to the genus *Rhynchobatus* were grouped collectively and referred to as '*Rhynchobatus* spp.'.

Both *Rhina ancylostoma* and *Rhynchobatus* spp. have second dorsal fins large enough to be confused with first dorsal fins after removal from the shark. As such, the second dorsal fins of these two species were analysed as individual pseudo-species, and were named '*Rhina ancylostoma* D2', and '*Rhynchobatus* spp. D2'. The decision to analyse them separately was taken because the mis-identification of a large second dorsal fin as first dorsal fin may influence species counts in catch data, overestimating the number of individuals caught.

Dorsal Fin Specimens

For this study, total of 634 dorsal fins representing 35 shark[1] species, commonly encountered in northern Australian waters were used. These fins were collected from a variety of sources and locations in both Australia and Thailand (see Chapter 2). Of these samples, 450 were derived from

[1] Although classed as rays, for convenience, animals belonging to the families Pristidae, Rhinidae, Rhinobatidae, and Rhynchobatidae are referred to herein as 'sharks'.

'known' specimens, that is, the species identification could be verified using the whole specimen from which it was removed[2] (see Chapter 2). The remaining 184 samples were 'unknown' dorsal fins, from the confiscated catch of FFVs apprehended in northern Australian waters. These samples were identified to species using molecular methods (see Appendix 9.1).

The 634 dorsal fins were split into two groups consisting of 'training' and 'testing' data (Table 4.1). 'Training' data were dorsal fin samples used to create the identification protocols. These were the 450 'known' samples as well as an additional 91 'unknown' samples with a genetic species identification (see Appendix 9.1). To maximise the accuracy of the identification procedure, the 91 'unknown' samples were used in order to supplement the sample size of species with < 15 'known' samples (Table 4.1). 'Testing' data were used to verify the accuracy of the identification protocols. 'Testing' samples were the remaining 93 'unknown' dorsal fins.

Rationale for the Allocation of Training and Testing Samples

As the sampling method was opportunistic (see Chapter 2) sample numbers of training and testing data were uneven between species groups (Table 4.1). For the unknown fin samples, up to 10 samples were chosen for each species group (based on an *a priori* visual identification by myself) to be identified using molecular methods (see Appendix 9.1 for full molecular methods). Of these samples, 193 produced viable sequences. Of these, 174 produced a final species identification. The remaining 19 samples could not be reliably identified to species, but could be identified to a species group. These were 11 samples from the '*Carcharhinus altimus/plumbeus*' group and 8 samples from the '*Carcharhinus limbatus/tilstoni/amblyrhynchoides*' group (Table 4.1). Therefore, molecular identifications did not always result in 10 samples per species group (Table 4.1), as 1) there may not have been 10 samples in the species group, 2) some of the sequences did not produce

[2]In the case of the nine *Alopias superciliosus* samples (Table 4.1), these were derived from the confiscated catch of a vessel that was apprehended in northern Australian waters. CO1 genetic sequencing identified one of these specimens to the genus *Alopias* but could not provide a definite species identification. In spite of this, these specimens were labelled as 'known' as I was confident in identifying these dorsal fin specimens to the species *Alopias superciliosus* after investigating photographs of whole animals from the three species within the genus *Alopias* (*A. pelagicus*, *A. superciliosus*, and *A. vulpinus*).

Table 4.1 Summary of the number of dorsal fin samples used to train and test the species identification protocol. Training refers to specimens used to create the identification protocol. Testing data were used to verify the accuracy of the identification protocol. 'Known' refers to samples derived from a whole specimen, which could be identified to species. 'Unknown' refers to samples, which were derived from the seized catch of illegal foreign fishing vessels. The species identification of the 'Unknown' samples was verified using genetic methods. Some specimens could not be conclusively identified to species using genetic methods, and were grouped into broad categories (grey). As not all specimens had associated total length data, the size range for each species or species group is given as dorsal fin base length (BL) (mm).

	Training					Testing	
	Known		Unknown		Total	Unknown	
	n	BL (mm)	*n*	BL (mm)	*n*	*n*	BL (mm)
Alopias superciliosus	9	162.6–232.8	.	.	9	.	.
Carcharhinus albimarginatus	25	70.6–261.8	.	.	25	7	159.6–215.9
Carcharhinus altimus	3	100.3–295.3	12	137–308.5	15	2	195.6–264.8
Carcharhinus altimus/plumbeus	.	.	.	.	.	11	118.3–238.4
Carcharhinus amblyrhynchoides	19	93–189.5	.	.	19	.	.
Carcharhinus amblyrhynchos	15	84.1–199.1	.	.	15	2	106.3–106.3
Carcharhinus amboinensis	14	103.9–410.9	.	.	14	.	.
Carcharhinus brevipinna	16	36.1–204.3	.	.	16	4	61–239.4
Carcharhinus cautus	21	48.4–154.1	.	.	21	.	.
Carcharhinus dussumieri	19	50.2–77	.	.	19	8	53.2–67.5
Carcharhinus falciformis	15	70–256.8	.	.	15	7	114.2–212.9
Carcharhinus leucas	26	99.4–408.1	.	.	26	1	268.7–268.7
Carcharhinus limb/tils/am-ides	.	.	.	.	.	8	94.2–162
Carcharhinus limb/tils	56	68.5–277.5	.	.	56	15	99.1–166.4
Carcharhinus longimanus	.	.	5	173–219.6	5	.	.
Carcharhinus macloti	1	78.7	10	39–66.7	11	.	.
Carcharhinus melanopterus	8	71.4–156	.	.	8	.	.
Carcharhinus obscurus	10	88.2–306.6	28	129.8–265	38	10	129.3–252.8
Carcharhinus plumbeus	3	104.9–252.8	8	198.9–283.8	11	.	.
Carcharhinus sorrah	38	36.6–143.4	13	56.3–112.9	51	10	49–110.6
Eusphyra blochii	3	120.9–163.1	1	134.3–134.3	4	.	.
Galeocerdo cuvier	17	63.2–372.9	.	.	17	3	119.4–255.9
Hemigaleus australiensis	9	47.9–105.7	.	.	9	.	.
Isurus oxyrinchus	3	114–292.9	.	.	3	.	.
Loxodon macrorhinus	2	42.3–45.7	.	.	2	.	.
Negaprion acutidens	8	60.1–236.9	.	.	8	.	.
Prionace glauca	9	161.2–246.3	.	.	9	.	.
Rhina ancylostoma	6	59–192.4	.	.	6	.	.
Rhina ancylostoma D2	6	46.5–133.4	.	.	6	.	.
Rhizoprionodon acutus	21	48.5–84.0	.	.	21	.	.
Rhizoprionodon taylori	8	42.3–83.9	.	.	8	.	.
Rhynchobatus spp.	18	29.5–115	.	.	18	1	79.4–79.4
Rhynchobatus spp. D2	18	20.9–96.8	.	.	18	.	.
Sphyrna lewini	13	57.8–249.4	2	235.9–316.3	15	4	56.2–213.8
Sphyrna mokarran	5	141.7–248.9	3	223.4–237.6	8	.	.
Sphyrna zygaena	2	135.1–145.9	9	205.6–307	11	.	.
Triaenodon obesus	4	96.2–122.4	.	.	4	.	.
	450		91		541	93	

a definitive result, and 3) the tally of final molecular identifications produced more than 10 samples from a particular species. Given that the resulting number of FFV samples that produced an identification via molecular methods was uneven between species groups, training and testing data were allocated in order to 1) maximise the number of training samples per species group, and then 2) maximise the number of genetically identified testing samples. Therefore, for each species group, a maximum of 10 genetically identified samples (unless the number of 'known' training samples was < 15) were reserved as testing samples and the remainder were used to substitute the training data (Table 4.1). If the number of 'known' training samples was > 15 per species, genetically identified 'unknown' samples were randomly allocated to the training set until the sample size reached 15. The remainder were allocated to the testing data set. This resulted in 0–10 testing samples per species group, meaning that not all species groups could be validated using testing data because of low sample numbers. An exception to this was the *Carcharhinus limb/tils* group, which had a large number of samples (n = 56) in the 'known' group, and also a large amount of 'unknown' testing samples (n = 15), which produced viable species identifications via molecular methods. Therefore, all 15 'unknown' samples were used in the testing group for this species (Table 4.1).

4.2.2 Processing and Photography Procedure

Fins were cleaned and then photographed using a handheld Pentax Optio W10 digital camera (Chiari, *et al.* 2008), set to the 'soft flash' setting, from directly above the subject. To avoid edge distortion, a wide border was left around the subject, which was later cropped (Zelditch 2004). Each photograph contained a scale, specimen number and, for images used to analyse fin colour, a standard blue mat as a background (Figure 4.1). A tissue sample was removed from each sample and kept for molecular analysis. It should be noted that, because of limited resources, not all tissue samples were sequenced.

Figure 4.1 Example photograph of a shark fin sample containing a scale, specimen number and the standard blue mat used to standardise RGB colour values.

4.2.3 Species Identification Approach

The approach to the identification of all 38 shark species is summarised in Figure 4.2. Because of their simplicity, characters such as fin-tip colour, fin colour and simple primary measurements were used for the first steps of the identification procedure. However, preliminary analysis found that these characters, when used alone, could only be used to identify six of the 38 species. For the remaining 32 species, more powerful discrimination using a combination of morphological characters was necessary. This was achieved using discriminant analysis (DA), a statistical method which finds a linear combination of features that characterise, or separate, two or more classes of objects or events. The resulting combination may be used as a linear classifier, or for dimensionality reduction before later classification (Tabachnick & Fidell 2006). Statistical errors (singularity errors) occur in DA when the number of groups is larger than the within-group sample size (Tabachnick & Fidell 2006). Therefore, the 32 species were divided into four groups that could be identified from simple characters such as fin-tip colour, fin colour and simple primary measurements. These groups were named Discriminant Analysis Groups (DAGRPS). This was done using a dichotomous key created from this simple character information (Figure 4.5). Six

species could also be identified using this key (Table 4.3). The species within each DAGRP were then were then analysed using a separate discriminant analysis for each DAGRP. In some cases singularity errors occurred, therefore the DAGRP was further divided (visually) into morphologically similar groups of species (MSGs), which were then analysed using DA.

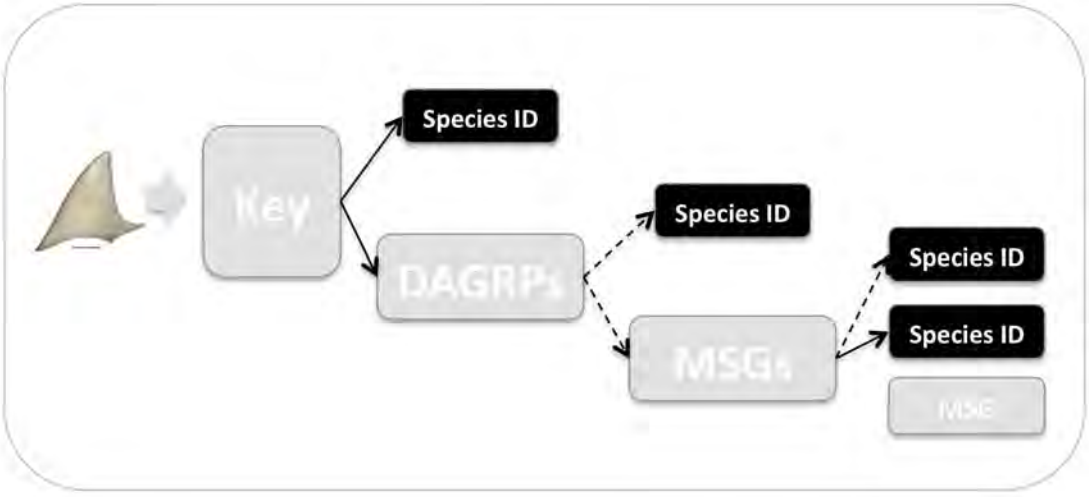


Figure 4.2 Flow diagram outlining the approach taken to identify dorsal fins, from 93 fin samples from the testing group, from 13 species of shark found in northern Australian waters. A dichotomous key is used to identify the dorsal fin sample to either species or discriminant analysis group (DAGRP). Classification equations (generated for each DAGRP) are then used to identify the fin to either species or morphologically similar group (MSG). MSGs are then identified to species or another MSG, until the dorsal fin was identified to species. Arrows with closed lines represent where fin colour, fin-tip colour or simple primary measurements are used for classification, arrows with broken lines represent where DA equations are used for classification.

4.2.4 Morphological Characters Used for Discriminant Analysis Variables

For each discriminant analysis, linear measurements of the dorsal fin and quantitative data on fin colour were used as variables to separate species or MSGs.

Fin Measurement Procedure

All fin morphometric distance measurements were taken from digital images imported into *SigmaScan Pro.* 5 software. Images were calibrated using the scale photographed within the image. A series of 17 linear distance measurements were taken on each dorsal fin (Figure 4.4). Primary measurements were those taken from identifiable points on the fin (primary landmarks) (Figure 4.3b). Secondary measurements were those taken from ‘primary apex landmarks’ located using the primary landmarks (Figure 4.3b). Tertiary measurements were those taken from ‘secondary apex

landmarks' (Figure 4.3b). Primary measurements were preferred as they were the easiest to locate and the most robust, followed by secondary and tertiary measurements, respectively (see Chapter 2). Accurate location of both the primary and secondary apex landmarks was carried out in *SigmaScan Pro.* 5 using the 'annotation lines tool' to locate apex landmarks using perpendicular distances (Figure 4.3b). From these measurements, an additional five triangle heights (Figure 4.3a) were calculated by computing the triangle area using Heron's Formula (Heath 1921):

$$A = \sqrt{\frac{(a+b+c)(a+b-c)(b+c-a)(c+a-b)}{16}} \quad (1)$$

where, A is the area of a triangle with sides a, b, and c, and determining the triangle height using the standard formula:

$$height = \frac{A}{\frac{1}{2} \times base} \quad (2)$$

To remove the confounding influence of size each fin measurement, and hence use shape (allometric) alone for the analyses, size correction was applied to the raw morphometric data. By reducing linear measurements to ratios, the variables become dimensionless and scale-free, *i.e.* the isometric component is removed leaving only the allometric component (Human 2006). Therefore, prior to analysis all measurements were divided by the fin base length (B), thus B was not included as a variable in the DA (Figure 4.4a). What is referred to herein as 'measurement data' consists of 22 measurements (A, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, Ah, Bh, Ch, Dh, and Eh) expressed as a ratio of B. As fin base length was not always the largest measurement, ratio values could be larger than one.

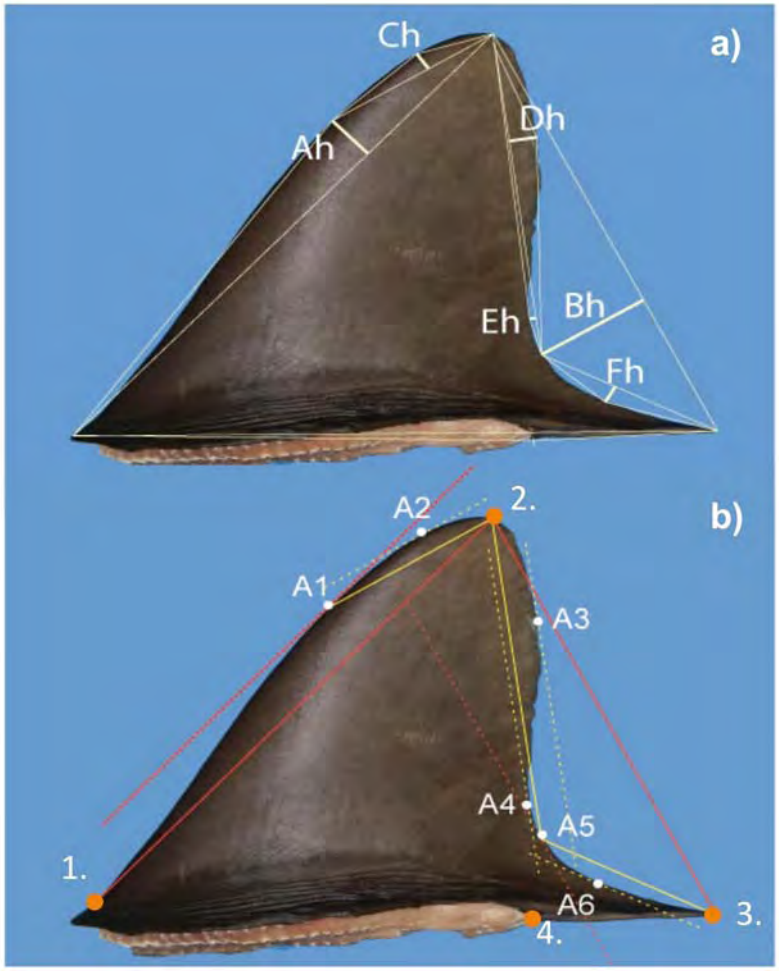


Figure 4.3 a) The five height measurements calculated from lengths in Figure 4.4 using Heron's Formula (Equations 1 and 2). Ah (anterior margin height), Bh (posterior margin height), Ch (outer anterior margin height) Dh (outer posterior margin height), Eh (inner posterior margin height), Fh (free rear tip margin height), Gh (inner free rear tip margin height), Hh (free rear tip depth); b) Location of the primary (orange circles) and apex (white circles) landmarks for which all primary, secondary and tertiary distance measurements are based. Solid lines represent the original primary (red) or secondary (yellow) measurements and dotted lines represent the largest perpendicular distance from these to the edge of the fin, by which the apex landmark is located. Labels correspond to: 1. fin origin, 2. fin-tip, 3. free rear tip, 4. fin insertion A1 (major convex anterior apex), A2 (minor convex anterior apex), A3 (minor convex posterior apex), A4 (minor concave posterior apex), A5 (major concave posterior apex), A6 (concave free rear tip apex).

Fin Colour

Fin colour was quantified by measuring the average red (R), green (G) and blue (B) values of each fin using *SigmaScan Pro.* 5. In each image, the average R, G, and B levels were recorded for 1) the largest coloured area of each fin, and 2) a clean, dry area of the blue mat. To reduce variation that may result from differences in exposure and brightness between images taken in a range of field conditions, the average R, G, and B values were standardized relative to all images in the dataset (Dimond & Carrington 2007, Edmunds, *et al.* 2003). To achieve this, first the pooled

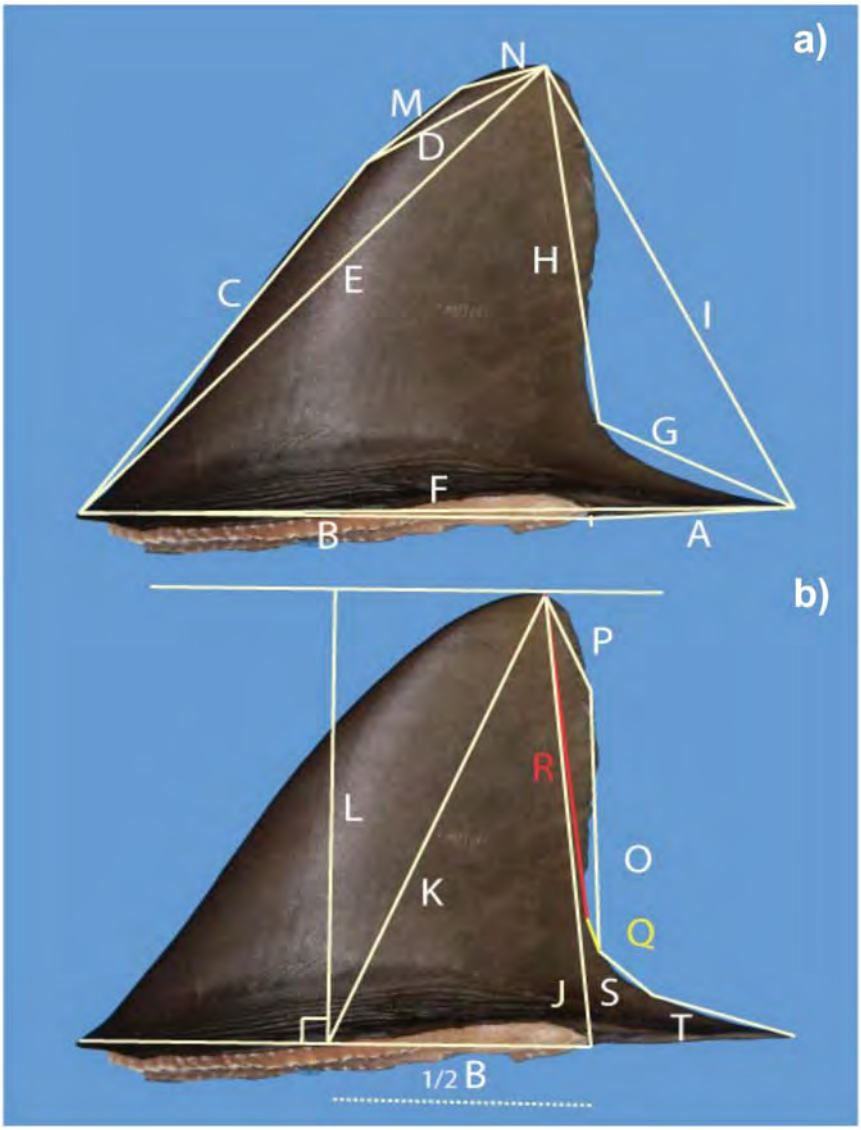


Figure 4.4 The 17 linear distances measured on each dorsal fin. a) A^1 (inner margin), B^1 (fin base), C^2 (upper anterior margin), D^2 (lower anterior margin), E^1 (anterior margin), F^1 (total fin width), G^2 (lower posterior margin), H^2 (upper posterior margin), I^1 (posterior margin), M^3 (lower outer anterior margin), N^3 (upper outer anterior margin). b) J^1 (fin height), K^1 (direct mid fin height), L^1 (absolute fin height), O^3 (lower outer posterior margin), P^3 (upper outer posterior margin), Q^3 (lower inner posterior margin), R^3 (upper inner posterior margin), S^3 (lower outer free rear tip margin), T^3 (upper outer free rear tip margin). [1]primary measurements, [2]secondary measurements, [3]tertiary measurements.

average R, G, and B values for the blue mat in all images was calculated (PRMat, PGMat and PBMat). Second, for each image, the difference between the R, G, and B values for the blue mat and PRMat, PGMat and PBMat was calculated. This difference was then subtracted from the average R, G, and B values of the fin in that image resulting in the variables *Red*, *Green*, and *Blue*. As measuring R, G, and B colour levels was not part of the original study design, not all 'known' fins were photographed with the standard blue mat in the background. This created missing *Red*,

Green, and *Blue* values in the dataset for DA (Table 4.2). As eliminating these samples would result in inadequate sample size for many species, missing values were replaced with the average *Red*, *Green*, and *Blue* values for that species. However, all 'testing' data included the standard blue mat and thus did not contain missing colour values, therefore the validation study (Section 4.2.6) was not subject to bias from substituting average colour values.

4.2.5 Discriminant Analysis Procedure

The independent variables used for discriminant analysis (DA) were the colours *Red*, *Green* and *Blue* and the 23 proportional distance measurements (A, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, Ah, Bh, Ch, Dh, and Eh). The grouping variables used for analysis were either 'species' or MSGs'. For every DA performed, evaluation of assumptions of linearity and normality were satisfactory (Tabachnick & Fidell 2006). Samples that were multivariate outliers were identified using Mahalonobis distance and eliminated when $p < 0.001$(Tabachnick & Fidell 2006).
In order to overcome problems of multicollinearity and singularity in each DA, stepwise DA was first performed to determine the best combination and smallest number of variables that would separate groups (Tabachnick & Fidell 2006). Discriminant loadings were then used to assess the contribution of each variable to a discriminant function as a standardised measure of importance (ranging from 0 to 1).

Loadings exceeding ± 0.40 were considered substantive for interpretation purposes. A structure matrix was created, showing pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions. Variables were ordered by the absolute size of correlation within the function, listing the variables in a step-wise manner that contributes the most to function 1 first, then function 2 *etc*. The contribution of each variable to the effectiveness of the classification model (success rate) was assessed by sequential addition of each measurement to direct discriminant analysis (DDA). The structure matrix determined the order in which the variables were entered. The most useful variable was entered first into the DDA

Table 4.2 A summary of the number of dorsal fin samples which had associated RGB colour data for both the 'training' and 'testing' datasets. For each of the samples that did not have colour data ('No Colour'), the missing RGB colour values were replaced with the average RGB colour values for that species.

	Training		Testing	
	No Colour	RGB Colour	No Colour	RGB Colour
Alopias superciliosus	-	9	-	-
Carcharhinus albimarginatus	10	15	-	7
Carcharhinus altimus	7	8	-	2
Carcharhinus amblyrhynchoides	9	10	-	-
Carcharhinus amblyrhynchos	7	8	-	2
Carcharhinus amboinensis	6	8	-	-
Carcharhinus brevipinna	5	11	-	4
Carcharhinus cautus	9	12	-	-
Carcharhinus dussumieri	10	9	-	8
Carcharhinus falciformis	5	10	-	7
Carcharhinus leucas	12	14	-	1
Carcharhinus limb/tils	25	31	-	15
Carcharhinus longimanus	-	5	-	-
Carcharhinus macloti	4	7	-	-
Carcharhinus melanopterus	4	4	-	-
Carcharhinus obscurus	16	22	-	10
Carcharhinus plumbeus	-	11	-	-
Carcharhinus sorrah	18	33	-	10
Eusphyra blochii	3	1	-	-
Galeocerdo cuvier	5	12	-	3
Hemigaleus australiensis	1	8	-	-
Isurus oxyrinchus	-	3	-	-
Loxodon macrorhinus	-	2	-	-
Negaprion acutidens	3	5	-	-
Prionace glauca	4	5	-	-
Rhina ancylostoma	6	-	-	-
Rhina ancylostoma D2	6	-	-	-
Rhizoprionodon acutus	3	18	-	-
Rhizoprionodon taylori	2	6	-	-
Rhynchobatus spp.	16	2	-	1
Rhynchobatus spp. D2	16	2	-	-
Sphyrna lewini	7	8	-	4
Sphyrna mokarran	4	4	-	-
Sphyrna zygaena	-	11	-	-
Triaenodon obesus	4	-	-	-

and the percent of species correctly classified (%CC) was recorded. The next most useful variable was then entered into DDA and the %CC recorded, until all variables from the structure matrix were included in the analysis. Variables were kept for analysis until the difference in success rate

achieved by their addition was less than 2%. The resulting list of variables was then used for canonical discriminant analysis using SPSS (DA procedure) (SPSS Inc., Chicago IL).

Direct canonical discriminant function analysis was performed using the reduced variable set identified in the stepwise DA procedures to derive discriminant functions (linear combinations of variables) that maximise between-group variation in the DAGRP or MSG. Classification functions were then generated to determine to which group each case most likely belongs. For each group, a classification function was generated and a classification score computed, by applying the formula:

$$S_i = c_i + w_{i1} \times x_1 + w_{i2} \times x_2 + ... + w_{im} \times x_{im} \quad (3)$$

The subscript *i* denotes the respective group; the subscripts *1*, *2*, ..., *m* denote the *m* variables; c_i is a constant for the *i*'th group, w_{ij} is the weight for the *j*'th variable in the computation of the classification score for the *i*'th group; x_j is the observed value for the respective case for the *j*'th variable. S_i is the resultant classification score. The classification functions are used to directly compute classification scores for new observations, with the highest score indicating the most likely group. For each testing sample that was classified using the above method, SPSS was used to determine the posterior probability (PP) that the case belongs to the assigned MSG or species group. The posterior probability was calculated as being proportional to the Mahalonobis distance from the assigned group centroid, and has a value of 0-1. For samples assigned to multiple groups during classification, for example DAGRP4 to MSG3 to MSG7 to *Carcharhinus sorrah* (Figure 4.2), each classification had a calculated posterior probability. To calculate the total posterior probability for the sample, the PP of group membership for each classification was multiplied (*e.g.* PP(DAGRP4) x PP(MSG3) x PP(MSG7) x PP(*Carcharhinus sorrah*) = PP(sample)).

As not all species could be validated with molecular techniques, to assess the predictive accuracy of each DA model, a ‘leave-one-out’ cross validation method was employed (Tabachnick

& Fidell 2006). In 'leave-one-out' classification, each case in the analysis is classified by the functions derived from all cases other than itself, and is considered a reliable estimate of error (Brun, *et al.* 2008).

4.2.6 Validation of the Identification Procedure

To validate the predictive accuracy of the identification procedure described above, each sample from the training data set was identified using the key and the relevant DA classification functions derived for the DAGRP or MSG. To assess the accuracy of the method, the resulting identifications were cross-referenced with DNA species identifications from a tissue sample of the fin. Appendix 9.1 provides a detailed explanation of the molecular analysis used, the results of which are used in this chapter.

4.2.7 Shark Size Estimation

To predict shark size from the identified dorsal fin, the relationship between shark total length (TL cm) and dorsal fin base length (B mm) was examined using linear regression in order to generate predictive equations for those species with total length data (Warton, *et al.* 2006). Specimens from the 'known' group, which had associated total length data (n = 380) were used to generate these equations. This resulted in low sample numbers for some species (Table 4.41). Therefore, 64 photographs of whole specimens, sourced from other researchers for as many species as possible, were used to supplement the data set (Table 4.41). Total length and dorsal fin base length were measured from these photographs using *SigmaScan Pro.* 5 software. Where more than two samples were available, regression equations for these relationships were calculated. The correlation coefficient (r^2) value (0-1) was used to describe the proportion of variation explained by the linear model. The significance value of the F statistic ($P \leq 0.05$) was used to test if the linear relationship between total length and fin base length was statistically significant.

4.3 Results

4.3.1 Species Identification from Dorsal Fins

Six species, and four DAGRPS were identified using the dichotomous key (Table 4.3). Once identified, the DAGRPS were analysed using discriminant analysis. Three of the four DAGRPs were split into six subsequent MSGs, and one of these MSGs was further split into three subsequent MSGs (Figure 4.5). These four DAGRPs and nine MSGs were used to identify the 29 species, which could not be identified by the key, using discriminant analysis of morphometric and colour data (Figure 4.5). Some species were assigned to multiple groups, for example *Carcharhinus sorrah*, which was assigned to both DAGRP 3 and DAGRP 4 as dorsal fin specimens from this species did not always have black tips.

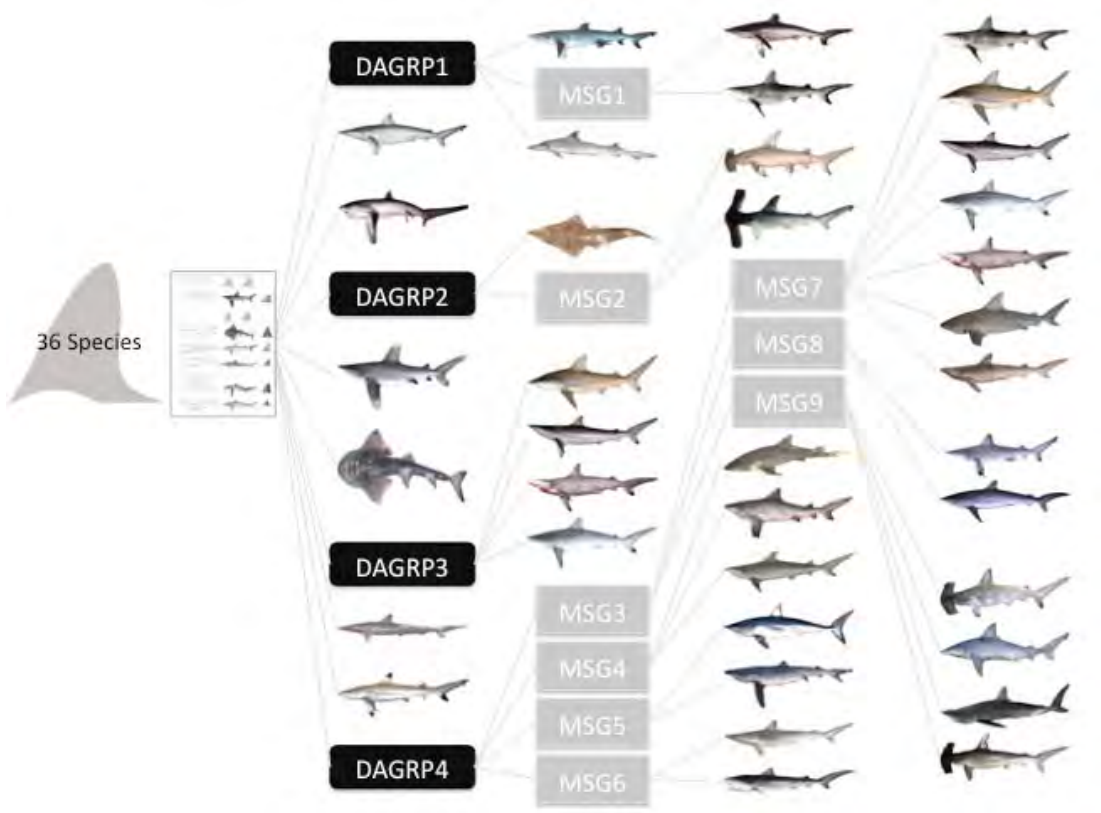


Figure 4.5 Shows how each of the 35 species were divided into the 4 DAGRPs and nine MSGs during analysis. Each species is represented by a picture of a whole animal. Some species are repeated as they were assigned to multiple groups.

Table 4.3. Key to species and DAGRPs using dorsal fins for northern Australian sharks.

1 Fin has distinct white tip (1a) …… **2**

Fin **does not** have distinct white tip (1b)…… **3**


1a


1b

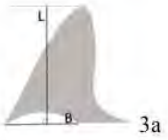
2 Fin-tip is broadly rounded (2a) …… **Oceanic White Tip (*Carcharhinus longimanus*)**

Fin-tip is not broadly rounded…… **DAGP1**

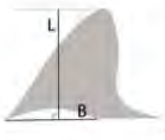

2a

3 L/B> 1.44 (3a)…… **4**

L/B< 1.41 (3b)…… **5**



3a



3b

4 Fin purple/grey with white spots (4a)…… **Shark Ray (*Rhina ancylostoma*)**

Fin **not** purple/grey with white spots…… **DAGP2**


4a

5 Fin has a sharply demarcated black tip covering at least 4% of the fin-tip (5a)……**Black Tip Reef Shark (*Carcharhinus melanopterus*)**

Not as above …… **6**


5a

6 Fin has a dusky black tip which covers > 10% of the fin area **and** base length (B) < 40 mm (6a)……**Sliteye Shark (*Loxodon macrorhinus*)**

Not as above …… **7**


6a

7 Fin-tip no colour (7a)…… **8**

Fin has a black tip (may be very slight) (7b)…… **DAGRP3**


7a


7b

8 Fin has longitudinal (anterior to posterior) striations (8a)…… **Big Eye Thresher (*Alopias superciliosus*)**

Fin does not have longitudinal striations…… **9**


8a

9 A/B < 6.2 **and** fin does not have a grey striped pattern (9a)……**Hardnose Shark (*Carcharhinus macloti*)**

A/B > 6.2 **or** fin has a horizontal striped pattern (9b)…… **DAGRP4**


9a

8a


9b

DAGRP1

Table 4.4 The four shark species, *Carcharhinus albimarginatus*, *C. amblyrhynchos*, *Hemigaleus australiensis* and *Triaenodon obesus*, and number of dorsal fin samples (*n*), included in DAGRP1 analysed using discriminant analysis. After initial analysis, all samples of *Carcharhinus albimarginatus* and *C. amblyrhynchos* were pooled to create morphologically similar group 1 (MSG1). DA groups column indicates the groups used in the DA procedure.

DAGRP1				
Species	*n*	DA Groups		
Carcharhinus albimarginatus	25	MSG1		
Carcharhinus amblyrhynchos	15			
Hemigaleus australiensis	9	HA		
Triaenodon obesus	4	TO		

DAGRP1 consisted of 53 dorsal fin samples from four species *Carcharhinus albimarginatus*, *C. amblyrhynchos*, *Hemigaleus australiensis* and *Triaenodon obesus* (Table 4.4). Initial stepwise DA showed low classification values for *Carcharhinus albimarginatus* and *C. amblyrhynchos*, which were often misclassified as each other. Therefore, these two species were pooled to form MSG1. A second analysis of MSG1, *Hemigaleus australiensis* (HA) and *Triaenodon obesus* (TO) identified measurements L, J and R as most important for discriminating between these. The discriminant index successfully distinguished between the three groups (Wilks' $\lambda = 0.144$; $\chi^2 = 100.91$, df = 6, $P < 0.001$). The first canonical discriminant function explained 74.6% of the morphometric variance (canonical correlation = 0.852) and the second canonical discriminant function explained 25.4% (canonical correlation = 0.689). Classification functions for each group are given in Table 4.5. Using the 'leave-one-out' cross validation method, 96.2% of the original 53

cases were classified correctly into their groups (95% for MSG1, 100% for *H. australiensis* and 100% for *T. obesus*, Table 4.6). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from function 2 to visually represent how well these functions differentiated the dorsal fin specimens (Figure 4.6). Samples from *Triaenodon obesus* formed a discrete group in the upper left side of the plot. Samples from *Hemigaleus australiensis* and MSG1 occupied the lower half of the plot, with *H. australiensis* falling to the lower left side and MSG1 falling to the lower right side. This shows that function 1 differentiates between MSG1 and both *Hemigaleus australiensis* and *Triaenodon obesus*, while function 2 differentiates between *H. australiensis* and *T. obesus.*

Table 4.5 Classification function coefficients derived from Fisher's linear discriminant functions for DAGRP1.

	MSG1	*H. australiensis*	*T. obesus*
L	171.097	103.045	164.838
J	32.492	80.73	91.086
R	2.014	-39.51	-75.418
(Constant)	-105.114	-66.193	-118.142

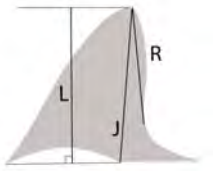


Table 4.6. Results of direct discriminant analysis of DAGRP1 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		MSG1 (%)	HA (%)	TO (%)	*n*	Global accuracy (%)
Original	MSG1	**95**	.	5	40	
	H. australiensis	.	**100**	.	9	96.2
	T. obesus	.	.	**100**	4	
Cross-validated	MSG1	**95**	.	5	40	
	H. australiensis	.	**100**	.	9	96.2
	T. obesus	.		**100**	4	

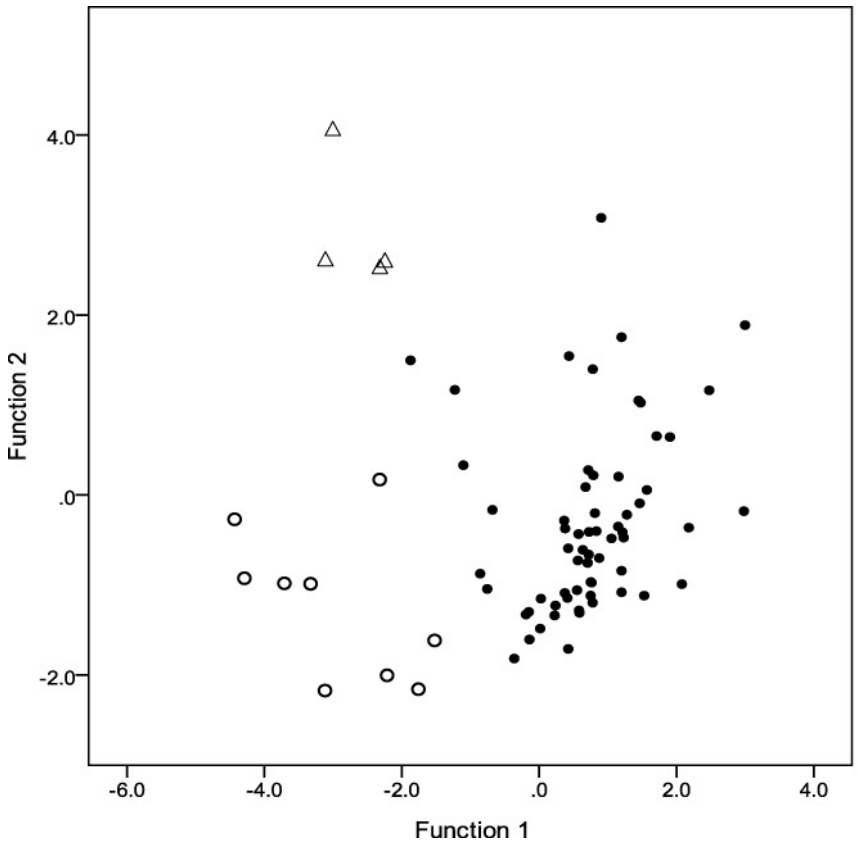


Figure 4.6 Discriminant function scores for the 53 dorsal fin samples in DAGRP1 showing the how the first two functions discriminate between the three groups using the linear measurements L, J and R. Symbols: ●, MSG1; ○, *Hemigaleus australiensis*; △, *Triaenodon obesus*.

MSG1

As morphometric measurements were not able to separate the species Carcharhinus albimarginatus and C. amblyrhynchos in MSG1, stepwise DA was performed using the three colour variables, Red, Green and Blue which were all found to be important for discriminating between the two species. The discriminant index successfully distinguished between the two species (Wilks' $\lambda = 0.026$; $\chi 2 = 144.017$, df = 3, $P < 0.001$), explaining 100% of the colour variance (canonical correlation = 0.987). Classification functions for each species are given in Table 4.7. Using the 'leave-one-out' cross validation method, 97.5% of the original 40 cases were classified correctly into their groups (100% for Carcharhinus albimarginatus and 93.3% for C. amblyrhynchos, Table 4.8).

Table 4.7 Classification function coefficients derived from Fisher's linear discriminant functions for MSG1.

	Carcharhinus albimarginatus	*Carcharhinus amblyrhynchos*
Red	24.360	16.551
Green	-32.143	-20.077
Blue	15.824	10.413
(Constant)	-658.345	-467.494

Table 4.8 Results of direct discriminant analysis of MSG1 based on HIS colour data for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		C. albimarginatus	*C. amblyrhynchos*	*n*	Global accuracy (%)
Original	*C. albimarginatus*	**100**	.	25	100
	C. amblyrhynchos	.	**100**	15	
Cross-validated	*C. albimarginatus*	**100**	.	25	97.5
	C. amblyrhynchos	6.7	**93.3**	15	

DAGRP2

Table 4.9 The four shark species, *Eusphyra blochii*, *Sphyrna mokarran*, *Rhynchobatus* spp., and *Rhynchobatus* spp. D2, and number of dorsal fin samples (*n*), included in DAGRP2 analysed using discriminant analysis. After initial analysis, all samples of *Eusphyra blochii* and *Sphyrna mokarran* were pooled to create morphologically similar group 2 (MSG2), and all dorsal and second dorsal fins of *Rhynchobatus* spp. were pooled to make group RB. DA groups column indicates the groups used in the DA procedure.

DAGRP2				
Species	*n*	DA Groups		
Eusphyra blochii	4	MSG2		
Sphyrna mokarran	8			
Rhynchobatus spp.	18	RB		
Rhynchobatus spp. D2	18			

DAGRP2 consisted of 48 dorsal fin samples from four groups (Table 4.9). Initial stepwise DA showed low classification values for *Eusphyra blochii* and *Sphyrna mokarran*, which were often misclassified as each other. Therefore, these two species were pooled to form MSG2. The dorsal and second dorsal fins of *Rhynchobatus* spp. could not be distinguished from each other by morphometrics and were pooled as '*Rhynchobatus* spp.'. A second analysis of the two groups MSG2 and *Rhynchobatus* spp. (RB) identified measurements Bh and F as most important for discriminating these groups Figure 4.4. The discriminant index successfully distinguished between both groups (Wilks' $\lambda = 0.161$; $\chi^2 = 80.45$, df = 2, $P < 0.001$). The canonical discriminant function explained 100 % of the morphometric variance (canonical correlation = 0.916). Classification

equations for each group are shown in Table 4.10. Using the 'leave-one-out' cross validation method, 97.9% of the original 48 cases were classified correctly into their groups (100% for MSG2 and 97.2% for *Rhynchobatus* spp., Table 4.11).

Table 4.10 Classification function coefficients derived from Fisher's linear discriminant functions for DAGRP2.

	MSG2	*Rhynchobatus* spp.
Bh	-24.276	-56.575
F	101.608	152.372
(Constant)	-64.362	-134.776

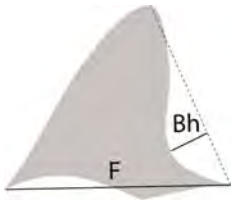


Table 4.11 Results of direct discriminant analysis of DAGR2 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		MSG2 (%)	*Rhynchobatus* spp. (%)	*n*	Global accuracy (%)
Original	MSG2	**100**	.	12	97.9
	Rhynchobatus spp.	2.8	**97.2**	36	
Cross-validated	MSG2	**100**	.	12	97.9
	Rhynchobatus spp.	2.8	**97.2**	36	

MSG2

The measurements P and Ah (Figure 4.4) were identified by stepwise DA as being most important for classifying the species constituting MSG2, *Eusphyra blochii* and *Sphyrna lewini* (Table 4.9). The discriminant index successfully distinguished between both species (Wilks' $\lambda = 0.091$, $\chi^2 = 19.177$, df = 2, $P < 0.001$). The canonical discriminant function explained 100% of the morphometric variance (canonical correlation = 0.953). Classification functions for each species are given in Table 4.12. Using the 'leave-one-out' cross validation method, 91.6% of the original 12 cases were classified correctly into their groups (75% for *Eusphyra blochii* and 100% *Sphyrna mokarran)* (Table 4.13).

Table 4.12 Classification function coefficients derived from Fisher's linear discriminant functions for MSG2.

	Eusphyra blochii	*Sphyrna mokarran*
P	438.07	140.873
Ah	62.856	22.014
(Constant)	-39.848	-5.058

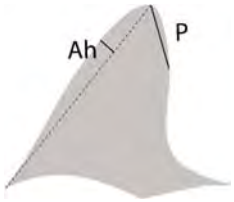
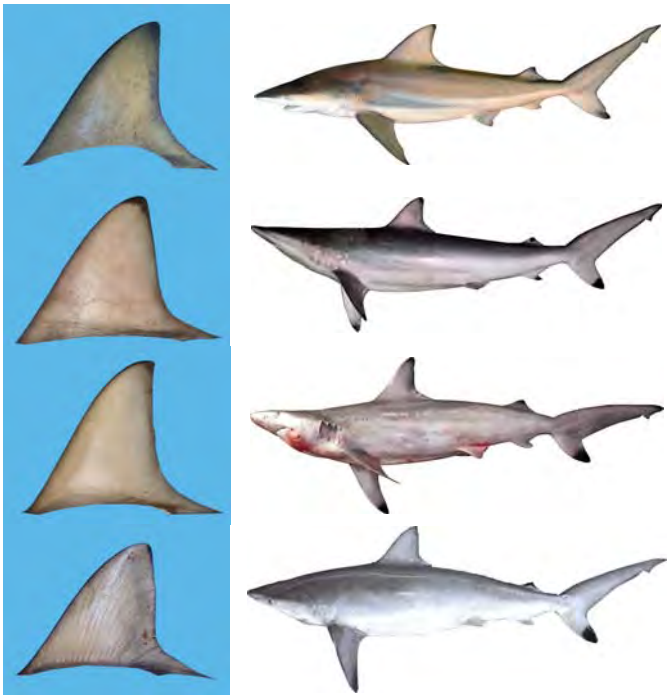


Table 4.13 Results of direct discriminant analysis of MSG2 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		Eusphyra blochii (%)	*Sphyrna mokarran* (%)	*n*	Global accuracy (%)
Original	*Eusphyra blochii*	**100**	.	4	**100**
	Sphyrna mokarran	.	**100**	8	
Cross-validated	*Eusphyra blochii*	**75**	25	4	**91.6**
	Sphyrna mokarran	.	**100**	8	

DAGRP3

Table 4.14 The four shark species, *Carcharhinus amblyrhynchoides*, *C. brevipinna*, *C. limb/tils* and *C. sorrah*, and number of dorsal fin samples (*n*), included in DAGRP3 analysed using discriminant analysis. DA groups column indicates the groups used in the DA procedure.

DAGRP3			
Species	*n*	DA Groups	
Carcharhinus amblyrhynchoides	19	CA	
Carcharhinus brevipinna	16	CB	
Carcharhinus limb/tils	56	CLT	
Carcharhinus sorrah	51	CS	

DAGRP3 consisted of 142 dorsal fin samples from four species, *Carcharhinus amblyrhynchoides*, *C. brevipinna*, *C. limb/tils* and *C. sorrah* (Table 4.14). The measurements C, F, G, H, I, J, N, O, P, Ah, Bh, and Dh were identified by stepwise DA as being most important for classifying these species (Figure 4.4). The discriminant index successfully distinguished between all species (Wilks' $\lambda = 0.025$, $\chi^2 = 433.878$, df = 36, $P < 0.001$). The first of three canonical discriminant function explained 57.9% of the variance (canonical correlation = 0.915), the second 35.3% (canonical correlation = 0.871) and the third 6.8% (canonical correlation = 0.614). Classification functions for each species are given in Table 4.15. Using the 'leave-one-out' cross validation method, 94.4% of the original 142 cases were classified correctly to species (100% for *Carcharhinus amblyrhynchoides*, 87.5% for *C. brevipinna*, 94.6% for *C. limb/tils* and 94.1% for *C. sorrah*, Table 4.16). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from functions 2 and 3 to visually represent how well these functions

differentiated each of the dorsal fin specimens (Figure 4.7). *Carcharhinus sorrah* formed a tight group to the right of the plot, and to the left of the three remaining species, which were more widely distributed and slightly intermingled (Figure 4.7). Of these three remaining species, *Carcharhinus limb/tils* occupied the upper part of the plot, while *C. brevipinna* and *C. amblyrhynchoides* the lower right and lower left portions, respectively (Figure 4.7). Therefore, function 1 differentiates *Carcharhinus sorrah*, *C. ambyrhynchoides* and *C. brevipinna* from each other, while function 2 differentiates *C. amblyrhynchoides* from *C. limb/tils*, and function 3 differentiates *C. brevipinna* from all other species (Figure 4.7).

Table 4.15 Classification function coefficients derived from Fisher's linear discriminant functions for DAGRP3.

	C. amblyrhynchoides	*C. brevipinna*	*C. limb/tils*	*C. sorrah*
C	63.452	61.330	121.994	48.601
F	874.853	872.091	790.846	888.941
G	1403.780	731.819	705.147	677.256
H	2189.708	1323.948	1082.006	1288.870
I	-1537.952	-953.167	-873.167	-857.271
J	583.203	437.989	433.465	348.968
N	294.269	173.516	147.160	218.634
O	-1257.525	-866.478	-698.719	-840.376
P	-1242.882	-826.549	-653.058	-747.628
Ah	-530.757	-372.978	-361.709	-414.267
Bh	-1583.247	-953.511	-785.731	-795.639
Dh	69.856	-51.161	-89.007	-78.052
(Constant)	-559.338	-527.168	-530.584	-569.045

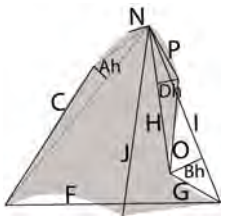


Table 4.16 Results of direct discriminant analysis of DAGRP3 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		CA	CB	CLT	CS	*n*	Global accuracy (%)
Original	*C. amblyrhynchoides*	**100**	.	.	.	19	**97.2**
	C. brevipinna	.	**93.8**	6.2	.	16	
	C. limb/tils	1.8	1.8	**96.4**	.	56	
	C. sorrah	.	2	.	**98**	51	
Cross-validated	*C. amblyrhynchoides*	**100**	.	.	.	19	**94.4**
	C. brevipinna	.	**87.5**	12.5	.	16	
	C. limb/tils	1.8	3.6	**94.6**	.	56	
	C. sorrah	.	5.9	.	**94.1**	51	

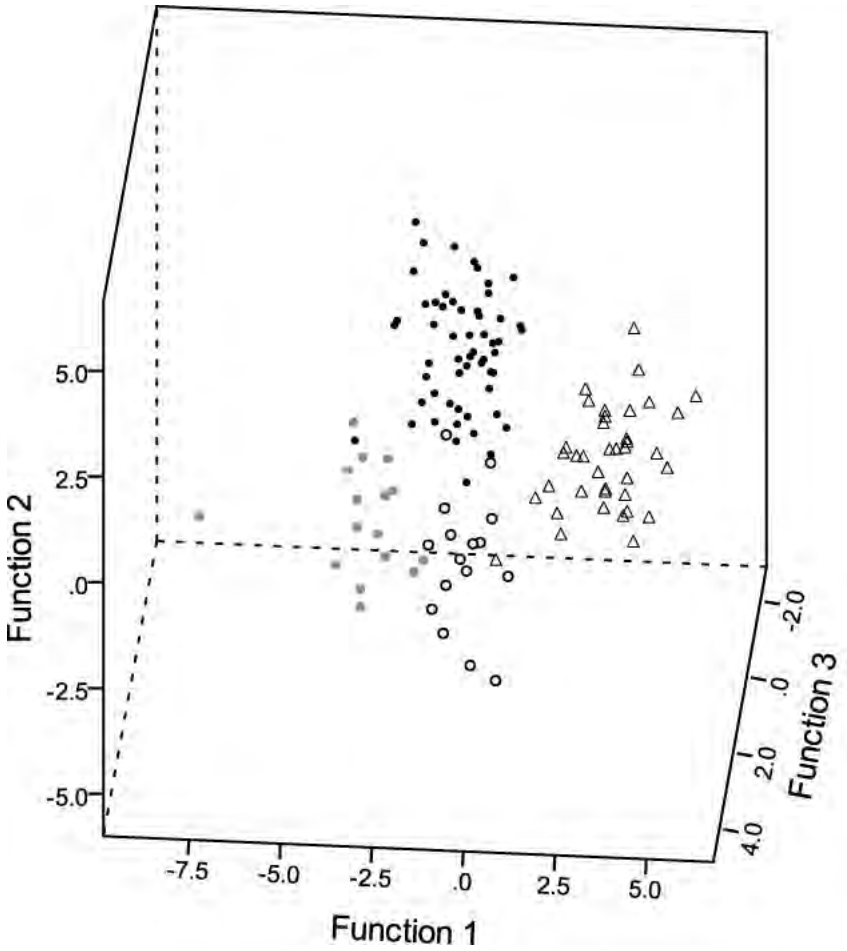


Figure 4.7 Three-dimensional plot of the first 3 discriminant functions from a canonical DA of morphological measurements from the dorsal fins of 142 dorsal fin samples from four known species of which DAGRP3 comprises. Symbols: ●, *Carcharhinus amblyrhynchoides*; ○, *C. brevipinna*; ●, *C. limbatus/tilstoni*; △, *C. sorrah*.

DAGRP4

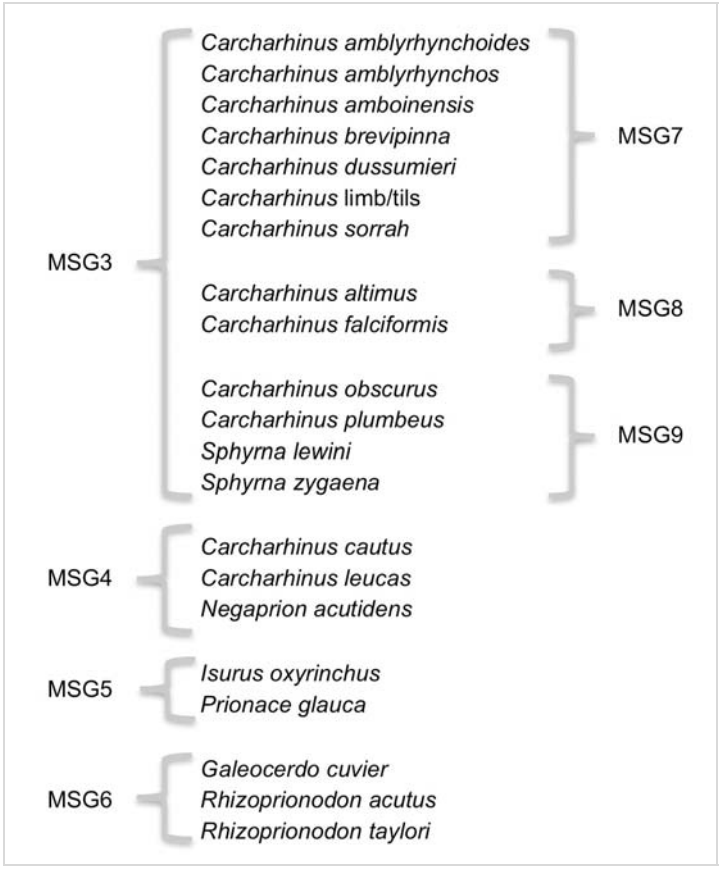


Figure 4.8 The 21 species groups included in DAGRP4 and their allocation to the four morphologically similar groups MSG3, MSG4, MSG5, and MSG6. MSG3 was further divided into three morphologically similar groups, MSG7, MSG8, and MSG9.

DAGRP4 consisted of 408 dorsal fin samples from 21 species (Figure 4.8). DAGRP4 was then partitioned into four morphologically similar groups MSG3, MSG4, MSG5, and MSG6, for further analysis (Figure 4.8). The colours Red, Green and Blue and the measurements A, C, D, F, I, J, K, L, Ah, Bh, and Dh were identified by stepwise DA as being most important in separating the four groups MSG3, MSG4, MSG5 and MSG6 (Figure 4.4). The discriminant index successfully distinguished between the four groups (Wilks' $\lambda = 0.01$; $\chi^2 = 1929.23$, df = 42, $P < 0.001$). The first canonical discriminant function explained 83.3% of the variance (canonical correlation = 0.972), the second canonical discriminant function explained 11.5% (canonical correlation = 0.837) and the third function explained 5.2% of the variance (canonical correlation = 0.716). Classification functions for each group are given in Table 4.17. Using the 'leave-one-out' cross validation method, 96.8% of the original 408 cases were classified correctly into their groups (96.6% for MSG3, 100%

for MSG4, 100% for MSG5, and 93.5% for MSG6, Table 4.18). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from functions 2 and 3 to visually represent how well these functions differentiated each of the dorsal fin specimens (Figure 4.9). MSG5 formed a tight group to the left of the plot, and to the right of the three remaining groups, which were more widely distributed and slightly intermingled (Figure 4.9). Of these three remaining groups, MSG3 and MSG6 occupied the upper middle and lower middle of the plot, respectively, while MSG4 was more widely distributed across the upper and lower right hand side of the plot (Figure 4.9). Therefore function 1 discriminates MSG5 from all other groups, function 2 discriminates MSG3 from MSG6, and function 3 discriminates MSG4 from MSG6 (Figure 4.9). Functions 2 and 3, in combination, best discriminate MSG3 from MSG4 (Figure 4.9).

Table 4.17 Classification function coefficients derived from Fisher's linear discriminant functions for DAGRP4.

	MSG3	MSG4	MSG5	MSG6
Red	1.661	1.684	0.828	1.697
Green	1.278	1.523	-0.652	0.907
Blue	-2.332	-2.553	-0.188	-2.035
A	-31210.000	-31090.000	-31060.000	-30890.000
C	2213.000	2188.000	2078.000	2291.000
D	1598.000	1598.000	1478.000	1663.000
F	32550.000	32430.000	32430.000	32280.000
I	-4076.000	-4080.000	-4157.000	-4063.000
J	8798.000	8719.000	9003.000	8851.000
K	-7217.000	-7142.000	-6979.000	-7312.000
L	238.605	251.373	12.643	184.427
Ah	724.683	663.241	777.374	678.820
Bh	34.021	-30.773	-21.783	-38.515
Dh	1480.000	1441.000	1391.000	1387.000
(Constant)	-16540.000	-16400.000	-16390.000	-16290.000

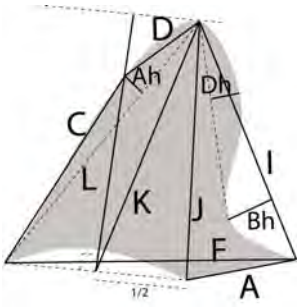


Table 4.18 Results of direct discriminant analysis of DAGRP4 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		MSG3	MSG4	MSG5	MSG6	*n*	Global accuracy (%)
Original	MSG3	**96.9**	3.1	.	.	295	**97.3**
	MSG4	.	**100**	.	.	55	
	MSG5	.	.	**100**	.	12	
	MSG6	4.3	.	.	**95.7**	46	
Cross-validated	MSG3	**96.6**	3.4	.	.	295	**96.8**
	MSG4	.	**100**	.	.	55	
	MSG5	.	.	**100**	.	12	
	MSG6	6.5	.	.	**93.5**	46	

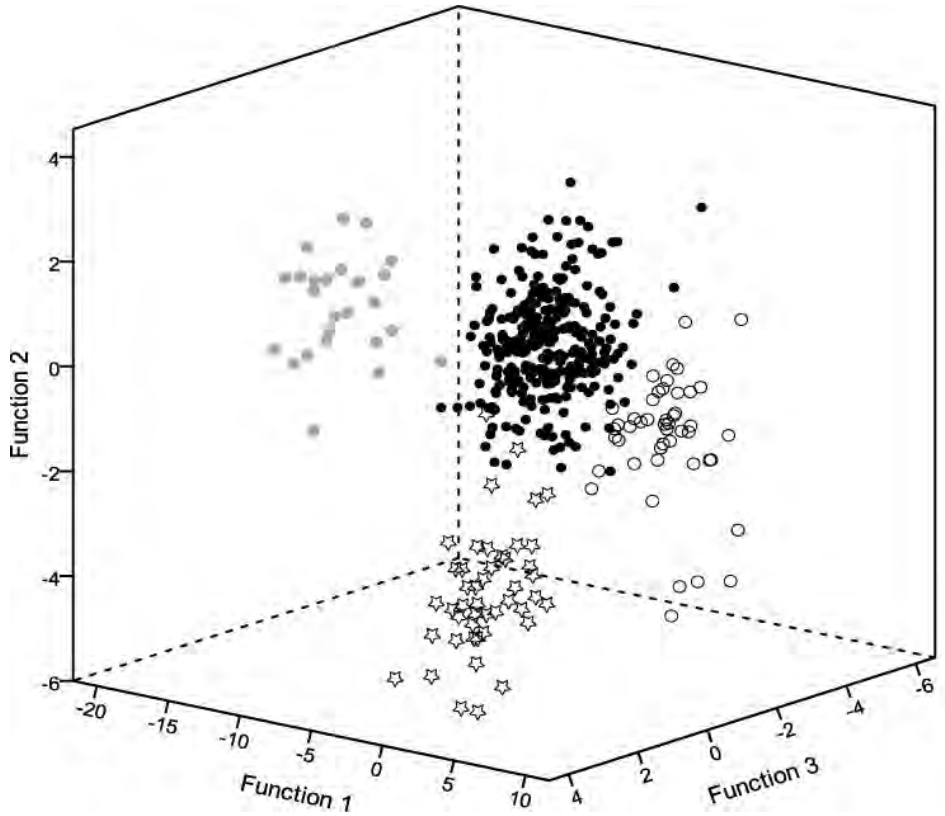


Figure 4.9 Three-dimensional plot of the first 3 discriminant functions from a canonical discriminant analysis of morphological measurements and colour data from the dorsal fins of 408 dorsal fin samples from four morphologically similar groups (● MSG3, ○MSG4, ●MSG5, ☆MSG6) of which DAGRP4 comprises.

MSG3

MSG3 consisted of 295 dorsal fin samples from 13 species. MSG3 was then partitioned into three morphologically similar groups MSG7, MSG8 and MSG9 for further analysis (Figure 4.8). The colours Red, Green and Blue and the measurements H, I, J, K, L, and R were identified by stepwise DA as being most important in separating these three groups (Figure 4.4). The discriminant index

successfully distinguished between the three groups (Wilks' $\lambda = 0.17$, $\chi^2 = 504.86$, df = 18, $P < 0.001$). The first canonical discriminant function explained 82.5% of the variance (canonical correlation = 0.855), the second canonical discriminant function explained 17.5% (canonical correlation = 0.605). Classification functions for each group are given in Table 4.19. Using the 'leave-one-out' cross validation method, 95.9% of the original 295 cases were classified correctly into their groups (95.8% for MSG7, 96.6% for MSG8, and 96.0% for MSG9, Table 4.20). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from function 2 to visually represent how well these functions differentiated each of the dorsal fin specimens (Figure 4.10). The samples from all three groups formed one cluster, in which each group occupied a distinct area with a slight intermingling of samples in the centre (Figure 4.10). Samples from MSG7 fell to the left side of the cluster, while samples from MSG8 and MSG9 fell to the lower right and upper right side of the plot, respectively (Figure 4.10). Therefore, function 1 differentiates MSG7 from MSG8 and MSG9, while function 2 differentiates MSG8 from MSG9 (Figure 4.10).

Table 4.19 Classification function coefficients derived from Fisher's linear discriminant functions for MSG3.

	MSG7	MSG8	MSG9
Blue	-0.613	-0.473	-0.521
Green	0.404	-0.125	-0.059
Red	0.899	1.138	1.151
H	-46.678	-37.268	-22.660
I	158.928	160.970	133.558
J	-194.390	-188.133	-202.286
K	164.108	182.415	135.336
L	-1.982	-36.616	66.838
R	23.542	35.415	28.493
(Constant)	-127.260	-117.542	-141.045

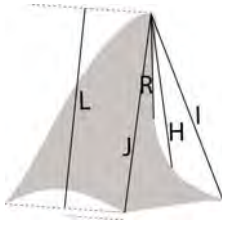


Table 4.20 Results of direct discriminant analysis of MSG3 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		MSG7	MSG8	MSG9	*n*	Global accuracy (%)
Original	MSG7	**96.8**	1.6	1.6	190	**96.6**
	MSG8	.	**96.6**	3.4	30	
	MSG9	2.7	1.3	**96**	75	
Cross-validated	MSG7	**95.8**	2.1	2.1	190	**95.9**
	MSG8	.	**96.6**	3.4	30	
	MSG9	2.7	1.3	**96**	75	

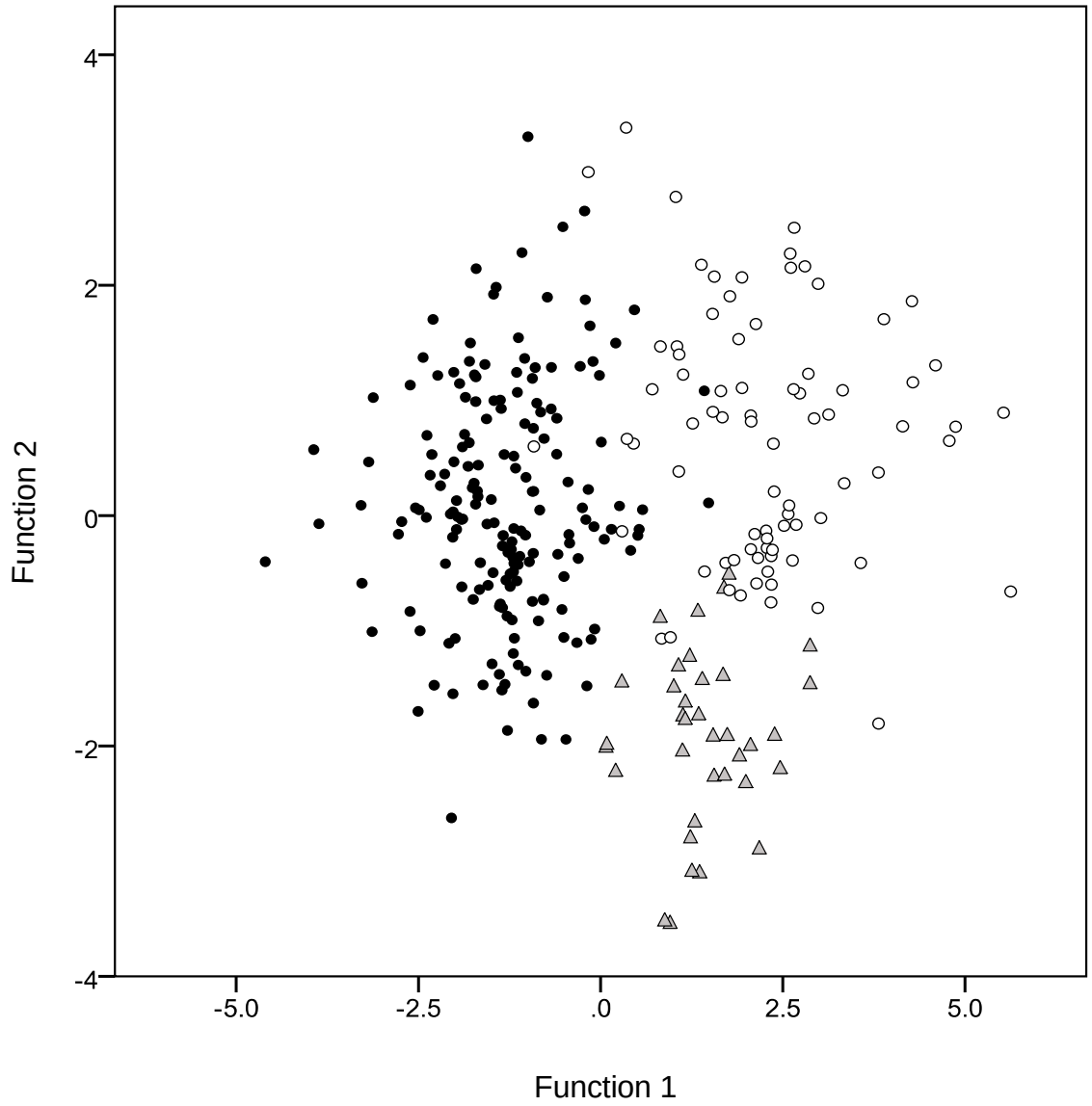
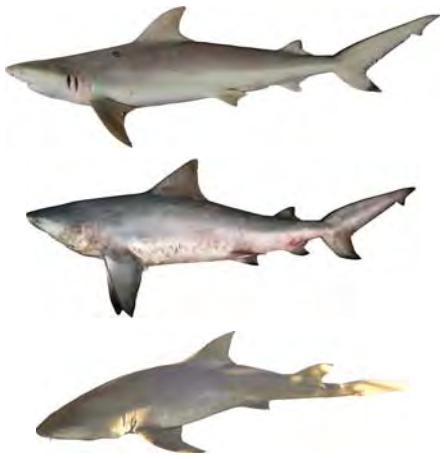


Figure 4.10 Two-dimensional plot of the first two discriminant functions derived from a canonical discriminant analysis, using morphological measurements and colour data, of 295 dorsal fin samples from the three morphologically similar groups (●MSG7, □MSG8, ○MSG9), derived from MSG3.

MSG4

Table 4.21 The three shark species *Carcharhinus cautus*, *C. leucas* and *Negaprion acutidens*, and number of dorsal fin samples (*n*), included in morphologically similar group 4 (MSG4) analysed using discriminant analysis.

MSG4			
Species	*n*		
Carcharhinus cautus	21		
Carcharhinus leucas	26		
Negaprion acutidens	8		

MSG4 consisted of 55 dorsal fin samples from 3 species *Carcharhinus cautus*, *C. leucas* and *Negaprion acutidens* (Table 4.21). The measurements A, O, Bh, and Dh were identified by stepwise DA as being most important in separating these three species (Figure 4.4). The discriminant index successfully distinguished between the three species (Wilks' $\lambda = 0.033$, $\chi^2 = 142.76$, df = 10, $P < 0.001$). The first canonical discriminant function explained 79.5% of the variance (canonical correlation = 0.946), the second canonical discriminant function explained 20.5% (canonical correlation = 0.828). Classification functions for each group are given in Table 4.22. Using the 'leave-one-out' cross validation method, 100% of the original 55 cases were classified correctly into their groups (100% for *Carcharhinus cautus*, *C. leucas* and *Negaprion acutidens*, respectively, Table 4.23). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from function 2 to visually represent how well these functions differentiated each of the dorsal fin specimens (Figure 4.11). Samples of *Carcharhinus leucas* formed a discrete group to the left of the plot, while the samples of *C. cautus* and *Negaprion acutidens* formed discrete groups to the upper and lower right, respectively (Figure 4.11). Therefore, function 1

clearly differentiated *Carcharhinus leucas*, while function 2 differentiated the remaining two groups, *C. cautus* and *Negaprion acutidens* from each other (Figure 4.11).

Table 4.22 Classification function coefficients derived from Fisher's linear discriminant functions for MSG4.

	Carcharhinus cautus	*Carcharhinus leucas*	*Negaprion acutidens*
Green	1.437	1.045	1.437
A	2.612	-18.463	81.274
O	82.085	92.705	14.653
Bh	243.650	130.400	198.368
Dh	327.827	413.779	96.883
(Constant)	-183.692	-103.214	-165.980

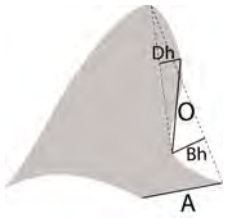


Table 4.23 Results of direct discriminant analysis of MSG4 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		CC	CL	NA	*n*	Global accuracy (%)
Original	*Carcharhinus cautus*	**100**	.	.	21	**100**
	Carcharhinus leucas	.	**100**	.	26	
	Negaprion acutidens	.	.	**100**	8	
Cross-validated	*Carcharhinus cautus*	**100**	.	.	21	**100**
	Carcharhinus leucas	.	**100**	.	26	
	Negaprion acutidens	.	.	**100**	8	

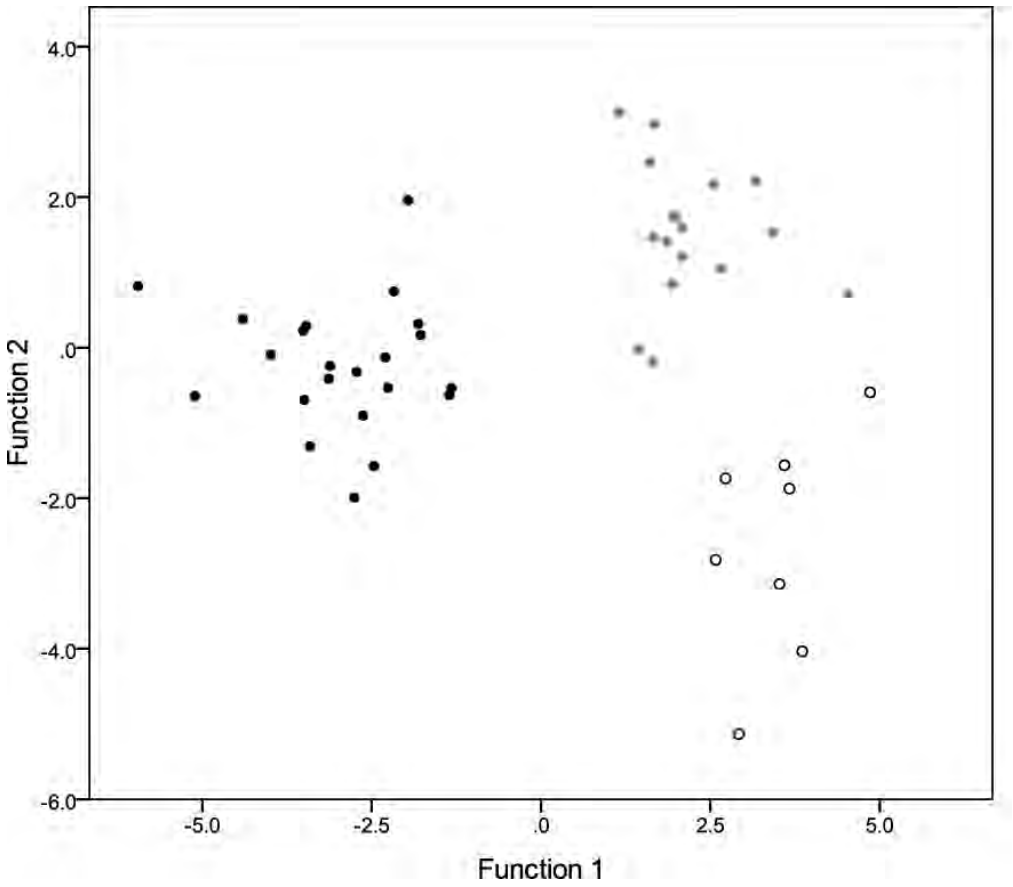


Figure 4.11 Two-dimensional plot of the first two discriminant functions derived from a canonical discriminant analysis, using morphological measurements and colour data, of 55 dorsal fin samples from the three species derived from MSG4 (●*Carcharhinus cautus*, ●*C. leucas* and ○*Negaprion acutidens*).

MSG5

Table 4.24 The two shark species *Isurus oxyrinchus* and *Prionace glauca*, and number of dorsal fin samples (*n*), included in morphologically similar group 5 (MSG5) analysed using discriminant analysis.

MSG5			
Species	*n*		
Isurus oxyrinchus	3		 Photos: W. White
Prionace glauca	9		

MSG5 consisted of 12 dorsal fin samples from two species *Isurus oxyrinchus* and *Prionace glauca* (Table 4.24). The measurements F and O were identified by stepwise DA as being most important for classifying these species (Figure 4.4). The discriminant index successfully distinguished between both species (Wilks' $\lambda = 0.015$, $\chi^2 = 96.684$, df = 2, $P < 0.001$). The first canonical discriminant function explained 100% of the variance (canonical correlation = 0.993). Classification functions for both species are given in Table 4.25. Using the 'leave-one-out' cross validation method, 100% of the original 12 cases were classified correctly into their species groups (100% for *Isurus oxyrinchus* and *Prionace glauca*, respectively, Table 4.26).

Table 4.25 Classification function coefficients derived from Fisher's linear discriminant functions for MSG5.

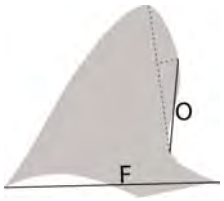
	Isurus oxyrinchus	*Prionace glauca*	
F	2627.83	3384.945	
O	-253.748	-378.483	
(Constant)	-1475.361	-2412.198	

Table 4.26 Results of direct DA of MSG5 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		Isurus oxyrinchus	*Prionace glauca*	*n*	Global accuracy (%)
Original	*Isurus oxyrinchus*	**100**	.	3	**100**
	Prionace glauca	.	**100**	9	
Cross-validated	*Isurus oxyrinchus*	**100**	.	3	**100**
	Prionace glauca	.	**100**	9	

MSG6

Table 4.27 The three shark species, *Galeocerdo cuvier*, *Rhizoprionodon acutus* and *Rhizoprionodon taylori*, and number of dorsal fin samples (*n*), included in morphologically similar group 6 (MSG6) analysed using discriminant analysis.

MSG6			
Species	*n*		
Galeocerdo cuvier	17		
Rhizoprionodon acutus	21		
Rhizoprionodon taylori	8		

MSG6 consisted of 46 dorsal fin samples from three species *Galeocerdo cuvier*, *Rhizoprionodon acutus* and *Rhizoprionodon taylori* (Table 4.27). During analysis, *R. acutus* and *R. taylori* could not be separated, and so were pooled to form species group '*Rhizoprionodon* spp.'. The colours Red and Blue and the measurements E and Bh were identified by stepwise DA as being most important for classifying these species (Figure 4.4). The discriminant index successfully distinguished between both species (Wilks' $\lambda = 0.119$, $\chi^2 = 89.406$, df = 4, $P < 0.001$). The first canonical discriminant function explained 100% of the variance (canonical correlation = 0.939). Classification functions for both species are given in Table 4.28. Using the 'leave-one-out' cross validation method, 100% of the original 46 cases were classified correctly into their species groups (100% for *Galeocerdo cuvier* and *Rhizoprionodon* spp., respectively, Table 4.29).

Table 4.28 Classification function coefficients derived from Fisher's linear discriminant functions for MSG6.

	Galeocerdo cuvier	*Rhizoprionodon* spp.
Red	1.955	1.657
Blue	-1.475	-1.018
E	399.136	298.317
Bh	-306.758	-187.147
(Constant)	-284.920	-199.688

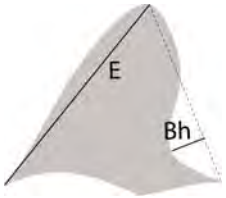


Table 4.29 Results of direct DA of MSG6 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		Galeocerdo cuvier	*Rhizoprionodon* spp.	*n*	Global accuracy (%)
Original	*Galeocerdo cuvier*	**100**	.	17	**100**
	Rhizoprionodon spp.	.	**100**	29	
Cross-validated	*Galeocerdo cuvier*	**100**	.	17	**100**
	Rhizoprionodon spp.	.	**100**	29	

MSG7

Table 4.30 The seven shark species *Carcharhinus amblyrhynchoides*, *C. amblyrhynchos*, *C. amboinensis*, *C. brevipinna*, *C. dussumieri*, *C. limb/tils* and *C. sorrah*, and number of dorsal fin samples (*n*), included in morphologically similar group 7 (MSG7) analysed using discriminant analysis.

MSG7			
Species	*n*		
Carcharhinus amblyrhynchoides	19		
Carcharhinus amblyrhynchos	15		
Carcharhinus amboinensis	14		
Carcharhinus brevipinna	16		
Carcharhinus dussumieri	19		
Carcharhinus limb/tils	56		
Carcharhinus sorrah	51		

MSG7 consisted of 190 dorsal fin samples from seven species *Carcharhinus amblyrhynchoides, C. amblyrhynchos, C. amboinensis, C. brevipinna, C. dussumieri, C. limb/tils,* and *C. sorrah* (Table 4.30). The colours Red, Green and Blue and the measurements A, C, E, H, J, K, L, R, and Bh were identified by stepwise DA as being most important for classifying these species (Figure 4.4). The discriminant index successfully distinguished between all seven species (Wilks' $\lambda = 0.015$, $\chi^2 = 96.684$, df = 2, $P < 0.001$). The first of six canonical discriminant functions explained 40.2% of the variance (canonical correlation = 0.894), the second 30.4% (canonical correlation = 0.867), the third

13.4% (canonical correlation = 0.756), the fourth 7.5% (canonical correlation = 0.652), the fifth 4.9% (canonical correlation = 0.574) and the sixth function explained 3.5% of the total variance (canonical correlation = 0.508). Classification functions for each of the seven species are given in Table 4.31. Using the 'leave-one-out' cross validation method, 88.9% of the original 190 cases were classified correctly to species (100% for *Carcharhinus amblyrhynchoides*, 66.7% *C. amblyrhynchos*, 85.7% for *C. amboinensis*, 87.5% for *C. brevipinna*, 89.5% for *C. dussumieri*, 85.7% for *C. limb/tils* and 96.1% for *C. sorrah*, Table 4.32). The discriminant scores for each sample for functions 1 to 6 are plotted in to visually represent how well these functions differentiated each of the dorsal fin specimens (Figure 4.12). Function 1 differentiates *Carcharhinus brevipinna*, *C. amboinensis*, and *C. amblyrhynchoides* from *C. dussumieri*, *C. sorrah*, and *C. amblyrhynchos*, as well as differentiating *C. dussumieri* from *C. limb/tils* (Figure 4.12). Function 2 differentiates, *C. dussumieri* from all species except *C. limb/tils*, as well as differentiating *C. limb/tils* from *C. brevipinna* (Figure 4.12). A combination of functions 3 and 4 differentiate *C. amblyrhynchoides* from *C. limb/tils*, while function 4 alone differentiates *C. sorrah* from *C. amblyrhynchos*, and *C. amblyrhynchoides* from *C. amboinensis* (Figure 4.12). Functions 6 and 7 differentiate *C. amboinensis* from *C. brevipinna* (Figure 4.12).

Table 4.31 Classification function coefficients derived from Fisher's linear discriminant functions for MSG7.

	C. am_ides	*C. am_chos*	*C. am_nsis*	*C. br_inna*	*C. du_ieri*	*C. limb/tils*	*C. sorrah*
Red	0.28	0.11	0.48	0.86	0.14	0.22	0.13
Green	3.14	3.68	2.40	2.21	4.09	3.27	3.36
Blue	-1.74	-2.29	-1.44	-1.51	-2.20	-1.78	-1.90
A	-237.02	-167.31	-235.89	-197.25	-193.45	-251.40	-176.06
C	626.05	628.13	653.43	622.09	674.99	673.51	629.82
E	6751.40	6740.73	6806.56	6803.03	6730.11	6717.70	6802.51
H	-303.63	-194.90	-209.83	-243.61	-204.11	-261.39	-182.34
J	6601.09	6483.13	6567.16	6543.86	6620.30	6588.71	6600.76
K	-10371.76	-10372.46	-10423.11	-10447.72	-10240.90	-10335.21	-10453.43
L	-1848.96	-1845.86	-1891.11	-1848.44	-2088.15	-1899.09	-1955.29
R	-19.44	-12.69	-33.45	-11.78	-17.32	-21.50	-7.01
Bh	318.81	348.08	293.87	309.71	374.67	420.34	388.99
(Cons.)	-1671.16	-1641.37	-1654.91	-1642.75	-1774.88	-1700.55	-1669.64

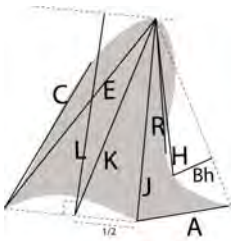


Table 4.32 Results of direct discriminant analysis of MSG7 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		CAI	CRO	CN	CB	CD	CLT	CS	*n*	Global accuracy (%)
Original	*C. amblyrhynchoides*	**100**							19	
	C. amblyrhynchos		**86.7**					13.3	15	
	C. amboinensis			**92.9**				7.1	14	
	C. brevipinna		6.2	6.2	**87.5**				16	**94.2**
	C. dussumieri					**100**			19	
	C. limb/tils	3.6	1.8	1.8	1.8	1.8	**89.3**		56	
	C. sorrah							**100**	51	
Cross-validated	*C. amblyrhynchoides*	**100**							19	
	C. amblyrhynchos		**66.7**			11.1		22.2	15	
	C. amboinensis	7.1		**85.7**				7.1	14	
	C. brevipinna		6.2	6.2	**87.5**				16	**88.9**
	C. dussumieri					**89.5**	5.3	5.3	19	
	C. limb/tils	3.6	1.8	3.6	3.6	1.8	**85.7**		56	
	C. sorrah			2	2			**96**	51	

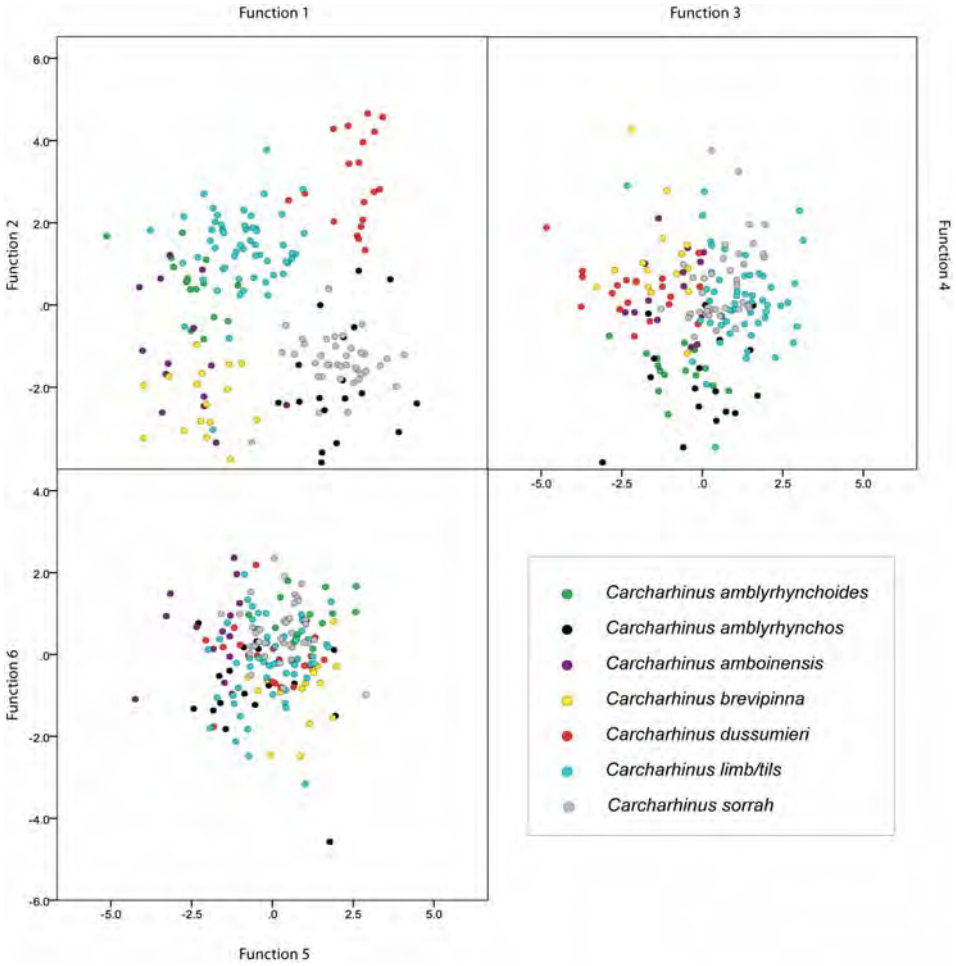
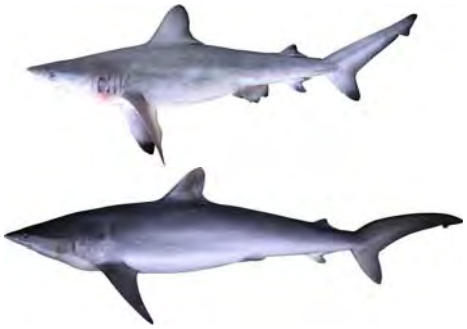


Figure 4.12 Three two-dimensional plots of the first six discriminant functions derived from a canonical discriminant analysis, using morphological measurements and colour data, of 190 dorsal fin samples from the seven species derived from MSG7.

MSG8

Table 4.33 The two shark species *Carcharhinus altimus* and *C. falciformis*, number of dorsal fin samples (*n*), included in morphologically similar group 8 (MSG8) analysed using discriminant analysis.

MSG8			
Species	*n*		
Carcharhinus altimus	15		
Carcharhinus falciformis	15		

MSG8 consisted of 30 dorsal fin samples from two species *Carcharhinus altimus* and *C. falciformis* (Table 4.33). The measurements H, J, L, Bh, and Dh were identified by stepwise DA as being most important for classifying these species (Figure 4.4). The discriminant index successfully distinguished between both species (Wilks' $\lambda = 0.305$, $\chi^2 = 152.488$, df = 5, $P < 0.001$). The first canonical discriminant function explained 100% of the variance (canonical correlation = 0.834). Classification functions for both species are given in Table 4.34. Using the 'leave-one-out' cross validation method, 93.3% of the original 30 cases were classified correctly into their species groups (93.3% for both *Carcharhinus altimus* and *C. falciformis*, respectively, Table 4.35).

Table 4.34 Classification function coefficients derived from Fisher's linear discriminant functions for MSG8.

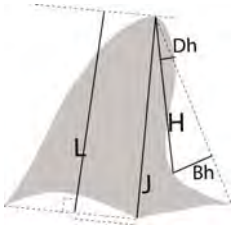
	Carcharhinus altimus	*Carcharhinus falciformis*	
H	-118.874	-43.621	
J	104.061	-158.282	
L	448.897	631.777	
Bh	-25.430	33.092	
Dh	-0.809	38.216	
(Constant)	-226.256	-219.872	

Table 4.35 Results of direct discriminant analysis of MSG8 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		Carcharhinus altimus	*Carcharhinus falciformis*	*n*	Global accuracy (%)
Original	*Carcharhinus altimus*	**93.3**	6.7	15	**93.3**
	Carcharhinus falciformis	6.7	**93.3**	15	
Cross-validated	*Carcharhinus altimus*	**93.3**	6.7	15	**93.3**
	Carcharhinus falciformis	6.7	**93.3**	15	

MSG9

Table 4.36 The two shark species *Carcharhinus altimus* and *C. falciformis*, and number of dorsal fin samples (*n*), included in morphologically similar group 9 (MSG9) analysed using discriminant analysis.

MSG9			
Species	*n*		
Carcharhinus obscurus	38		
Carcharhinus plumbeus	11		
Sphyrna lewini	15		
Sphyrna zygaena	11		

MSG9 consisted of 75 dorsal fin dorsal fin samples from four species *Carcharhinus obscurus*, *C. plumbeus*, *Sphyrna lewini*, and *S. zygaena* (Table 4.36). The colour Red and the measurements A, C, E, G, I, K, O, Ah, Bh, and Eh were identified by stepwise DA as being most important for classifying these species (Figure 4.4). The discriminant index successfully distinguished between all

species (Wilks' $\lambda = 0.015$, $\chi^2 = 295.534$, df = 33, $P < 0.001$). The first of three canonical discriminant function explained 76.8% of the variance (canonical correlation = 0.953), the second 15.7% (canonical correlation = 0.819) and the third 7.5% (canonical correlation = 0.703). Classification functions for each species are given in Table 4.37. Using the 'leave-one-out' cross validation method, 93.3% of the original 75 cases were classified correctly into their species groups (100% for *Carcharhinus obscurus*, 100% for *C. plumbeus*, 86.7% for *Sphyrna lewini* and 72.7% for *S. zygaena*, Table 4.38). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from functions 2 and 3 (Figure 4.13).

Table 4.37 Classification function coefficients derived from Fisher's linear discriminant functions for MSG9.

	C. obscurus	*C. plumbeus*	*S. lewini*	*S. zygaena*
Red	1.125	1.431	1.329	1.206
A	-540.466	-620.096	-655.959	-714.317
C	165.827	222.763	195.147	242.174
E	2540.228	2389.575	2533.696	2464.608
G	243.874	370.633	371.902	403.823
I	899.740	830.443	785.196	774.618
K	-2856.388	-2655.808	-2663.908	-2611.773
O	67.809	94.452	86.148	96.029
Ah	-239.748	-289.006	-396.004	-349.883
Bh	230.163	171.342	144.568	167.328
Eh	498.197	493.575	609.501	609.473
(Constant)	-780.134	-853.146	-912.082	-915.099

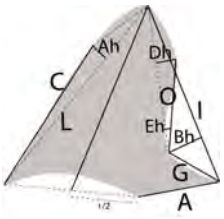


Table 4.38 Results of direct DA of MSG9 based on morphometric measurements for both the original model (including all cases) and the cross-validated model (leave-one-out classification). Bold indicates percent correctly classified.

		CO	CP	SL	SZ	*n*	Global accuracy (%)
Original	*Carcharhinus obscurus*	**100**	.	.	.	38	**98.7**
	Carcharhinus plumbeus	.	**100**	.	.	11	
	Sphyrna lewini	.	.	**100**	.	15	
	Sphyrna zygaena	.	.	9.1	**90.9**	11	
Cross-validated	*Carcharhinus obscurus*	**100**	.	.	.	38	**93.3**
	Carcharhinus plumbeus	.	**100**	.	.	11	
	Sphyrna lewini	.	.	**86.7**	13.3	15	
	Sphyrna zygaena	.	.	27.3	**72.7**	11	

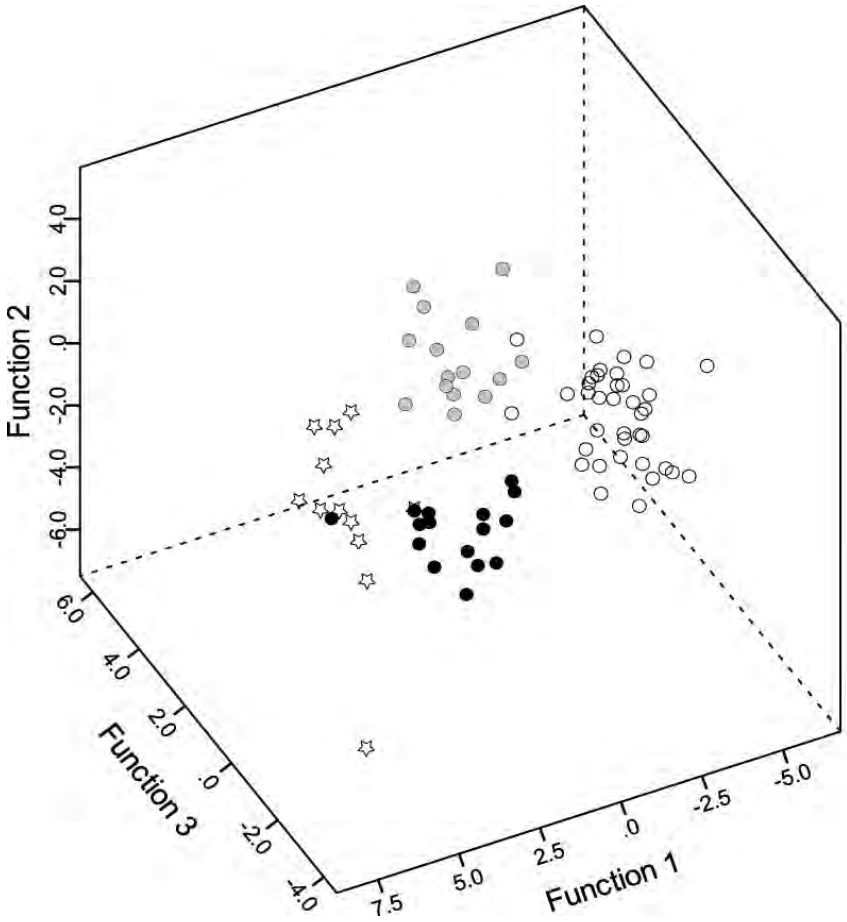


Figure 4.13 Three-dimensional plot of the first three discriminant functions derived from a canonical discriminant analysis, using morphological measurements and colour data, of 75 dorsal fin samples from the four species (○ *Carcharhinus obscurus*, ● *C. plumbeus*, ● *Sphyrna lewini*, ☆ *S. zygaena*) of which MSG9 comprises.

Validation of the Classification Procedure

Of the 93 'unknown' dorsal fins used as 'testing' samples, 80.4% could be correctly identified to species, or species group, using the morphological identification protocol developed in this chapter (Table 4.39). Of the 15 species, or species groups, which could be identified using molecular techniques, 11 had a high proportion (≥80%) of correctly classified samples (Table 4.39). The remaining four species, *Carcharhinus brevipinna*, *C. limb/tils*, *Rhynchobatus* spp., and *Sphyrna lewini* produced lower classification values with 50, 66.7, 0, and 50% correctly classified, respectively. When these species were misclassified *Carcharhinus brevipinna* and *C. limb/tils* were most often misclassified as *C. amblyrhynchoides*, *Rhynchobatus* spp. was most often misclassified

as *Sphyrna mokarran*, and *S. lewini* was misclassified as both *C. sorrah* and *S. zygaena* (Table 4.39).

When only the 64 'unknown' dorsal fin samples with a resulting posterior probability of correct classification of > 0.90 were considered (see section 4.2.5), the proportion of samples that could be correctly identified to species, or species group, increased to 84.4% (Table 4.40). Of the 14 species, or species groups, which could be identified using molecular techniques, 11 had a high proportion (≥80%) of correctly classified samples (Table 4.40). The remaining three species, *Carcharhinus brevipinna*, *C. limb/tils*, and *Sphyrna lewini* produced lower classification values with 50, 66.7, and 50% correctly classified, respectively. When these species were misclassified *Carcharhinus brevipinna* and *C. limb/tils* were most often misclassified as *C. amblyrhynchoides*, and *S. lewini* was misclassified as *S. zygaena* (Table 4.40).

Table 4.39 Contingency table of the classification results (%) of testing samples that were classified using both the morphological procedure (columns) and the genetic procedure (rows). Bold indicates the percent of samples correctly classified. Grey indicates species that could not be isolated using the genetic procedure and so were grouped together as a species complex (see section 4.2.1. 'Rationale for the Allocation of Training and Testing Samples').

Genetic ID \ Morphological ID	*Carcharhinus albimarginatus*	*Carcharhinus altimus*	*Carcharhinus altimus/plumbeus*	*Carcharhinus amblyrhynchoides*	*Carcharhinus amblyrhynchos*	*Carcharhinus amboinensis*	*Carcharhinus brevipinna*	*Carcharhinus cautus*	*Carcharhinus dussumieri*	*Carcharhinus falciformis*	*Carcharhinus leucas*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*	*Carcharhinus limb/tils*	*Carcharhinus obscurus*	*Carcharhinus plumbeus*	*Carcharhinus sorrah*	*Galeocerdo cuvier*	*Rhynchobatus sp.*	*Sphyrna lewini*	*Sphyrna mokarran*	*Sphyrna zygaena*	*n*	Total % Correct
Carcharhinus albimarginatus	**85.7**	.	.	.	14.3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	7	
Carcharhinus altimus	.	**100**	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2	
Carcharhinus altimus/plumbeus	.	**18.2**	.	.	.	.	9.1	.	.	.	.	.	.	.	**72.7**	.	.	.	.	.	.	11	
Carcharhinus amblyrhynchoides	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Carcharhinus amblyrhynchos	.	.	.	.	**100**	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	
Carcharhinus amboinensis	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Carcharhinus brevipinna	.	.	.	50	.	.	**50**	.	.	.	.	.	.	.	.	.	.	.	.	.	.	4	
Carcharhinus cautus	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Carcharhinus dussumieri	.	.	.	.	.	.	.	12.5	**87.5**	.	.	.	.	.	.	.	.	.	.	.	.	8	
Carcharhinus falciformis	.	.	.	.	.	.	.	.	.	**100**	.	.	.	.	.	.	.	.	.	.	.	7	
Carcharhinus leucas	.	.	.	.	.	.	.	.	.	.	**100**	.	.	.	.	.	.	.	.	.	.	1	**80.4**
Carcharhinus limbatus/tilstoni/amblyrhynchoides	.	.	.	**37.5**	.	12.5	.	.	.	.	.	.	**50**	.	.	.	.	.	.	.	.	8	
Carcharhinus limb/tils	.	.	.	33.3	.	.	.	.	.	.	.	.	**66.7**	.	.	.	.	.	.	.	.	15	
Carcharhinus obscurus	.	20	.	.	.	.	.	.	.	.	.	.	.	**80**	.	.	.	.	.	.	.	10	
Carcharhinus plumbeus	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Carcharhinus sorrah	.	.	.	.	.	.	20	.	.	.	.	.	.	.	.	**80**	.	.	.	.	.	10	
Galeocerdo cuvier	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	**100**	.	.	.	.	3	
Rhynchobatus sp.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	100	.	1	
Sphyrna lewini	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	25	.	.	**50**	.	25	4	
Sphyrna mokarran	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Sphyrna zygaena	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
																						92	

Table 4.40 Contingency table of the classification results (%) of testing samples that were classified using both the morphological procedure (columns) and the genetic procedure (rows). The data in this table consists of specimens for which the morphological classification resulted in a posterior probability of > 0.9. Bold indicates the percent of samples correctly classified. Grey indicates species that could not be isolated using the genetic procedure and so were grouped together as a species complex (see section 4.2.1. 'Rationale for the Allocation of Training and Testing Samples').

Genetic ID \ Morphological ID	*Carcharhinus albimarginatus*	*Carcharhinus altimus*	*Carcharhinus altimus/plumbeus*	*Carcharhinus amblyrhynchoides*	*Carcharhinus amblyrhynchos*	*Carcharhinus brevipinna*	*Carcharhinus dussumieri*	*Carcharhinus falciformis*	*Carcharhinus leucas*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*	*Carcharhinus limb/tils*	*Carcharhinus obscurus*	*Carcharhinus plumbeus*	*Carcharhinus sorrah*	*Galeocerdo cuvier*	*Sphyrna lewini*	*Sphyrna zygaena*	*n*	Total % Correct
Carcharhinus albimarginatus	**85.7**	.	.	.	14.3	.	.	.	.	.	.	.	.	.	.	.	.	7	
Carcharhinus altimus	.	**100**	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	
Carcharhinus altimus/plumbeus	.	.	.	.	.	.	.	.	.	.	.	.	**100**	.	.	.	.	6	
Carcharhinus amblyrhynchoides	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Carcharhinus amblyrhynchos	.	.	.	.	**100**	.	.	.	.	.	.	.	.	.	.	.	.	1	
Carcharhinus brevipinna	.	.	.	100	.	.	.	.	.	.	.	.	.	.	.	.	.	2	
Carcharhinus dussumieri	.	.	.	.	.	.	**100**	.	.	.	.	.	.	.	.	.	.	6	
Carcharhinus falciformis	.	.	.	.	.	.	.	**100**	.	.	.	.	.	.	.	.	.	3	
Carcharhinus leucas	.	.	.	.	.	.	.	.	**100**	.	.	.	.	.	.	.	.	1	**84.4**
Carcharhinus limbatus/tilstoni/amblyrhynchoides	.	.	.	**50**	.	.	.	.	.	.	**50**	.	.	.	.	.	.	6	
Carcharhinus limb/tils	.	.	.	40	.	.	.	.	.	.	**60**	.	.	.	.	.	.	10	
Carcharhinus obscurus	.	16.7	.	.	.	.	.	.	.	.	.	**83.3**	.	.	.	.	.	6	
Carcharhinus plumbeus	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Carcharhinus sorrah	.	.	.	.	.	11.1	.	.	.	.	.	.	.	**88.9**	.	.	.	9	
Galeocerdo cuvier	.	.	.	.	.	.	.	.	.	.	.	.	.	.	**100**	.	.	3	
Sphyrna lewini	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	**66.7**	33.3	3	
Sphyrna zygaena	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
																		64	

4.3.2 Estimating Shark Size

For each of the 35 species that had associated length data for more than one specimen, the correlation coefficient (r^2) and a regression equation, for predicting TL from B, were calculated (Table 4.41). The relationships between fin base length (B) and total length (TL) for each shark species showed significant ($P \leq 0.5$) positive linear relationship (Table 4.41). For 34 of the 35 species, a high amount of variance was explained with the linear function ($r^2 = 0.83–1.00$). The remaining species, *Carcharhinus dussumieri*, had a smaller r^2 value of 0.76.

Table 4.41 Total length-dorsal fin base length relationships (sexes combined) for each species (for which there was sufficient data). TL, total length (cm); BL, dorsal fin base length (mm); *n*, number of samples; r^2, coefficient of determination based on linear regression of (TL) against (BL); SE, standard error of the estimate. 'Known' corresponds to whole samples of known species and total length. 'Photo' corresponds to samples derived from photographs of whole animals.

				n		
Species	Equation	SE	r^2	Known	Photo	Total
Alopias superciliosus	TL = 9.79BL + 12.31	(± 73.0)	0.967	.	15	15
Carcharhinus albimarginatus	TL = 0.82BL + 25.45	(± 7.8)	0.942	24	.	24
Carcharhinus altimus	TL = 0.80BL + 11.88	(± 11.5)	0.974	3	4	7
Carcharhinus amblyrhynchoides	TL = 0.76BL + 10.80	(± 4.9)	0.97	12	.	12
Carcharhinus amblyrhynchos	TL = 0.79BL + 26.67	(± 6.1)	0.961	15	.	15
Carcharhinus amboinensis	TL = 0.78BL + 9.86	(± 11.7)	0.938	13	.	13
Carcharhinus brevipinna	TL = 0.95BL + 8.12	(± 6.8)	0.973	21	.	21
Carcharhinus cautus	TL = 0.82BL + 18.66	(± 7.6)	0.932	10	.	10
Carcharhinus dussumieri	TL = 0.89BL + 10.52	(± 3.9)	0.756	20	.	20
Carcharhinus falciformis	TL = 1.02BL + 29.18	(± 19.3)	0.92	18	.	18
Carcharhinus leucas	TL = 0.79BL + 10.97	(± 21.7)	0.901	22	.	22
Carcharhinus limb/tils	TL = 1.04BL – 8.39	(± 16.3)	0.962	46	.	46
Carcharhinus longimanus	TL = 0.82BL + 6.09	(± 10.5)	0.96	.	5	5
Carcharhinus melanopterus	TL = 0.88BL + 16.89	(± 8.4)	0.881	8	.	8
Carcharhinus obscurus	TL = 1.23BL - 6.90	(± 35.1)	0.855	7	.	7
Carcharhinus plumbeus	TL = 0.66BL + 17.55	(± 13.1)	0.89	3	8	11
Carcharhinus sorrah	TL = 0.88BL + 19.47	(± 7.0)	0.931	44	.	44
Eusphyra blochii	TL = 0.95BL + 2.35	(± 6.0)	0.991	3	1	4
Galeocerdo cuvier	TL = 0.92BL + 35.17	(± 6.1)	0.995	19	.	19
Hemigaleus australiensis	TL = 0.85BL + 16.08	(± 6.5)	0.903	4	.	4
Isurus oxyrinchus	TL = 1.07BL + 1.63	(± 6.9)	0.982	1	5	6
Negaprion acutidens	TL = 1.10BL + 1.56	(± 11.9)	0.984	5	.	5
Prionace glauca	TL = 11.27BL + 69.20	(± 57.6)	0.909	.	15	15
Rhina ancylostoma	TL = 0.97BL + 35.06	(± 11.4)	0.968	6	.	6
Rhina ancylostoma D2	TL = 1.48BL + 16.44	(± 6.2)	0.99	6	.	6
Rhizoprionodon spp.	TL = 0.84BL + 18.84	(± 5.9)	0.866	12	.	12
Rhynchobatus spp.	TL = 1.33BL + 12.16	(± 2.8)	0.997	12	.	12
Rhynchobatus spp. D2	TL = 1.85BL + 14.15	(± 7.1)	0.983	13	.	13
Sphyrna lewini	TL = 0.93BL + 4.66	(± 5.1)	0.99	12	.	12
Sphyrna mokarran	TL = 0.80BL + 26.96	(± 4.1)	0.997	4	.	4
Sphyrna zygaena	TL = 10.25BL + 8.82	(± 41.6)	0.972	2	7	9
Triaenodon obesus	TL = 1.19BL + 4.78	(± 8.7)	0.962	2	4	6
				380	64	444

4.4 Discussion

4.4.1 Evaluation of the Procedure

Of the 40 groups[3] analysed using 13 separate discriminant analysis models, 37 groups (92.5%) had more than 80% of their specimens correctly classified during the cross validation (leave-one-out) procedure. Additionally, when the entire identification procedure was used to identify dorsal fin specimens sourced from foreign fishing vessels, 80.4% of all specimens were identified correctly. Furthermore, 84.4% of fins were identified correctly when only specimens with a resulting probability of group membership of > 0.9 were considered. Such findings demonstrate how fins can be used to identify the species composition of a catch in the absence of whole specimens. These results also indicate that morphological characters can be confidently (> 80% accuracy) used to identify most northern Australian sharks from their dorsal fins. In the case of many northern Australian commercial shark fisheries, where shark species are still reported in broad categories (such as 'black tip'), and logbook data is questionable, a species classification accuracy of 80% correct species would be a vast improvement on accuracy. As the models could not be tested using a full range of unknown species this is not a complete verification of the methods. However, the results indicate that accurate species identifiations can be obtained (using actual FFV specimens) and that it would be worthwile to conduct a larger verification study, given adequate resources to do so. A broader verification study using a greater number of samples may even result in improved levels of classification and would more accurately pinpoint which species are the most difficult to identify correctly.

The species that did not perform well in the cross validation (leave-one-out) procedure were *Carcharhinus amblyrhynchos*, *Eusphyra blochii*, and *Sphyrna zygaena*, with 66.7, 75, and 72.7% of specimens correctly classified, respectively. While these percentages are still high, to prevent incorrect classification, other prominent features or visual characters can be used in conjunction

[3] In this instance, 'groups' refer to each time a group was analysed in one of the 13 discriminant analysis models. This number includes species that were analysed in more than one DA model as well as MSGs that were analysed in the DA models.

with this method. In many instances illegal Indonesian fishing operators will group the fins of single sharks together in a bundle containing not only the dorsal fin but also the pectoral and lower caudal fins (Figure 4.14). When this occurs, prominent colour features can be used to assist in the identification process. For instance, *Carcharhinus amblyrhynchos* can be easily discriminated from other species in the family Carcharhinidae by the presence of a black bar on the posterior margin of the caudal fin. Alternatively, when fins are not tied together, denticles on the skin may be used (see Chapter 3) as supporting evidence with which to conclusively identify *C. amblyrhynchos*. *Eusphyra blochii* may have performed less well in the discriminant analysis because of low sample numbers (*n*=4). More specimens of *E. blochii* should be collected to determine if this is the case. In the case of *Sphyrna zygaena*, this species of hammerhead was most often (27.3% of cases) misclassified as a similar hammerhead species, *S. lewini*. *Sphyrna zygaena* and *S. lewini* can alternatively be differentiated using the pectoral fins, with *S. lewini* having a clearly demarcated black tip on the ventral side of the pectoral fin, while *S. zygaena* has no markings, or slightly dusky markings, on the ventral side of the pectoral fin (Figure 4.15).

Figure 4.14 An ‘unknown’ fin set, from the seized catch of an Indonesian fishing vessel that was apprehended fishing illegally in northern Australian waters. The image shows how fins from the same shark (in this case the dorsal, lower caudal and left and right pectoral fins from a tiger shark (*Galeocerdo cuvier*)) are often tied together for drying.

When the morphological identifications of the 15 species from the 'testing' group were compared to their respective genetic identifications, 12 groups had more than 80% of their specimens classified correctly. Overall, 80.4% of the 93 'testing' dorsal fin specimens were correctly classified to species. The three species groups that performed less well were *Carcharhinus brevipinna*, *C. limb/tils*, and *Sphyrna lewini*, with 50, 66.7, and 50% correctly classified, respectively. The species *Carcharhinus brevipinna* and *C. limb/tils* experience a change in dorsal fin colouration with growth. As such, smaller specimens of *C. brevipinna* (< 80 cm TL) show no fin tip colouration, while larger specimens have a distinct dark tip on the dorsal fin. Conversely, *Carcharhinus limbatus* shows an opposite pattern, with distinct black tips on smaller specimens (< 100 cm TL) and very faint, or absent tip colouration on larger specimens. As the difference in dorsal fin shape and colour between size classes within the same species was not considered in the scope of this study, these differences may have contributed to the low classification scores of these species. Therefore, to strengthen the classification procedure, ontogenetic differences in fin shape and colour should be considered and incorporated in future studies.

When dorsal fin specimens from the two species *Carcharhinus brevipinna* and *C. limb/tils* were misclassified, they were misclassified as *C. amblyrhynchoides*. Even for scientists who are familiar with the family Carcharhinidae, these three species are difficult to distinguish as whole specimens. Furthermore, when these species are examined using cytochrome oxidase c subunit 1 (otherwise known as CO1 or 'barcode of life') molecular sequencing, they are often identified as the species complex *Carcharhinus amblyrhynchoides/limbatus/tilstoni*, as this provides greater confidence than when the specimens are identified to species individually (Salini, *et al.* 2007a). In other words, these species are often misclassified as each other, even when using genetic techniques. The same technique of grouping these species as a species complex could be applied to the morphological identification protocol to provide greater confidence for the identifications of this group. Preliminary investigation of fin tip colour indicates that the pattern of dorsal fin tip colouration may be of use when separating the species *C. amblyrhynchoides*, *C. brevipinna*,

C. limbatus, and *C. tilstoni*, however more specimens are needed to confirm this observation. As the identification of these commonly caught northern Australian species is currently an issue for management, further investigation is warranted.

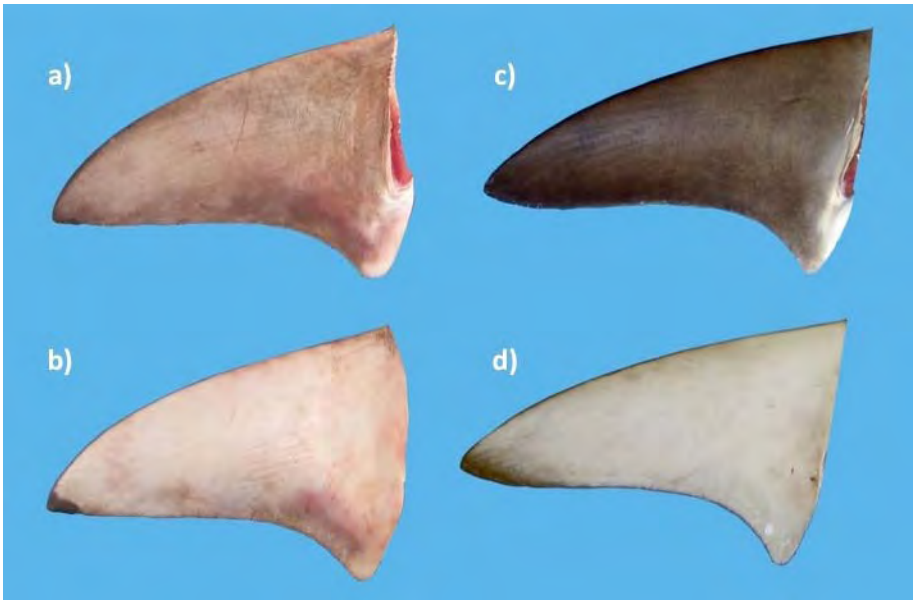


Figure 4.15 The left pectoral fins from two species of hammerhead shark, a) *Sphyrna lewini* dorsal view and b) ventral view; c) *Sphyrna zygaena* dorsal view and d) ventral view.

The most useful character for separating species during the discriminant analysis procedure was 'Bh' (posterior margin height), which was used in eight of the 13 discriminant analysis models. This was followed by 'J' (fin height), and 'Red', which were both used in six discriminant analysis models, and 'L' (absolute fin height), 'Blue', and 'Green', which were used in five discriminant analysis models. All colours and measurements except 'M', 'Q', and 'Ch' were used during the procedure. From these results, it is clear that fin colour is a useful character for separating the shark species investigated in this study. This was not considered at the onset of this study, therefore future studies should incorporate the colour standardisation techniques such as incorporating a Kodak Colour Bar™ or Munsell ColorChecker™ in each image. The standard blue mat worked well as a colour calibration device in this study, however the mat is also subject to changes in colour from dirt or wetness. During this study, care was taken to sample only the clean, dry areas of the blue

mat, however future studies should incorporate a colour calibration device that is not susceptible to such variation.

The original intention was that the methods be developed for field application. As such, simple distance measurements were used to investigate and compare shape variation of the dorsal fins. In reality however, many measurements were ultimately needed to discriminate between the dorsal fins of the 35 species of shark, using 13 discriminant analysis models and a binomial key. Such a complex procedure is therefore not conducive to field use. The key to adapting these methods for use *in situ* is in their automation, *e.g.* a computer program that can be used on board vessels or an iPhone applet. If this were to be developed, it is suggested that outline shape analysis methods may be more appropriate than simple distance measurements, as outline methods incorporate more shape information (MacLeod 1999).

Most species investigated showed strong positive linear relationships between the length of the dorsal fin base (BL) and the total length (TL) of the animal. Although 16 of the species investigated had $n < 10$ specimens, which is not favourable for regression analysis, the relationships were still very strong. Never the less, these should be improved by increasing the sample size. It is therefore recommended that the dorsal fin base length to total length relationship be incorporated, along with other standard relationships such as length-weight, as part of a biological assessment of a species. The ability to accurately predict total length from the size of the dorsal fin is extremely useful when trying to generate useful information on shark catch from fins alone. If the length and species of the animal can be estimated, then the maturity status can also be estimated (demonstrated in Chapter 5). The weight of the animal, and therefore the biomass of the catch, can also be estimated as the length-weight relationships for many shark species have been published (also demonstrated in Chapter 5).

4.4.2 What are the Implications for Fisheries Management?

In recent years, there has been a significant amount of illegal fishing in northern Australian waters (Field*, et al.* 2009, Salini*, et al.* 2007c). The vessels are mainly Indonesian, and target shark for their fin. The quantification of this exploitation is key to the effective management and conservation of the shark resource in northern Australia. Understanding the illegal harvesting, via investigation of seized fin catch, is the first step in this quantification process. As shark fins are the most valuable, and thus the most commonly retained product when sharks are exploited, examining the shark fin component may be the most effective means of quantifying true levels of shark exploitation.

Indeed, a major concern highlighted in the most recent Australian Shark Assessment Report is the need for an alternative methods to validate logbook data in commercial fisheries (Bensley, *et al.* 2010). As shark fisheries are typically allocated little management funding, this method would have to be cost effective. The proposed morphological identification method using fins may fulfil this requirement. However, to be effectively used for quantifying exploitation, this complex procedure must be incorporated into an automated system, such as a computer program. This would allow fisheries managers to quantify shark fin catches onboard vessels with simple tools, such as a digital camera and a laptop. Ultimately, such a system would automatically store the catch data that is generated (*i.e.* vessel type, gear type, species, and size of animals) in a database, which would reduce time spent on data management.

The aim of this chapter was to develop a method to identify sharks to species from their fin morphology in order to collect species-specific catch information that can be used to assess the exploitation rates of species. Considering that many commercial shark fisheries in northern Australia report shark catches in logbooks as ‘shark-unspecified’, an accuracy level of 80% of specimens correctly identified to species represents a vast improvement on the accuracy of catch data, even for the managed commercial fishery.

4.4.3 Conclusions and Future Directions

The overharvesting and exploitation of both terrestrial and aquatic animals is compromising global species diversity. Our failure to quantify this exploitation, particularly with respect to the illegal wildlife trade, undermines nations efforts to manage their resources sustainably. As markets represent the end-point of the supply chain, surveying them can be an effective means of estimating true levels of exploitation. Given the limited resources allocated for investigating and managing the wildlife trade, the future of effective species conservation relies on the development of innovative and cost effective techniques for quantifying exploitation. This study represents the first attempt to use morphological methods to quantify the species composition and length-frequencies of shark catches, with the specific aim of using these techniques to quantify illegal shark fin catches. This study not only addressed the specific problem of sharks being landed without their trunks, but also developed a protocol that is accurate and cost effective. In order for these techniques to be successful, aside from soliciting professional expertise, the next step is to incorporate them into an automated photographic identification tool (*i.e.* a computer program) and to use this tool via the implementation of trade and catch monitoring programs, using shark fins, in Australia.

5

The First Estimate of Shark Catch from IUU Vessels in Northern Australian Waters

Photo courtesy of the Australian Fisheries Management Authority (AFMA).

5.1 Introduction

In the period beginning in the year 2000 there has been an increase in illegal foreign fishing activity in northern Australian waters, mainly by small Indonesian vessels targeting sharks for their fins (Field, *et al.* 2009, Griffiths, *et al.* 2008, Salini, *et al.* 2007b, Salini, *et al.* 2007c). This activity peaked dramatically resulting in 368 vessel apprehensions (Figure 5.1) (AFMA 2006, Griffiths, *et al.* 2008). This number has since decreased, with only 27 apprehensions in the 2008-2009 financial year (AFMA 2009). The decrease in foreign fishing vessel (FFV) numbers in the last three years has been attributed to increased border security by the Australian Government, the global financial crisis, high petrol prices (Sumaila, *et al.* 2006), international government agreements and new domestic policies (Vince 2007), and a decrease in the abundance of target species (Field, *et al.* 2009). Despite reduced FFV numbers, the past and current impact of such fishing on shark populations in northern Australia remains unknown. This is largely due to the inability to identify shark species from isolated fins, which form a major component of the illegal shark catch (see Chapter 1). There is currently no data on the shark catch composition of these FFVs and, as such, fisheries managers are currently unable to produce accurate ecological risk assessments for the captured species in the well managed domestic commercial fisheries (Salini, *et al.* 2007b).

Although the specific composition of the catch is unknown, such high levels of illegal shark fishing are likely to have had an impact on Australian stocks as sharks, in general, are known to be long-lived, late maturing, slow growing and hence, extremely vulnerable to fishing pressure. However, shark species exhibit a range of life histories and experience differing vulnerability to these fishing pressures (Stevens, *et al.* 2000). As such, current management practices within shark fisheries require species-specific enforcement, verified by species-specific data. Indeed, a significant challenge for the ongoing management of shark fisheries today is the lack of this specific catch data for both commercial and illegal shark fisheries (Bensley, *et al.* 2010, Lack & Sant 2009). This need is amplified by the historical scarcity of such data for shark fisheries, mainly due to the

similar commercial value of many species and the difficulty of identifying individual specimens (Chapter 1).

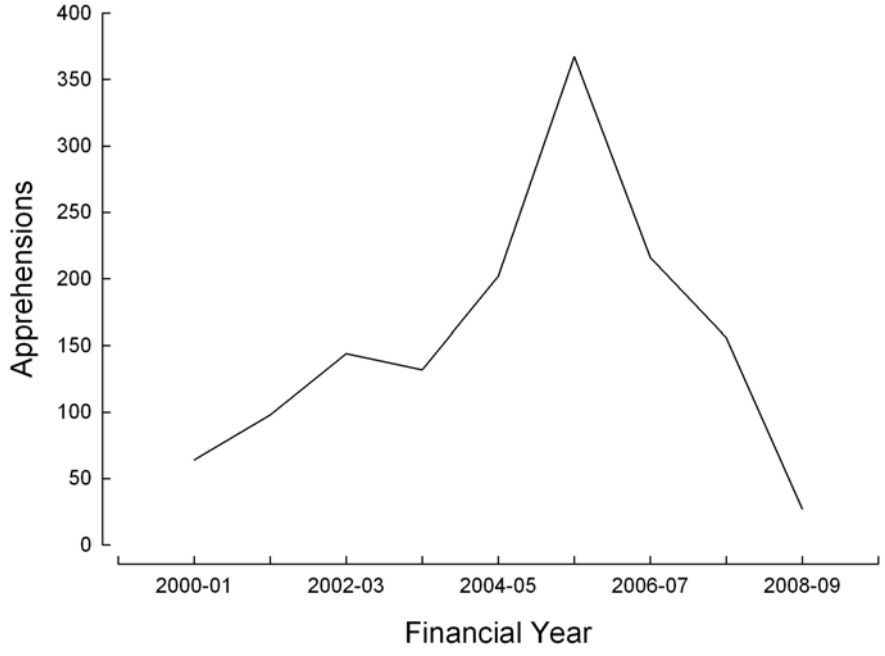


Figure 5.1 The number of illegal foreign fishing vessels (mostly Indonesian) apprehended in the Australian Fishing Zone between July 2000 and June 2009 (Data from the Australian Fisheries Management Authority).

Species-specific data is also useful for investigating changes in ecosystem dynamics due to fishing pressure. This is achieved by comparing baseline species-specific data to current species composition and identifying shifts in faunal composition and commercial catch content. In many cases, species composition shifts from large, k-selected species (slow growing, late maturing) toward the prevalence of smaller, more fecund, r-selected species (Pauly, *et al.* 1998, Warwick & Clarke 1994).

The main aim of this chapter is to provide the first detailed data of the species composition, size composition and relative abundances of the shark species in the catch of illegal FFV in northern Australian waters. Additionally, this chapter will provide the first quantitative information on these parameters using morphological methods to identify shark species from their fins. The

catch composition of these vessels is then used to estimate the total removal of sharks by the Indonesian IUU fishery in northern Australian waters in 2006, the heaviest year of fishing.

5.2 Materials and Methods

5.2.1 Sample Collection

Shark fins were obtained from the seized catch of 12 illegal foreign fishing vessels (FFVs) apprehended in northern Australian waters between February 2006 and July 2009 (Figure 5.2, Table 5.1). The Australian Fisheries Management Authority (AFMA) seized this catch. An additional three bags of fin were seized in 2006 from Indonesian FFVs, but could not be linked with a vessel. These bags were therefore treated as individual 'vessels', making 15 vessels in total (Table 5.1). Of the 12 vessels that had associated data, ten were small Indonesian boats (10–20m in length). These vessels were classed, by AFMA, as either Type II or Type III (Table 5.1). Type II vessels are traditional Indonesian Perahu sailing vessels, with no alternate form of mechanical propulsion. Type III vessels are all small (< 20 m) motorised vessels, with wooden hulls, from the Indonesian coastal fleet. The remaining two vessels were much larger Taiwanese owned boats (28 m in length), which were classed as large steel-hulled longliners (Table 5.1). These vessels had a large freezer capacity and more sophisticated fishing gear. Preliminary investigation showed the catch of the Indonesian (Type II and III) and Taiwanese (steel-hulled longliner) vessels varied greatly in both species and size composition, and were therefore investigated separately.

Table 5.1 The fifteen illegal foreign fishing vessels from which shark fin catch was sampled and associated data, collected by the Australian Fisheries Management Authority at the time of apprehension. Because of confidentiality issues, vessel names, apprehension dates and specific locations are not provided. Region: Refer to Figure 5.2. Season: SU = Summer, AU = Autumn, WI = Winter, SP = Spring. Type II vessels are traditional Indonesian Perahu sailing vessels, with no alternate form of mechanical propulsion. Type III vessels are all small (< 20 m) motorised vessels, with wooden hulls, from the Indonesian coastal fleet. Steel-hull longliners are large (> 20 m) non-wooden hulled vessels using longline fishing gear. Distance (nm) corresponds to the distance (in nautical miles) between the home port of the vessel and the site where the vessel was apprehended.

						Fishing Gear						
Vessel Number	**Region**	**Nationality**	**Season**	**Year**	**Longline Length (m)**	**Longline**	**Handline**	**Gill Net**	**Vessel type**	**Vessel Size (m)**	**Days at sea**	**Distance (nm)**
Vessel 1	E	Taiwanese	AU	2007	2000	LL	–	–	Steel-hull Longliner	28	90	–
Vessel 2	TS	Taiwanese	SU	2008	2000	LL	–	–	Steel-hull Longliner	28	–	–
Vessel 3	N	Indonesian	WI	2006	5000	LL	–	–	Type III	18	–	1536.04
Vessel 4	W	Indonesian	AU	2007	–	–	–	–	Type II	14	–	111.64
Vessel 5	W	Indonesian	SP	2007	100	LL	HL	–	Type II	15	14	633.73
Vessel 6	TS	Indonesian	SP	2007	2000	LL	–	–	Type III	15	–	168.46
Vessel 7	W	Indonesian	SP	2007	1000	LL	–	–	Type III	12	3	189.24
Vessel 8	N	Indonesian	SP	2007	100	LL	–	–	Type III	15	–	765.37
Vessel 9	N	Indonesian	SU	2007	100	LL	–	–	Type II	14	–	245.93
Vessel 10	N	Indonesian	AU	2009	1000	LL	–	GN	Type III	20	10	–
Vessel 11	TS	Indonesian	AU	2008	1000	LL	–	–	Type III	17	–	214.82
Vessel 12	W	Indonesian	WI	2009	500	LL	HL	–	Type III	10	3	220.13
Vessel 13	–	Indonesian	–	2006	–	–	–	–	Bag 1	–	–	–
Vessel 14	–	Indonesian	–	2006	–	–	–	–	Bag 2	–	–	–
Vessel 15	–	Indonesian	–	2006	–	–	–	–	Bag 3	–	–	–

5.2.2 Processing and Measuring

Each fin was photographed using a Pentax Optio W10 digital camera (Chiari, *et al.* 2008), on a contrasting background with a scale. A tissue sample from each fin was removed for genetic analysis. Samples were measured from images using the methods outlined in Chapters 2 and 4. Only the first dorsal fins were used for catch quantification, as only one fin type is needed to represent each individual shark in the catch.

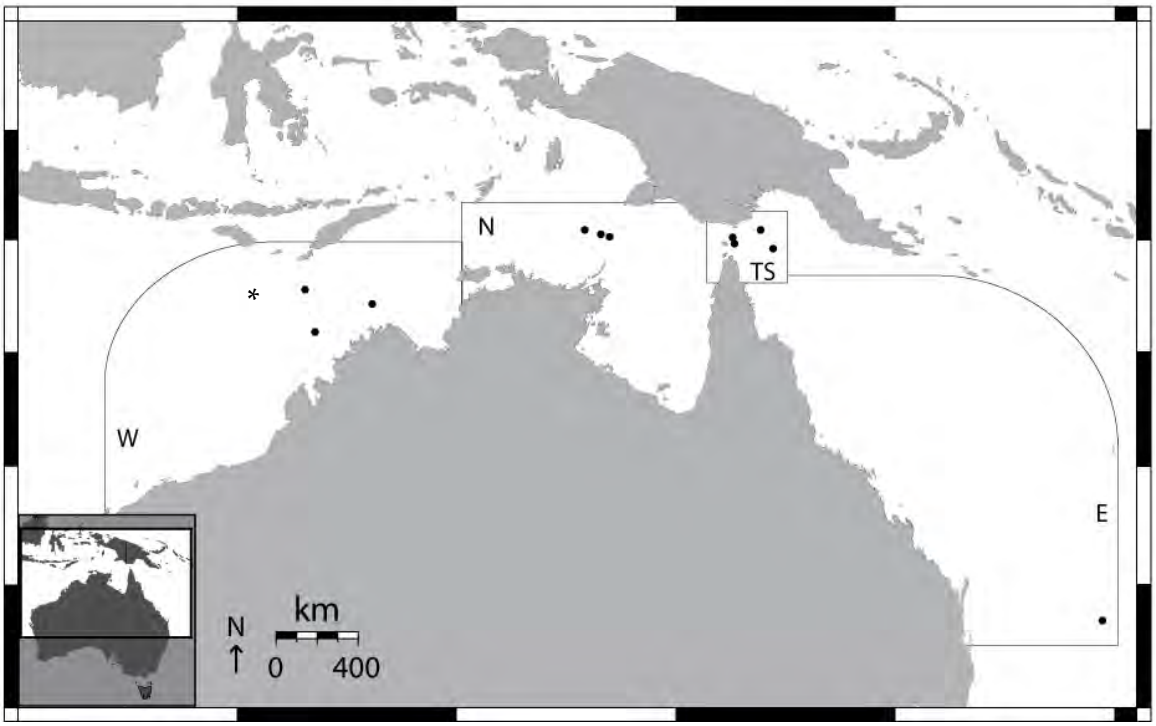


Figure 5.2 Location where each vessel was apprehended for the 12 foreign fishing vessels that had associated data (●). The four regions used for multivariate analysis are pictured: W (western region), N (northern region), TS (Torres Strait region), and E (eastern region) (Table 5.1). Two of the twelve vessels were apprehended in the same location, thus only 11 are visible (depicted by *).

5.2.3 Species Identification of Dorsal Fins

Dorsal fins were identified to species using a combination of denticle characters (Chapter 3), visual characters, and measurement data (Chapter 4). As the aim of this chapter was to accurately represent the species composition of the catch of illegal fishers, not to design an automated identification system (as in Chapter 4), the final identification of each specimen was determined by the author who has extensive experience visually identifying sharks to species using fin

morphology. The accuracy of these visual identifications can be verified by a subset of specimens, which were first identified visually by the author and then identified using genetic methods (see Appendix 9.2). Three pseudo-species (see section 4.2.1) are referred to in this chapter, *Carcharhinus limb/tils* (representing the species *C. limbatus* and *C. tilstoni*), *Rhynchobatus* spp. (representing all species belonging to the genus *Rhynchobatus*), and *Rhizoprionodon* spp. (representing all species belonging to the genus *Rhizoprionodon*). For simplicity, all species and pseudo-species are referred to herein as 'species'.

5.2.4 Shark Size and Estimated Biomass

After species identifications were assigned and verified, body size was estimated by converting dorsal fin base length (B mm) to total length (TL cm) using the species-specific conversion equations developed in Chapter 4 (Table 4.41). Weight of each shark was determined by converting TL (cm) or fork length (FL cm) to total weight (TW kg) for those species that had published TL/TW or FL/TW relationships (Table 5.3). Maturity status was assessed using the absolute minimum and maximum size (TL cm) at maturity for the combined sexes of each species (Last & Stevens 2009) (Table 5.3). Individuals were deemed 'Immature' if they had an estimated TL (cm) less than the minimum size at maturity for both males and females of that species. If the estimated TL (cm) was greater than the minimum TL at maturity but less than the maximum TL at maturity for both males and females of that species, the individual was deemed 'Maturing'. All individuals with greater estimated TL (cm) than the maximum TL at maturity for both males and females of that species were deemed 'Mature'.

5.2.5 Vessel Comparisons

If there are specific differences in catch composition that can be attributed to vessel or gear types, or location, these generalisations may be used to improve the accuracy of catch estimates based on IUU vessel sightings. A multivariate approach was used to identify such differences. For those

Indonesian vessels that had associated data, multivariate analysis was carried out using PRIMER 6 software (Clarke and Gorley 2006). A matrix of abundance data was created with each vessel as a sample and each species identified as a variable. The factors 'vessel size', 'region', 'year', 'longline length', 'vessel type' and 'season' were included for comparison (see Table 5.1). Before analysis, the data was square-root transformed and then used to build a Bray-Curtis similarity matrix (Clarke & Warwick 2001). For each factor, an analysis of similarities (ANOSIM) statistical test was used to assess if the difference in catch composition between groups was statistically significant. ANOSIM tested the null hypothesis that there was no difference between groups (Clarke & Warwick 2001).

5.2.6 Estimation of Total Fishing Mortality

Salini *et al.* (2007c) estimated the fleet number of FFVs in northern Australia to be 22 vessels per day in 2006, the heaviest year of fishing. In order to estimate the total removal of sharks by Indonesian vessels for this year the catch weight of each the four vessels for which trip length was known (Vessels 5, 7, 10 and 12) was estimated using the method described in section 5.2.4. For each vessel, the estimated catch weight was then divided by the trip length. The resulting estimates of catch weight per day for each of the four vessels is shown in Table 5.2. From this data, the average catch in kg per vessel per day (± 1SD) was calculated. In order to get the estimated total catch for Indonesian vessels in the year 2006 the average catch (kg^{-1} $vessel^{-1}$ day) was multiplied by the number of vessels (22) and the number of days (365).

Table 5.2 The estimated catch weight per day for the four Indonesian illegal foreign fishing vessels for which trip length was known.

Vessel Number	Est. Catch Weight (kg)	Days at Sea (days)	Est. Catch Weight (kg^{-1} day)
Vessel 5	98.46	14	7.03
Vessel 7	93.48	3	31.16
Vessel 10	765.23	10	76.52
Vessel 12	672.53	3	224.18

Table 5.3 For each species identified, the parameters (and corresponding literature reference) used to estimate weight and maturity status of each shark from its total length. The total length of each shark was first estimated from the base length of the dorsal fin (see Chapter 4).

	TL at Maturity (cm)		W = aTLb			FL = aTL + b		
Species	Min	Max	a	b	Units	a	b	Reference
*Carcharhinus albimarginatus**	170	195	4.66E-03	3.05	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus amblyrhynchoides	110	115	2.65E-03	3.21	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus amblyrhynchos	130	140	7.46E-03	2.98	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus amboinensis	210	215	1.94E-03	3.27	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus brevipinna	190	200	1.13E-03	3.33	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus dussumieri	70	70	3.03E-03	3.12	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus falciformis	200	210	4.66E-03	3.05	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus leucas	220	230	2.10E-05	2.98	(g) (cm)			(Cliff & Dudley 1991)
*Carcharhinus limb/tils***	110	190	4.75E-03	3.06	(g) (cm)			(Stevens & Wiley 1986)
Carcharhinus longimanus	175	200	1.41E-07	3.72	(kg) (cm)			(Stevens 1984)
Carcharhinus macloti	70	75	3.91E-04	3.55	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus melanopterus	95	110	3.25E-07	3.65	(kg) (cm)			(Lyle 1987)
Carcharhinus obscurus	265	310	1.08E-05	2.90	(kg) (cm)			(Stevens 1984)
Carcharhinus plumbeus	130	185	1.42E-03	3.31	(g) (cm)			(Stevens & McLoughlin 1991)
Carcharhinus sorrah	90	95	4.00E-06	3.03	(g) (mm)			(White 2007)
Eusphyra blochii	108	120	2.71E-04	3.56	(g) (cm)			(Stevens & Lyle 1989)
Galeocerdo cuvier	300	330	2.62E-04	3.57	(g) (cm)			(Stevens & McLoughlin 1991)
Isurus oxyrhinchus	195	280	4.83E-06	3.10	(kg) (cm)			(Stevens 1983)
Loxodon macrorhinus	60	60	4.79E-04	3.44	(g) (cm)			(Stevens & McLoughlin 1991)
Negaprion acutidens	220	220	1.21E-06	3.29	(g) (cm)			(Stevens 1984)
Prionace glauca	220	220	3.11E-06	3.04	(kg) (cm)			(Stevens 1984)
Rhizoprionodon spp. **	75	75	3.74E-03	3.01	(g) (cm)			(Stevens & McLoughlin 1991)
Rhynchobatus spp. ***	103	155	3.84E-03	3.06	(g) (cm)			(Torres 1991)
Sphyrna lewini	140	220	3.99E-03	3.03	(g) (cm)			(Stevens & Lyle 1989)
Sphyrna mokarran	225	228	1.23E-03	3.24	(g) (cm)			(Stevens & Lyle 1989)
Sphyrna zygaena	250	265	5.27E-07	3.42	(kg) (cm)			(Stevens 1984)
			WT = aFLb					
Alopias superciliosus	270	340	9.11E-06	3.08	(kg) (cm)			(Kohler, *et al.* 1996)
Carcharhinus altimus	190	225	1.02E-06	3.46	(kg) (cm)	0.81	7.77	(Kohler, *et al.* 1996)

* As published W-TL relationship could not be found, parameters were substituded from a similar species *C. falciformis* (Stevens & McLoughlin 1991)

** Used W-TL relationship for *R. diddjensis*, the only published one for a Rhynchobatid.

*** Used W-TL relationship for *R. acutus*

**** Use parameters for *C. tilstoni*

5.3 Results

5.3.1 Catch Composition

A total of 1182 individual sharks[4], with a total estimated biomass of 61.7 tonnes, (consisting of 33 species from eight families) were recorded from the 15 FFVs apprehended in northern Australian waters between February 2006 and July 2009. The catch of each of the 33 species by number, estimated biomass, and size range, for both Indonesian and Taiwanese vessels, is summarised in Table 5.4. The family Carcharhinidae dominated the catch in terms of both numbers (87.6%) and estimated biomass (85.2%) (Table 5.4). The two most abundant species in terms of both abundance and estimated biomass were the Silky Shark (*Carcharhinus falciformis*) and the Blue Shark (*Prionace glauca*), contributing 20.2% and 15.3%, respectively, to the number of all sharks, and 20.6% and 19.9%, respectively, to the total estimated biomass of all sharks. Due to the small size of the animals caught, the Blacktip Shark complex (*Carcharhinus limb/tils*), which was the third most abundant species (representing 12.7% of the catch by number) only contributed to 2.0% of the total estimated biomass. In contrast, larger Tiger Sharks (*Galeocerdo cuvier*) contributed to 19.0% of the total estimated biomass, but only 7.4% of the total catch by number (Table 5.4).

A total of 338 individual sharks from 23 species, with a total estimated biomass of 4.6 tonnes, were recorded from the 13 Indonesian FFVs (Table 5.4). The most abundant species were the Blacktip Shark, Spot-tail Shark (*Carcharhinus sorrah*) and the Whitecheek Shark (*C. dussumieri*), contributing to 44.4, 14.5 and 8.6% of the total number of sharks, respectively. In terms of estimated biomass, Blacktip Sharks, Bull Sharks (*Carcharhinus leucas*) and Pigeye Sharks (*C. amboinensis*) were the three most abundant species, contributing 26.8, 19.7, and 13.8% of the total estimated biomass, respectively.

The two Taiwanese vessels captured 844 individual sharks from 18 species, with a total estimated biomass of 57.1 tonnes (Table 5.4). The three most abundant species were the Silky

[4] Although classed as rays, for convenience, animals belonging to the families Pristidae, Rhinidae, Rhinobatidae, and Rhynchobatidae are referred to herein as ‘sharks’.

Shark, Blue Shark, and Tiger Shark in terms of numbers, contributing to 28.3, 21.4 and 9.8%, respectively, and estimated biomass contributing 22.3, 21.5 and 20.0%, respectively.

Table 5.4 The contribution by number and estimated biomass and minimum and maximum lengths of each species recorded from the seized fin catch of fifteen Indonesian and two Taiwanese illegal foreign fishing vessels operating in the Australian Fishing Zone (AFZ).

	Indonesian				Taiwanese				All		
			Length (cm)				Length (cm)				
Species	Number (%)	Biomass (%)	Max	Min	Number (%)	Biomass (%)	Max	Min	Number *n*	Number (%)	Biomass (%)
Alopias superciliosus	.	.	.	.	2	3	154.3	229	17	1.4	2.7
Anoxypristis cuspidata	1.2	–	.	.	.	.	.	.	4	0.3	–
Carcharhinus albimarginatus	.	.	.	.	3.7	2.2	120	228.4	31	2.6	2.1
Carcharhinus altimus	.	.	.	.	5.2	2.7	98.9	259.7	44	3.7	2.5
Carcharhinus amblyrhynchoides	0.3	0.2	114.6	114.6	.	.	.	.	1	0.1	< 0.1
Carcharhinus amblyrhynchos	4.1	5.5	85.9	217.8	0.1	<0.1	138.8	138.8	15	1.3	0.4
Carcharhinus amboinensis	2.7	13.8	173.2	234.4	0.2	0.1	141.1	182.5	11	0.9	1.1
Carcharhinus brevipinna	2.7	5.6	61	260.9	0.1	0.2	249.9	249.9	10	0.8	0.6
Carcharhinus dussumieri	8.6	0.9	57.9	74.4	.	.	.	.	30	2.5	< 0.1
Carcharhinus falciformis	.	.	.	.	28.3	22.3	118	273.8	239	20.2	20.6
Carcharhinus leucas	1.5	19.7	77.7	240	0.2	0.9	204.2	266.9	7	0.6	2.3
Carcharhinus limb/tils	44.4	26.8	33.3	164.8	.	.	.	.	150	12.7	2
Carcharhinus longimanus	.	.	.	.	8.3	3.9	117.1	211.8	70	5.9	3.6
Carcharhinus macloti	3	0.2	57.8	69.9	.	.	.	.	10	0.8	< 0.1
Carcharhinus melanopterus	0.6	0.5	114.7	118.1	.	.	.	.	2	0.2	< 0.1
Carcharhinus obscurus	.	.	.	.	8.1	10.4	150.1	318.9	69	5.8	9.6
Carcharhinus plumbeus	0.9	1.4	132.9	163.7	2.3	1.1	140	205.1	22	1.9	1.1
Carcharhinus sorrah	14.5	4.5	63.4	121.8	.	.	.	.	48	4.1	0.3
Eusphyra blochii	0.6	0.5	141.1	143.5	.	.	.	.	2	0.2	< 0.1
Galeocerdo cuvier	1.5	6.9	144.4	323.6	9.8	20	149.2	442.1	87	7.4	19
Glaucostegus typus	2.1	–	.	.	.	–	.	.	7	0.6	–
Isurus oxyrhinchus	.	.	.	.	4.1	4.7	140.2	298.5	35	3	4.4
Isurus paucus	.	–	.	.	0.2	–	159.3	190.7	2	0.2	–
Loxodon macrorhinus	1.2	0.1	56.2	60.2	.	.	.	.	4	0.3	< 0.1
Negaprion acutidens	0.3	2.4	261.5	261.5	.	.	.	.	1	0.1	0.2
Prionace glauca	.	.	.	.	21.4	21.5	178.2	373	181	15.3	19.9
Rhina ancylostoma	0.6	–	102.3	149.7	.	–	.	.	2	0.2	–
Rhizoprionodon spp.	1.2	< 0.1	43.5	49.1	.	.	.	.	4	0.3	< 0.1
Rhynchobatus spp.	3.3	3.4	101.9	174.4	.	.	.	.	11	0.9	0.3
Sphyrna lewini	3.8	4.4	57.4	234.1	0.8	0.7	114.5	298.2	20	1.7	1
Sphyrna mokarran	0.9	3.2	181.1	268.5	0.4	0.4	225	276.9	6	0.5	0.6
Sphyrna zygaena	.	.	.	.	4.6	5.8	148	314.6	39	3.3	5.4
Triaenodon obesus	0.3	.	110.4	110.4	.	–	.	.	1	0.1	–
Total number (n) and mass (kg) of all sharks recorded:	338	4606.44			844	57116.05			1182		61722.49

Only eight of the 33 species recorded were found on both the Indonesian and Taiwanese vessels (Table 5.3). The Grey Reef Shark (*Carcharhinus amblyrhynchos*), Spinner Shark (*C. brevipinna*), Pigeye Shark, Bull Shark, and Scalloped Hammerhead (*Sphyrna lewini*) were recorded most commonly from Indonesian vessels, (93.3, 90.0, 81.8, 71.4, and 65.0% of individuals per species, respectively) while Tiger Sharks and Sandbar Sharks (*Carcharhinus plumbeus*) (94.3 and 86.4% of individuals per species, respectively) were more abundant on Taiwanese vessels. The Great Hammerhead (*Sphyrna mokarran*) was equally present on both vessel types (50%). Taiwanese vessels were typified by a greater numbers of larger sharks, with a mean TL of 218.6 (± 1.7) cm, twice that of the Indonesian vessels with a mean TL of 109.6 (± 2.6) cm (Figure 5.3). The majority of the catch for both Indonesian and Taiwanese vessel types were composed of immature individuals (59.4 and 44.1%, respectively, Figure 5.4). The remainder of the catch comprised 24.9% maturing and 15.7% mature individuals, for the Indonesian vessels, and 17.2% maturing and 38.7% mature individuals, for the Taiwanese vessels (Figure 5.3).

5.3.2 Maturity Data for Individual Species

Total length and maturity status could be estimated for 31 of the 33 species found in the IUU catch. Immature individuals dominated the catch (> 50%) of 15 of these 31 species (Figure 5.4). Mature individuals dominated the catch of only seven species, the Bigeye Thresher (*Alopias superciliosus*), Silvertip Shark (*Carcharhinus albimarginatus*), Blacktip Reef Shark (*C. melanopterus*), Winghead Shark (*Eusphyra blochii*), Lemon Shark (*Negaprion acutidens*), Blue Shark and Wedgefish (*Rhynchobatus* spp.) (Figure 5.4). The catch of the remaining eight species, the Graceful Shark (*Carcharhinus amblyrhynchoides*), Silky Shark, Bull Shark, Spot-tail Shark, Shortfin Mako (*Isurus oxyrinchus*), Scalloped Hammerhead (*Sphyrna lewini*), Great Hammerhead (*S. mokarran*) and Smooth Hammerhead (*S. zygaena*) had relatively even numbers of mature and immature individuals (Figure 5.4).

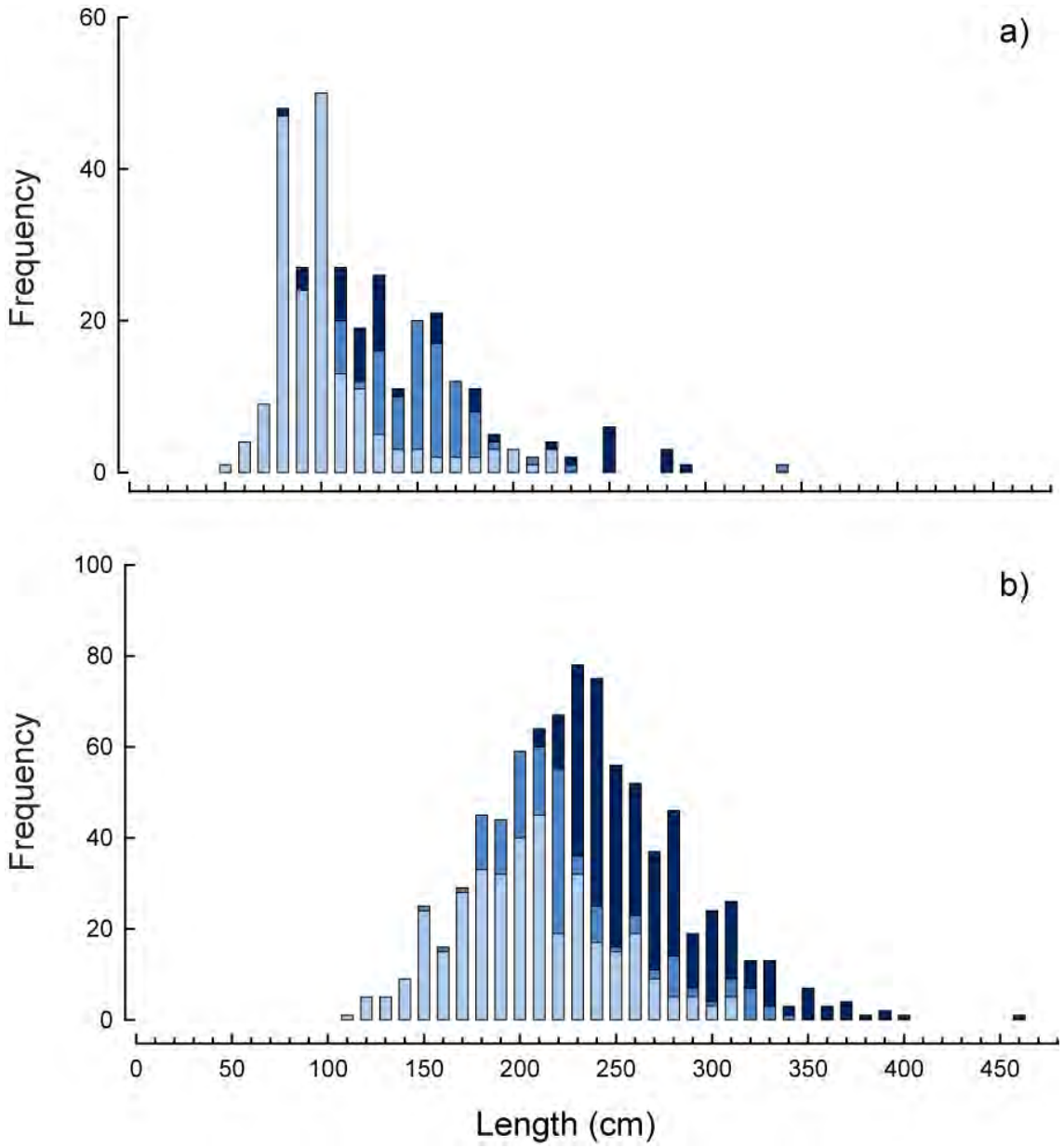


Figure 5.3 Pooled estimated length frequency histograms and maturity data for all shark species from a) the 15 Indonesian illegal foreign fishing vessels, and b) the two Taiwanese illegal foreign fishing vessels. Shades represent estimated maturity status, immature (), maturing () and mature (). Length represents total length (cm).

5.3.3 Indonesian Vessel Comparisons

For each of the factors 'vessel size', 'region', 'year', 'longline length', 'vessel type' and 'season', ANOSIM detected no significant difference ($P > 0.05$) between groups.

5.3.4 Impact of Illegal Fishing

The catch of each species, pooled by year, for both the Indonesian and Taiwanese vessels is shown in Table 5.5. Nine of the 23 species comprising the Indonesian catch were observed only in the year

2006, with no record in the catch in subsequent years. These were the Narrow Sawfish (*Anoxypristis cuspidata*), Graceful Shark (*Carcharhinus amblyrhynchoides*), Winghead Shark (*Eusphyra blochii*), Giant Shovelnose Ray (*Glaucostegus typus*), Lemon Shark (*Negaprion acutidens*), Milk Shark (*Rhizoprionodon* spp.), Shark Ray (*Rhina ancylostoma*), Wedgefish (*Rhynchobatus* spp.) and Whitetip Reef Shark (*Triaenodon obesus*) (Table 5.5).

For the Taiwanese vessels, the catch from the 2007 vessel was five times greater, both estimated biomass and numbers, than the 2008 vessel (Table 5.5). Six of the 18 species recorded from both vessels, the Grey Reef Shark (*Carcharhinus amblyrhynchos*), Pigeye Shark (*C. amboinensis*), Spinner Shark (*C. brevipinna*), Shortfin Mako (*Isurus paucus*), Blue Shark (*Prionace glauca*) and Smooth Hammerhead (*Sphyrna zygaena*) occurred only on the vessel apprehended in 2007 (Table 5.5). Conversely, only one species, the Great Hammerhead (*Sphyrna mokarran*), was found on the 2008 vessel and not on the 2007 vessel.

Salini *et al.* (2007c) estimated the fleet number of FFVs in northern Australia to be 22 vessels per day in 2006. For the present study, average daily catch weight was calculated to be 84.72 ± 48.66 kg^{-1} vessel^{-1} day. The resulting annual estimate of the removal of shark by Indonesian fishing vessels in 2006 is an average of 680.30 tonnes (ranging between 289.6 and 1071.04 tonnes).

Table 5.5 The percent contribution by number (% n) and estimated biomass (% bm) of each species to the pooled catch per year for both Indonesian and Taiwanese vessels.

	Indonesian						Taiwanese			
	2006		2007		2009		2007		2008	
Species	% n	% bm	% n	% bm	% n	% bm	% n	% bm	% n	% bm
Alopias superciliosus	.	.	.	.	.	.	2.3	3.3	0.7	0.9
Anoxypristis cuspidata	2.1	.	.	.	.	.	.	.	.	.
Carcharhinus albimarginatus	.	.	.	.	.	.	1.7	0.9	13.1	9.2
Carcharhinus altimus	.	.	.	.	.	.	6.2	3	0.7	0.9
Carcharhinus amblyrhynchoides	0.5	0.5	.	.	.	.	.	.	.	.
Carcharhinus amblyrhynchos	0.5	0.2	5.7	3.2	12.9	14.8	0.1	0	.	.
Carcharhinus amboinensis	2.7	15.1	2.3	18.2	3.2	8.3	0.3	0.1	.	.
Carcharhinus brevipinna	2.1	6.9	1.1	1	6.5	7.5	0.1	0.2	.	.
Carcharhinus dussumieri	11.2	1.5	9.1	0.9	.	.	.	.	.	.
Carcharhinus falciformis	.	.	.	.	.	.	23.2	21	53.1	29.3
Carcharhinus leucas	1.1	19.5	1.1	0.8	3.2	35.7	0.1	0.3	0.7	3.9
Carcharhinus limb/tils	48.9	17	38.6	46.8	38.7	23.9	.	.	.	.
Carcharhinus longimanus	.	.	.	.	.	.	8.3	3.7	8.3	4.7
Carcharhinus macloti	3.2	0.3	4.5	0.4	.	.	.	.	.	.
Carcharhinus melanopterus	.	.	2.3	1.9	.	.	.	.	.	.
Carcharhinus obscurus	.	.	.	.	.	.	9.6	12.2	0.7	0.8
Carcharhinus plumbeus	.	.	2.3	3.8	1.6	1.3	2.1	1	2.8	1.4
Carcharhinus sorrah	5.3	1.2	21.6	6.6	32.3	7.3	.	.	.	.
Eusphyra blochii	1.1	1.3	.	.	.	.	.	.	.	.
Galeocerdo cuvier	1.1	13.2	2.3	3.2	1.6	1.1	9	15.9	13.8	41.8
Glaucostegus typus	3.7	.	.	.	.	.	.	.	.	.
Isurus oxyrhinchus	.	.	.	.	.	.	4.7	5.2	1.4	2.4
Isurus paucus	.	.	.	.	.	.	0.3	.	.	.
Loxodon macrorhinus	.	.	4.5	0.2	.	.	.	.	.	.
Negaprion acutidens	0.5	5.5	.	.	.	.	.	.	.	.
Prionace glauca	.	.	.	.	.	.	25.9	25.6	.	.
Rhina ancylostoma	1.1	.	.	.	.	.	.	.	.	.
Rhizoprionodon spp.	2.1	0.1	.	.	.	.	.	.	.	.
Rhynchobatus spp.	5.9	7.8	.	.	.	.	.	.	.	.
Sphyrna lewini	5.3	7.2	3.4	5.2	.	.	0.4	0.4	2.8	2.2
Sphyrna mokarran	1.1	2.7	1.1	7.7	.	.	.	.	2.1	2.5
Sphyrna zygaena	.	.	.	.	.	.	5.6	6.9	.	.
Triaenodon obesus	0.5	.	.	.	.	.	.	.	.	.
Total number (n) and mass (kg) of all sharks:	188	1987	88	1182	62	1437.75	699	47998	145	9118

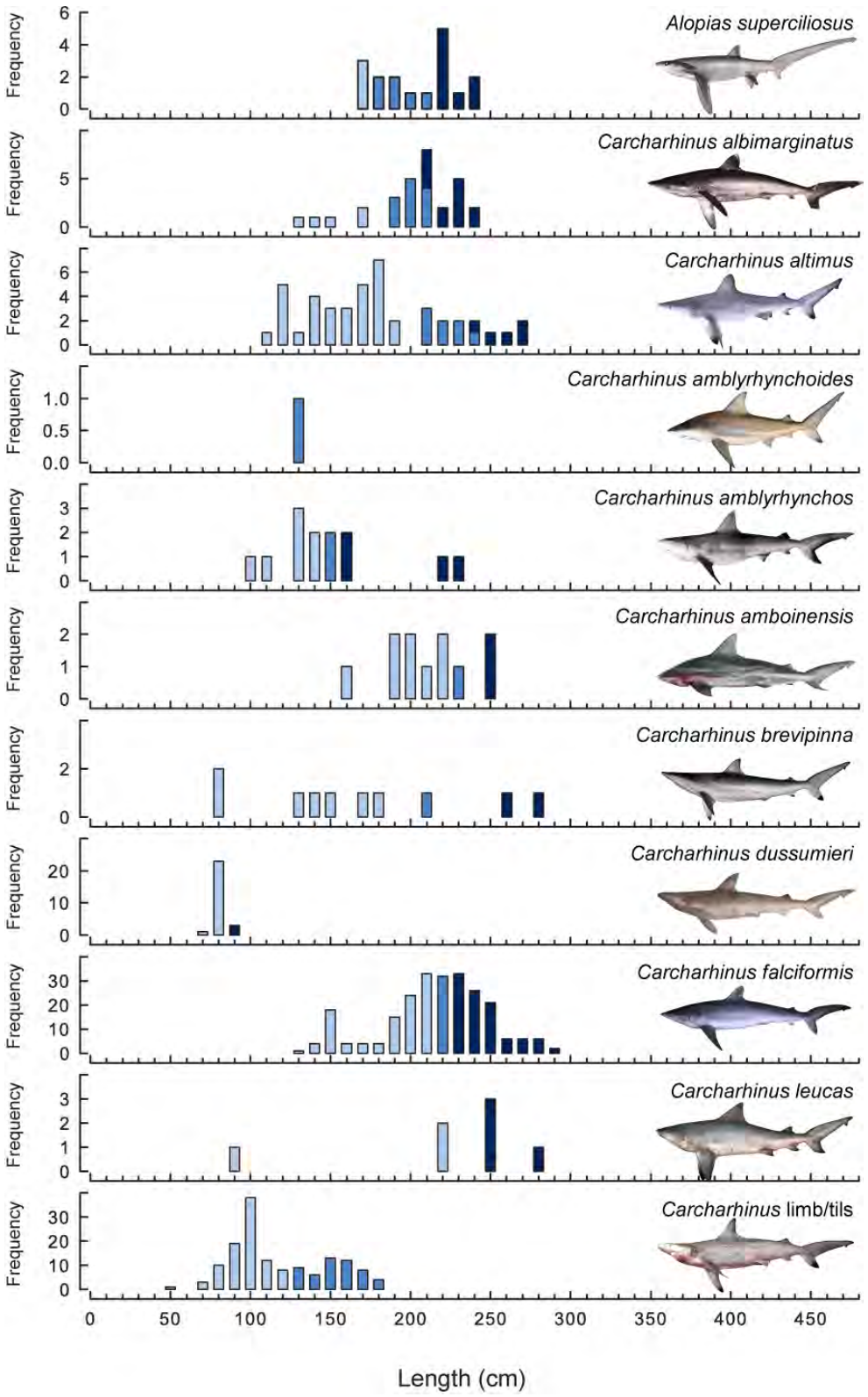


Figure 5.4 Length frequency histograms for the 31 species for which total length (TL) could be estimated from the catch of 15, both Indonesian and Taiwanese, foreign fishing vessels apprehended in northern Australia between February 2006 and July 2009. Colours represent estimated maturity status, immature (■), maturing (■) and mature (■). Length represents total length (cm) for all species except *Alopias superciliosus* where length represents fork length (cm).

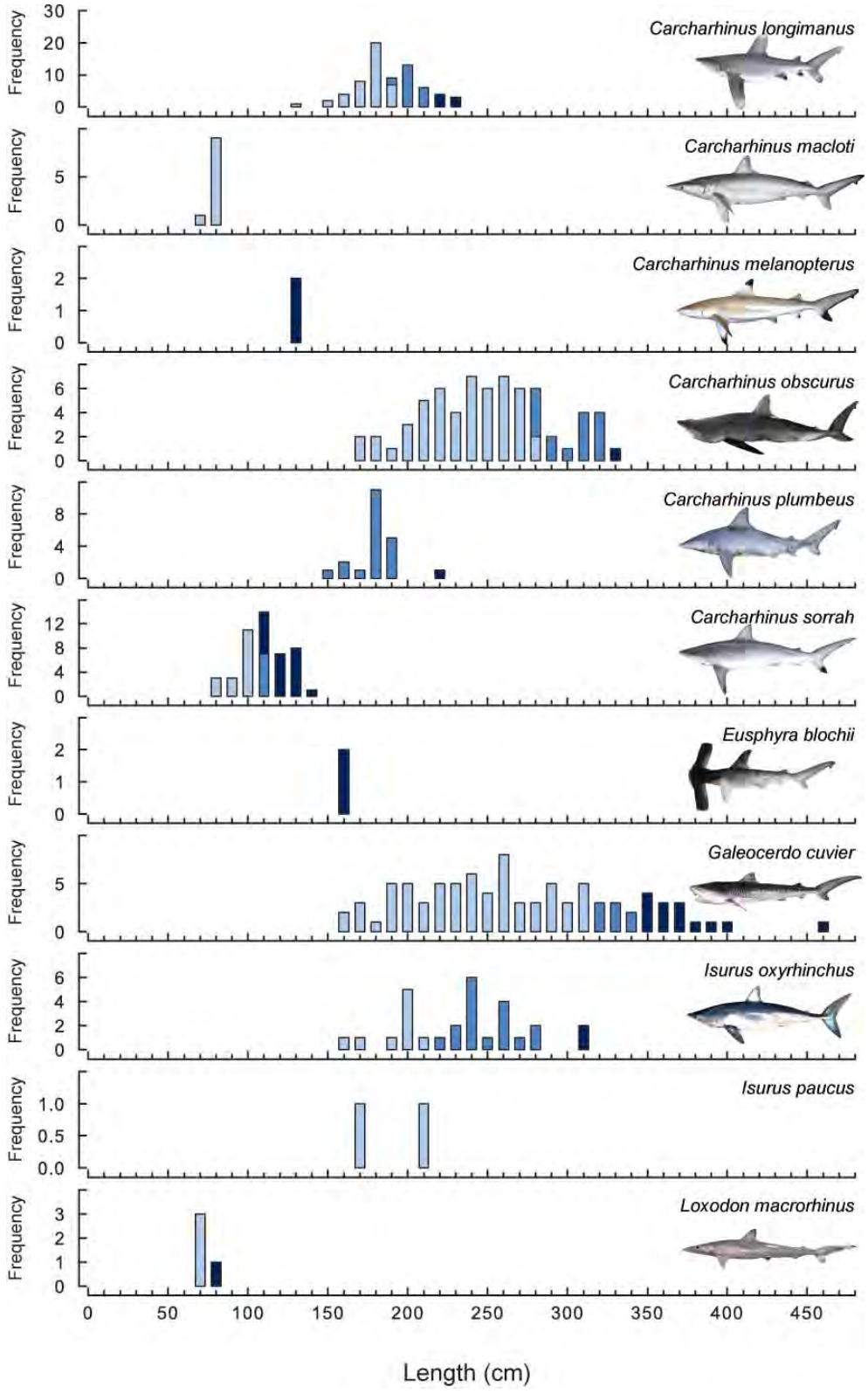


Figure 5.4 continued.

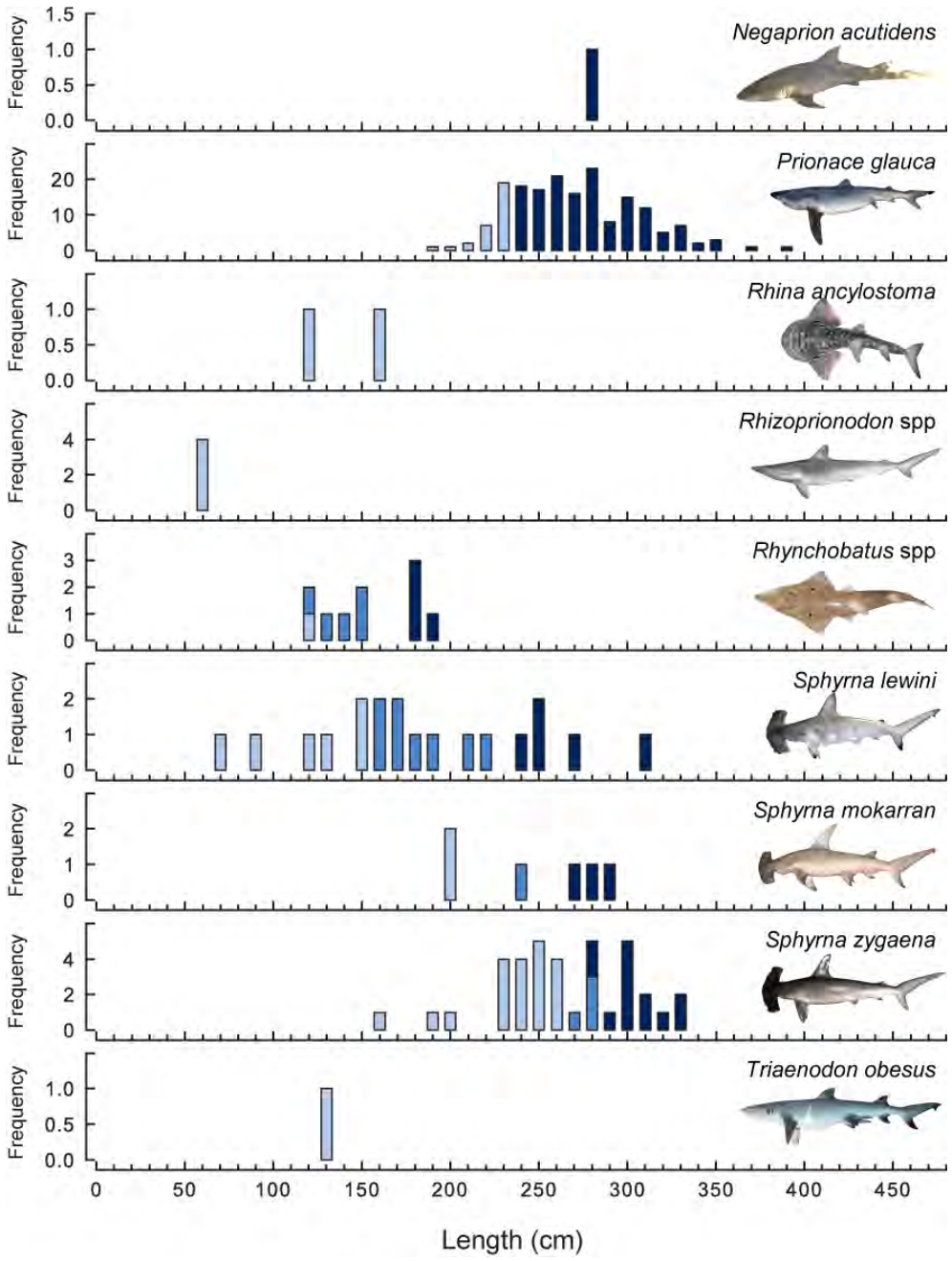


Figure 5.4 continued.

5.4 Discussion

This is the first detailed account of the shark catch composition of illegal FFVs operating in northern Australian waters. Prior to this study, the only such data consisted of a list of species, identified using genetic barcoding techniques, from the seized fin catch of a small number of Indonesian foreign fishing vessels (FFVs) (Salini, *et al.* 2007a). Furthermore, this study provides the first indication of the scale of the removal of sharks from northern Australian waters.

5.4.1 Catch Composition of the IUU Fleet

Accurate catch data for shark species, in both illegal and commercial fisheries, is historically and currently hard to obtain (see Chapter 1). This situation is further complicated when the individual sharks caught are reduced to single fins for the fin trade. In this chapter I have demonstrated the practical use of the methods developed in Chapter 4, by quantifying the shark catch of a number of FFVs apprehended in northern Australia. This has produced useful species and size data for the catch of these vessels that can be subsequently used to quantify the impact of both illegal and commercial fishing in the region.

The catch of the Indonesian fleet, as characterised by the 13 vessels investigated, was mainly composed of smaller inshore and benthic species such as Spot-tail Sharks (*Carcharhinus sorrah*), Whitecheek Sharks (*C. dussumieri*) and juvenile Blacktip Sharks (*C. limb/tils*). This species set was similar to the reported catch from commercial shark fisheries in northern Australia, with Blacktip and Spot-tail Sharks comprising the majority of the catch by numbers (Salini, *et al.* 2007b). Those species caught in proportionally higher numbers in the illegal, compared to the commercial fishery (Salini, *et al.* 2007b) were Grey Reef Sharks (*Carcharhinus amblyrhynchos*), Whitecheek Sharks, Blacktip Sharks, Hardnose Sharks (*C. macloti*), Giant Shovelnose Rays (*Glaucostegus typus*) and Wedgefish (*Rhynchobatus* spp.). Conversely, there were a greater proportion of Great Hammerheads (*Sphyrna mokarran*) and Scalloped Hammerheads (*S. lewini*) in the commercial catch, compared to the illegal catch (Salini, *et al.* 2007b). The Shark Ray (*Rhina ancylostoma*) was not recorded from the commercial fishery, however, was observed in the catch of illegal Indonesian vessels apprehended in 2006. Species not represented in the illegal, but observed in the commercial, catch were Silvertip Sharks (*Carcharhinus albimarginatus*), Bignose Sharks (*C. altimus*), Nervous Sharks (*C. cautus*), Creek Whalers (*C. fitzroyensis*), Dusky Whalers (*C. obscurus*), Grey Nurse Sharks (*Carcharias taurus*), Northern Rivers Sharks (*Glyphis garricki*), Fossil Sharks (*Hemipristis elongata*), Tawny Nurse Sharks (*Nebrius ferrugineus*), Green Sawfish (*Pristis zijsron*) and Smooth Hammerheads (*Sphyrna zygaena*) (Salini, *et al.* 2007b). However,

these species each constituted a relatively small percentage of the commercial fishery (< 2%), therefore the sample size of 13 vessels from the illegal fishery may not have been sufficient to encounter these species.

The Taiwanese catch, as represented by only two vessels, was characterised by larger, pelagic species such as the Blue Shark (*Prionace glauca*), Silky Shark (*Carcharhinus falciformis*), Oceanic Whitetip Shark (*C. longimanus*), and Smooth Hammerhead (*S. zygaena*). The catch composition of these vessels was markedly different to the northern Australian commercial shark fishery, largely due to the fishing activity of these vessels occurring in deeper, offshore waters. Instead, the catch of these vessels is comparable to that of the shark longline fishery currently operating in Papua New Guinea (Kumoru 2003). The Papua New Guinean (PNG) fishery consists of nine vessels, one of which was investigated in this study (Vessel 2) after being apprehended fishing illegally in Australian waters in 2008. Based on the catch information published in Kumoru (2003) for the PNG shark longline fishery the illegal Taiwanese catch differs from the PNG fishery mainly in the relative abundance of species, rather than the species composition. Although the Blue shark, a pelagic species usually found in more temperate waters, made up a significant proportion of the illegal catch (21.4% by number), it only constituted 2.2% of the catch of the PNG fishery. Furthermore, the Grey Reef Shark (*Carcharhinus amblyrhynchos*), a more tropical, inshore species, constituted a greater proportion of the PNG catch. These differences may be attributed to the fishing area of the PNG fleet being confined to tropical, inshore waters around Papua New Guinea, while the illegal fleet was generally more wide-ranging, with one vessel apprehended off the mid-east coast of Australia (Figure 5.1).

As catch composition varies between regions and gear type within and among the different commercial shark fisheries in northern Australia, it would be expected that such differences would exist in the illegal fishery. However, this was not observed. This may be due to either the nature of the fishery or to the small number of vessels sampled. In future, fisheries management should focus on more thorough sampling of the IUU catch to ascertain if these differences do indeed exist, and if

so, what these differences are. Ultimately, this will allow more detailed projection of the effect of such fishing.

5.4.2 Evidence of Fishing Impact

In the last ten years there has been a dramatic fluctuation in the number of FFVs (mainly Indonesian) in Australian waters, peaking dramatically in 2005-2006 and declining from 2006 till present. The level of fishing estimated in the current study (for Indonesian vessels) for the year 2006, of between 289.6 and 1071.04 tonnes, is comparable to the Northern Territory Offshore Net and Line Fishery, the largest commercial shark fishery that was operating in northern Australian waters at that time (Figure 5.5). Furthermore, this catch is higher than the reported catch for the other two main shark fisheries in northern Australian waters for that year, the Queensland Gulf of Carpentaria Inshore Fin Fish Fishery and the Western Australia Joint Authority Northern Shark Fishery (Figure 5.5). In order to provide a more robust estimate of total removal by foreign fishing vessels, more data were needed via the sampling of a larger percentage of the fin catch from apprehended vessels. Despite this, the estimated figures indicate that the scale of IUU shark fishing in 2006 may have been equivalent to, or in excess of, the largest commercial shark fisheries operating at the time. Furthermore, these estimates do not incorporate the much larger catch of Taiwanese vessels.

The risk a fishery poses to a population of animals is dependent on the fishing effort, fishing mortality rate of specific size classes, the catchability and the biology of individual species (Milton 2001, Stobutzki, *et al.* 2001). Generally, ecological risk assessments attempt to assess the risk to individual species based on their 'susceptibility' (*e.g.* capture by fishing) and their 'recovery' capacity (once populations are fished) (Griffiths, *et al.* 2006, Hobday, *et al.* 2007). Recent risk assessments for sharks and rays caught in commercial fisheries in northern Australia have identified the species that are least likely to be sustainable due to a combination of capacity for recovery and susceptibility to fishing (Salini, *et al.* 2007b). Seven of these high-risk species were found in the

illegal catch, the Pigeye Shark (*Carcharhinus amboinensis*), Spinner Shark (*C. brevipinna*), Bull Shark (*C. leucas*), Common Blacktip Shark (*C. limbatus*), Lemon Shark (*Negaprion acutidens*), Narrow Sawfish (*Anoxypristis cuspidata*) and Great Hammerhead (*Sphyrna mokarran*). These seven species constituted more than half of the illegal Indonesian catch, by both number and biomass. Conversely, low-risk species such as the Spot-tail Shark (*Carcharhinus sorrah*) and Milk Sharks (*Rhizoprionodon acutus* and *R. taylori*), constituted a much smaller proportion.

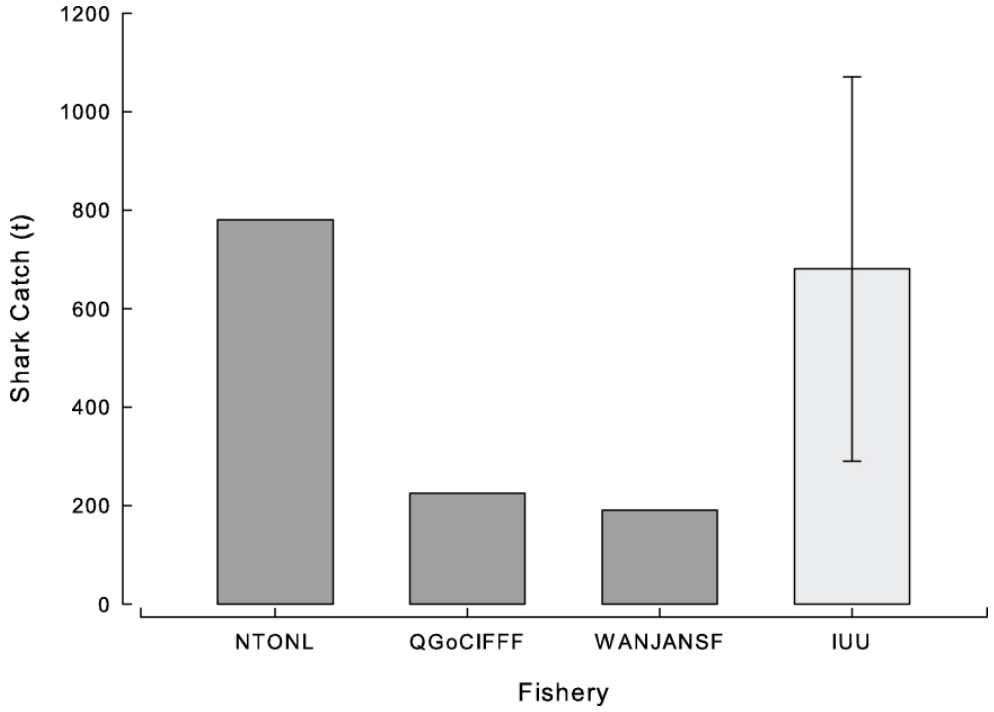


Figure 5.5 Shark catch in northern Australian waters in 2006. Dark bars (■) represent the reported shark catch for the three main commercial shark fisheries in northern Australia, the Northern Territory Offshore Net and Line Fishery (NTONL) (Buckworth & Beatty 2008), Queensland Gulf of Carpentaria Inshore Fin Fish Fishery (QGoCIFFF) (Roelofs 2009) and the Western Australia Joint Authority Northern Shark Fishery (WAJANSF) (McCauley, *et al.* 2000). Light bar (□) represents the estimated Illegal Unregulated and Unreported (IUU) catch by Indonesian foreign fishing vessels.

Further species that may be vulnerable to fishing by the IUU fleet are the Bigeye Thresher (*Alopias superciliosus*), Silvertip Shark (*Carcharhinus albimarginatus*), Blacktip Reef Shark (*C. melanopterus*), Winghead Shark (*Eusphyra blochii*), Lemon Shark, Blue Shark and Wedgefish (*Rhynchobatus* spp.). This is due to the majority of each of these species being represented in the catch by mature individuals. Indeed, the Bigeye Thresher, Lemon Shark and the Wedgefish (genus:

Rhynchobatus) are assessed as Vulnerable under The IUCN Red List of Threatened Species (IUCN 2009).

The difference in catch for the Taiwanese vessels between the years 2007 and 2008 is most likely due to the fishing region and trip length rather than the year of apprehension, and therefore the impact of fishing over time, by these vessel types, cannot be assessed. However, for the Indonesian fleet, the absence of high-risk species, such as the Shark Ray (*Rhina ancylostoma*) and the Narrow Sawfish (*Anoxypristis cuspitada*), from the catch of vessels apprehended after 2006 may be evidence that the high levels of fishing in previous years has had a marked impact on their populations. As the FFV catch could not be sampled extensively, with respect to the number of boats and the years of fishing, this speculation cannot be confirmed. Nonetheless, it exemplifies the importance collecting of species-specific baseline data for assessing fishing impact via changes in catch composition with time.

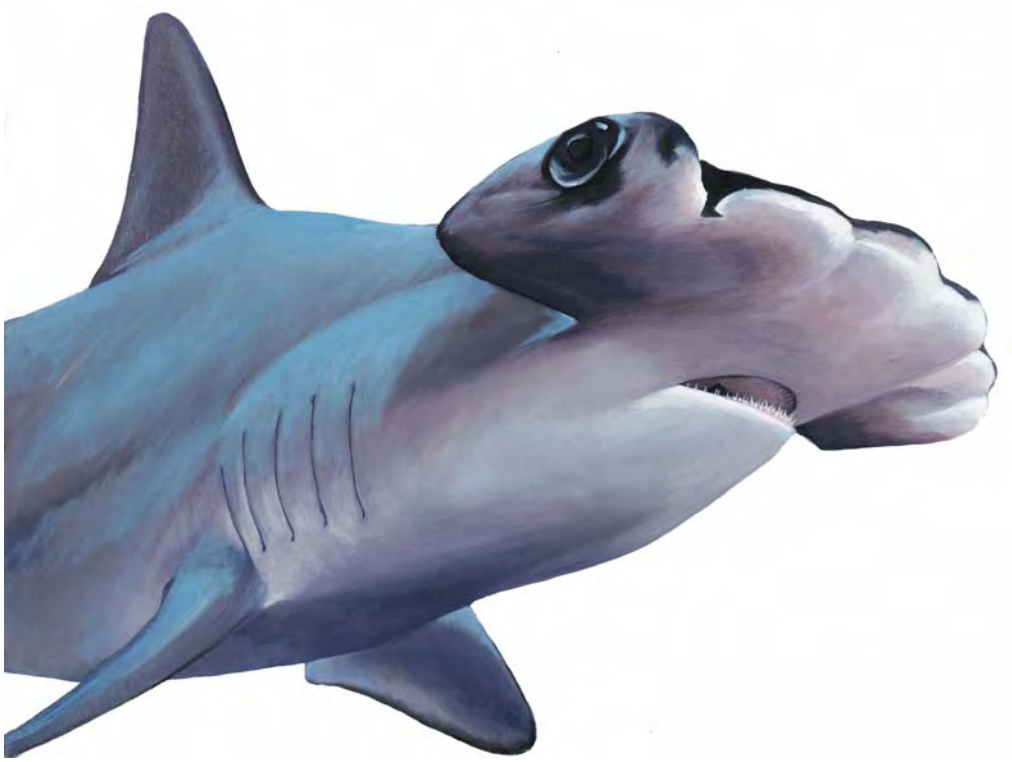
5.5 Conclusions

These results show that IUU fishing in northern Australia removes a substantial biomass of shark stocks in the region. Improvement of the quality of stock assessment, and of current ecosystem models that predict the ecological effects of IUU fishing on the broader ecosystem, via accurate estimation of the size and composition of the shark catch from these illegal FFVs is crucial for management and conservation of these already impacted shark stocks (Griffiths, *et al.* 2008). This study has shown that fishing impact cannot be equated to the number of fishing vessels alone, as vessel type can attribute a significant difference in both the catch composition and volume of captured species. This concept is illustrated by the marked difference in the fishing capacity of each of the Taiwanese vessels compared to the smaller Indonesian vessels, with one Taiwanese vessel capable of removing the same amount of estimated biomass as between 96 and 166 Indonesian vessels. These results bring to light the danger in the current method of assessing fishing impact by the number of vessels only, rather than incorporating the fishing capabilities of individual vessels,

in order to accurately estimate fishing impact. Despite the dramatic drop in FFV numbers between 2006 and 2009, an estimated 57 tonnes of shark were recorded from only two vessels in this time period. This suggests that low apprehension years may not indicate years of low fishing impact, as the catch of FFVs in northern Australian waters in low apprehension years may have been comparable (or higher) than in the high apprehension years. Therefore, total fishing impact cannot be reliably assessed without taking into account other data, such as vessel type. In this study we have demonstrated methods, using shark fin morphology, to accurately quantify the shark catch of FFVs. However, the number of vessels sampled did not allow for thorough investigation of the catch differences with location and gear type. In order to adequately assess the impact of IUU fishing on Australia's shark stocks and provide baseline data to assess future fishing impacts, the comprehensive collection of shark fins from the seized catch of FFVs must continue. Furthermore, the composition of the catch should be investigated and ecosystem modelling must be undertaken to predict the ecological effects of illegal fishing on the broader ecosystem (Okey, *et al.* 2004). Although FFV numbers have steadily decreased in recent years, foreign fishing has had, and is still having, a significant impact on northern Australian shark stocks.

6

Shark Fin Ecomorphology and Implications for Fisheries Management



6.1 Introduction

The ability to move is of crucial importance in many ecological contexts, for example prey capture (Rice & Hale 2010), predator avoidance (Langerhans, *et al.* 2004), and migration (Winkler & Leisler 1992). Consequently, the locomotor apparatus of many organisms are subject to similar interacting selective pressures, including the different wing shapes exhibited for many groups of

birds (Lockwood, *et al.* 1998, Swaddle & Lockwood 2003) and insects (Johansson, *et al.* 2009) and, the different fin shapes of many shark species (Chapter 4). For that reason, species performing a similar function in an ecosystem may have a similar morphology. If this is true, then it is equally valid to assume that morphology can also be used to predict the function of an organism in an ecosystem (Douglas & Matthews 1992, Hertel & Ballance 1999). The association between form and function may have implications for the monitoring and management of exploited ecosystems, particularly when rapid assessment is needed or monitoring resources are scarce.

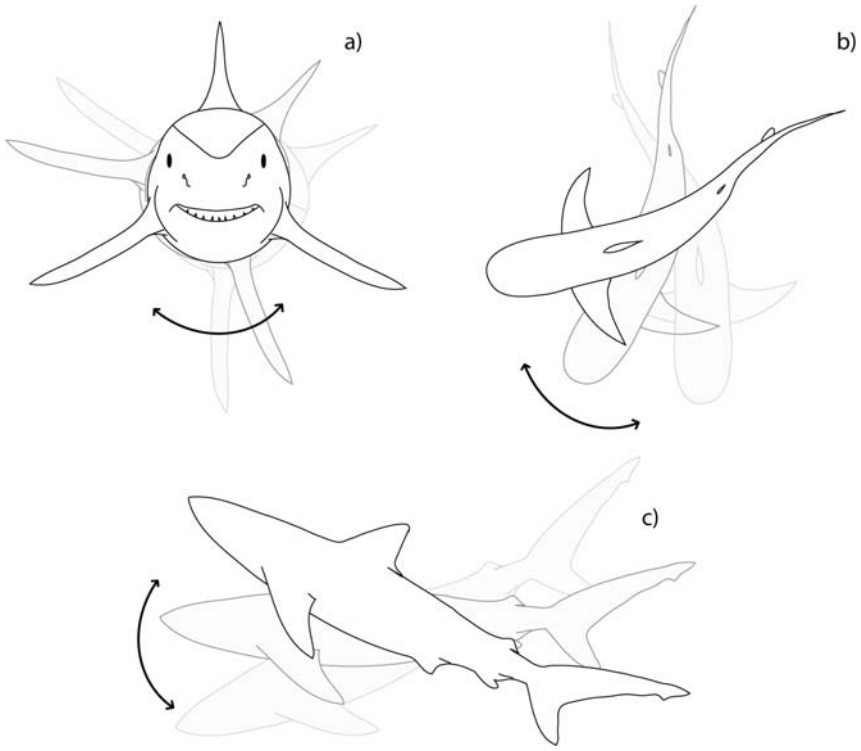


Figure 6.1 Schematic diagram demonstrating the hydrodynamic forces of a) roll, b) yaw, and c) pitch, acting on the shark body during swimming.

In the case of sharks, as for most aquatic organisms, the requirements for swimming are influenced by hydrodynamic factors such as drag, pitch (rotation about the horizontal axis), yaw (rotation about the vertical axis), and roll (rotation about the longitudinal axis) (Figure 6.1), as well as a need to counteract the negative buoyancy of the shark body (Harris 1936, Weihs 2002). The role of the position, amplitude, and structure of paired and unpaired fins in counteracting these forces during shark swimming and kinematics has been the subject of many studies. The bulk of

these focus on the caudal fin (Lauder 2000, Lauder, *et al.* 2003, Lingham-Soliar 2005a, b), and pectoral fins (Fish & Shannahan 2000, Wilga & Lauder 1999, 2001), with only one study focusing on the dorsal fin (Lingham-Soliar 2005c). It is hypothesised that the dorsal fin acts as a stabiliser during swimming, resisting yaw and roll (Lingham-Soliar 2005c), provides thrust (Lauder & Drucker 2004) and generates off-axis forces during turning (Lauder & Drucker 2004). Pectoral fins enhance manoeuvrability and induce low-speed manoeuvres (Lauder & Drucker 2004, Wilga & Lauder 2000). Caudal fins propel the shark and provide thrust (Wilga & Lauder 2004). It is hypothesised that the swimming performance characteristics required by each species based on their habitat, diet, and behaviour will vary depending on the morphology of the dorsal, pectoral and caudal fins.

Fish have evolved swimming performance characteristics to suit their habitat (Domenici 2010). In terms of habitat complexity, benthic habitats (*e.g.* coral reefs, reedy rivers) and inshore habitats are generally more structurally intricate than pelagic habitats (*e.g.* open ocean). Fish from structurally complex habitats have high performance during unsteady swimming (small turning radius and acceleration), and tend to swim slowly (while searching for prey) or perform acceleration bursts at high speed (while capturing prey, or avoiding predators) (Domenici 2003). In terms of fin morphology, it is hypothesised that sharks from complex habitats will exhibit functional modifications for sharp turns and burst-swimming such as shorter, sickle-shaped dorsal and pectoral fins, and a proportionally larger upper caudal lobe (Webb & Keyes 1982). Fish from open habitats have greater swimming endurance to search for widely dispersed food resources, tending to swim at intermediate speeds most of the time with poor performance during unsteady swimming (Domenici 2003). These sharks may exhibit functional modifications in fin morphology for constant cruising, such as longer, more upright dorsal and pectoral fins, and a larger lower caudal fin lobe (Webb & Keyes 1982). Therefore, fin shape plays an important role on swimming performance.

The Carcharhinidae (whaler sharks) are a group of about 54 species of shark that occupy a variety of habitats in tropical and temperate waters throughout the world. The species within this

family are often very similar in their overall morphology, which makes species identification difficult (Last & Stevens 2009). However, carcharhinid sharks occupy a variety of habitats, from oceanic to inshore pelagic, to benthopelagic, and freshwater. Consequently, carcharhinid sharks also exhibit variation in their diet, and therefore, functional role in the ecosystem. For example, the oceanic Blue Shark (*Prionace glauca*) feeds mainly on pelagic fishes and squid (Nakano & Stevens 2008), while the benthopelagic Lemon Shark (*Negaprion acutidens*) feeds mainly on inshore fish and rays (Compagno 1984, White, *et al.* 2004). Despite the overall morphological similarity of carcharhinid sharks, because there is such niche variation within the family it is expected that more subtle morphological differences may exist in their form, which reflect this niche diversity. Furthermore, if these differences in form can be used to predict ecological role, this may have implications for the monitoring and management of exploited ecosystems.

Ecosystem models describe the structure and function of an ecosystem with the aim of predicting changes that may occur with alterations to key variables. Within these models, a set of ecosystem components portray links within that ecosystem. In many ecosystem models (such as Ecopath and Ecosim) these components are represented by broad functional groups, of which all the members are assumed to exercise a similar function in the ecosystem (Pauly, *et al.* 2000). If an exploited animal can be identified to a broad functional group because of it's morphology, the exploitation rate of such functional groups may be ascertained. This study focuses on three functional groups within the Carcharhinidae; *oceanic epipelagic* sharks, *neritic epipelagic* sharks and *benthopelagic* sharks. *Oceanic epipelagic* species were defined as those that generally live and feed in the epipelagic zone of the open ocean. *Neritic epipelagic* species were defined as those that generally live and feed in the epipelagic zone over the continental shelf. *Benthopelagic* species were defined as living and feeding near (but not on) the bottom as well as in mid waters or near the surface.

In order to understand the relationship between fin shape and functional group, the first aim of this study was to determine if differences in fin shape exist between the three functional groups

oceanic epipelagic, *neritic epipelagic* and *benthopelagic*. Only species belonging to the family Carcharhinidae were investigated in order to 1) determine whether differences in fin morphology corresponding to function occur within an otherwise very morphologically similar group of sharks, and 2) to minimise the influence of phylogeny on the morphological differences that were observed, as phylogeny is also known to influence form. In order to investigate the use of fin morphology as a conservation tool, the second aim of this study was to assess if functional group could be predicted using fin morphology.

6.2 Methods

6.2.1 Specimens and Functional Groups

The dorsal, pectoral and caudal fins of 167 'known' specimens (see section 2.2.1) from 19 species were measured (Table 6.1). As differences in shape can occur with growth, only adult specimens (*i.e.* specimens with a total length (TL) greater than or equal to TL at first maturity) were used for analysis. Size at maturity information for each species was sourced from Last & Stevens (2009). Before the morphological features of the fins were measured, species were assigned to one of three functional groups, '*oceanic epipelagic*', '*neritic epipelagic*', and '*benthopelagic*' using information available in the literature on habitat use and diet for each species (Compagno 2008, Last & Stevens 2009). Again, the *oceanic epipelagic* species were defined as those that generally live and feed in the epipelagic zone of the open ocean. *Neritic epipelagic* species were defined as those that generally live and feed in the epipelagic zone over the continental shelf. *Benthopelagic* species were defined as living and feeding near (but not on) the bottom as well as in mid waters or near the surface. The *oceanic epipelagic* group was represented by 28 specimens from three species; *Carcharhinus falciformis*, *C. longimanus*, and *Prionace glauca* (Table 6.1). The *neritic epipelagic* group was represented by 73 specimens from six species; *Carcharhinus albimarginatus*, *C. brevipinna*, *C. limbatus*, *C. obscurus*, *C. plumbeus*, and *Galeocerdo cuvier* (Table 6.1). The *benthopelagic* group was represented by 66 specimens from ten species; *Carcharhinus altimus*,

C. amblyrhynchos, *C. amboinensis*, *C. cautus*, *C. fitzroyensis*, *C. leucas*, *C. sorrah*, *Negaprion acutidens*, *Rhizoprionodon acutus*, and *Rhizoprionodon taylori* (Table 6.1).

Fins were cleaned and then photographed using a handheld Pentax Optio W10 digital camera (Chiari, *et al.* 2008), set to the 'soft flash' setting, from directly above the subject. To avoid edge distortion, a wide border was left around the subject, which was later cropped (Zelditch 2004). Each photograph contained a scale and specimen number.

Table 6.1 Summary of all shark specimens used in this study, for each species, and the three functional groups to which they were assigned.

Functional group	Species	*n*
oceanic epipelagic	*Carcharhinus falciformis*	8
	Carcharhinus longimanus	10
	Prionace glauca	10
neritic epipelagic	*Carcharhinus albimarginatus*	10
	Carcharhinus brevipinna	4
	Carcharhinus limbatus	22
	Carcharhinus obscurus	18
	Carcharhinus plumbeus	7
	Carcharhinus sorrah	6
	Galeocerdo cuvier	12
benthopelagic	*Carcharhinus altimus*	12
	Carcharhinus amblyrhynchos	2
	Carcharhinus amboinensis	7
	Carcharhinus cautus	7
	Carcharhinus fitzroyensis	1
	Carcharhinus leucas	8
	Negaprion acutidens	2
	Rhizoprionodon acutus	16
	Rhizoprionodon taylori	5
		167

6.2.2 Measurements

All fin morphometric distance measurements were taken from digital images imported into *SigmaScan Pro.* 5 software. Images were calibrated using the scale photographed within the image.

For each specimen, 11 morphological measurements (including nine distance and two angle measurements) were taken from the dorsal (Figure 6.2a) and left pectoral fin (Figure 6.2b), and seven morphological distance measurements were taken from the caudal fin (Figure 6.2c). These measurements were then used to generate 20 'morphological variables' (Table 6.2). These morphological variables were 16 ratios derived from the 25 original measurements, and four angles calculated between measurements on the fin (Table 6.2, Figure 6.2). Each variable was considered to represent a morphological characteristic of the fin that could be used to derive inferences of hydrodynamic function. Morphological variables and the underlying measurement ratios are described in Table 6.2.

Table 6.2 The 20 morphological variables used to investigate the morphological properties of the dorsal, pectoral and caudal fins of all 167 specimens of sharks from 19 species from the family Carcharhinidae. The table shows the abbreviated name, description, and measurements (Figure 6.2) used to derive each morphological variable.

	Name	Description	Derivation
Dorsal Fin	D1FRT	Free rear tip	A/B
	D1AM	Anterior margin	Ah/E
	D1H	Height	L/B
	D1PMI	Posterior margin (inner)	Bh/I
	D1PMO	Posterior margin (outer)	Dh/H
	D1j	Angle j	j°
	D1e	Angle e	e°
Pectoral Fin	PFRT	Free rear tip	A/B
	PAM	Anterior margin	Ah/E
	PH	Height	L/B
	PPMI	Posterior margin (inner)	Bh/I
	PPMO	Posterior margin (outer)	Dh/H
	Pj	Angle j	j°
	Pe	Angle e	e°
Caudal Fin	CPD	Peduncle width	F/A
	CTR	Terminal margin	G/A
	CPU	Upper postventral margin	P/A
	CFW	Width	D/A
	CPV	Preventral margin	U/A
	CFL	Fork length	T/A

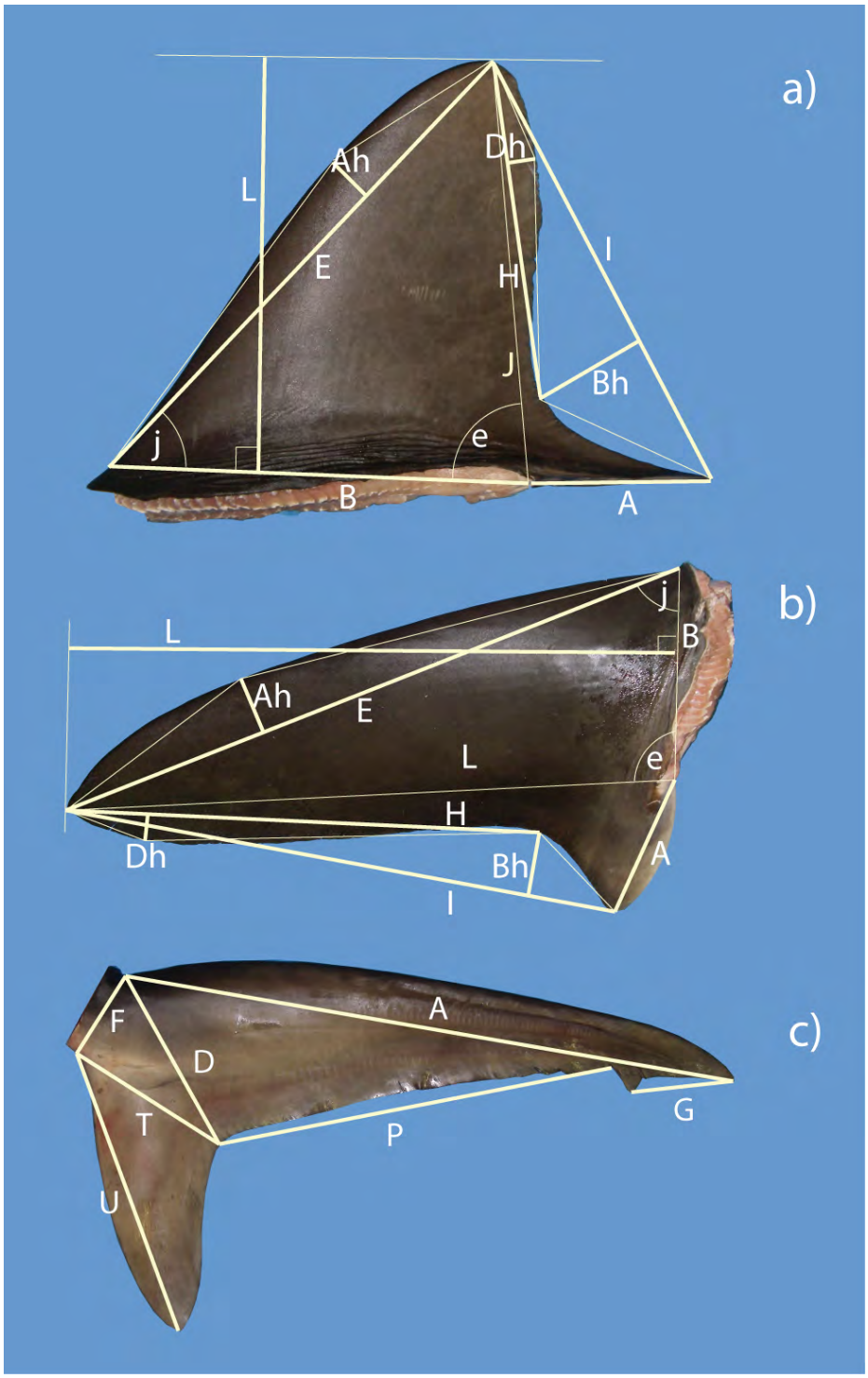


Figure 6.2 The morphometric measurements taken from the a) dorsal, b) left pectoral, and c) caudal fins of each of the 167 shark specimens from 19 species from the family Carcharhinidae. These measurements were used to construct the 20 morphological variables used in the multivariate analysis (Table 6.2).

6.2.3 Statistical Analysis

Multivariate analysis was carried out using PRIMER 6 software (Clarke and Gorley 2006), which was chosen as the package caters for both biological and physical data matrices. Furthermore, the method of analysis is robust as few assumptions are made about the form of the data. PRIMER 6

was originally designed for community ecology studies that use species sample data, however, the package is suitable for analysis of any multivariate matrices, including morphometric measurements in taxonomic discrimination (Clarke & Gorley 2006). A matrix of measurement data was created with each shark specimen as a sample and each morphological variable identified as a variable. The factor 'functional group' was included for comparison. Before analysis, the data were normalised, then used to build a similarity matrix using the Euclidean distance between samples (Clarke & Gorley 2006, Clarke 1993). Non-metric multidimensional scaling (MDS) of distances in this similarity matrix was used to visually evaluate differences in fin morphology between the 167 samples (Clarke 1993). Analysis of similarities (ANOSIM) statistical tests were used to assess if the differences observed in the MDS plots between functional groups were statistically significant. ANOSIM tested the null hypothesis that there was no difference between groups (Clarke & Warwick 2001). In the cases where differences were found, a SIMPER (similarities of percentages) analysis was carried out, using Euclidean distances, to determine the percentage contribution of each morphological variable to the overall difference between niches. This analysis was carried out until the cumulative differences were greater than 50%.

In order to create a model capable of correctly identifying carcharhinid sharks to one of the three functional groups using fin morphometrics, stepwise discriminant analysis was carried out using SPSS software. For a detailed explanation of the discriminant analysis procedure see Chapter 4. For the first procedure, all morphological variables were used and the model was constructed using a stepwise approach. As shark fins from the same shark are not usually kept together during illegal or commercial fin processing, a method to identify single fins is also required. Therefore, the stepwise discriminant analysis procedure was repeated for each of the three fin types. The second, third, and fourth procedures incorporated only morphological variables from the dorsal, pectoral, and caudal fins, respectively (Table 6.2). To test the accuracy of the discriminant functions a hold-out sample was used, whereby 117 randomly selected cases from the original data set of 167 specimens were assigned to the *analysis* sample (to create the discriminant functions), and the

remaining 50 cases were assigned to the hold-out sample and were classified using the resulting discriminant functions.

6.3 Results

The complete morphometric characterisation of the three functional groups is presented in Table 6.3. When considering the mean and ranges of measurements between the three functional groups, all measurements were very similar as most values showed overlap in their ranges (Table 6.3). In spite of this, when measurements were investigated using multivariate techniques, separation between the three functional groups occurred.

The multivariate visualisation shown in the MDS plot illustrated a separation between the three functional groups (Figure 6.3a). Furthermore, in all three pairwise tests, ANOSIM detected significant differences between each pair of functional groups (P = 0.01). Pairwise *R*-values were used to describe the extent of similarity between each pair in the ANOSIM analysis (Hyndes, *et al.* 1997). Values close to one indicate that the two groups are entirely separate, while values close to 0 indicate that no difference exists between such groups. Differences occurred between the functional groups *benthopelagic* and *neritic epipelagic*, *i.e.* $R = 0.339$, the groups *neritic epipelagic*, and *oceanic epipelagic*, *i.e.* $R = 0.320$, and between the groups *benthopelagic* and *oceanic epipelagic*, *i.e.* $R = 0.376$. These differences are evident in the spread of the MDS ordination (Figure 6.3), which shows a wide dispersion of points with no tight or discrete groupings, but a tendency for each group to radiate directionally from the centre of the cluster, becoming more differentiated with increasing distance from the cluster centre (Figure 6.3).

Table 6.3 The average values for each morphological variable for the three ecological groups *oceanic epipelagic*, *neritic epipelagic*, and *benthopelagic*, represented by 19 species of sharks, belonging to the family Carcharhinidae.

	oceanic epipelagic		*neritic epipelagic*		*benthopelagic*	
D1FRT	0.389	(0.284–0.507)	0.364	(0.247–0.581)	0.394	(0.233–0.581)
D1AM	0.154	(0.063–0.225)	0.118	(0.068–0.214)	0.097	(0.052–0.209)
D1H	1.019	(0.883–1.206)	0.989	(0.705–1.230)	0.873	(0.681–1.102)
D1PMI	0.148	(0.072–0.248)	0.213	(0.090–0.341)	0.211	(0.104–0.333)
D1PMO	0.094	(0.044–0.165)	0.041	(0.003–0.149)	0.045	(0.004–0.115)
D1e	0.467	(0.407–0.514)	0.453	(0.393–0.507)	0.45	(0.366–0.591)
D1j	0.269	(0.223–0.317)	0.271	(0.204–0.325)	0.251	(0.164–0.307)
PFRT	0.691	(0.548–0.838)	0.698	(0.483–0.916)	0.788	(0.460–1.200)
PAM	0.100	(0.056–0.150)	0.100	(0.059–0.144)	0.104	(0.066–0.158)
PH	3.345	(2.687–4.391)	2.644	(2.013–4.379)	2.368	(1.481–3.471)
PPMI	0.092	(0.055–0.131)	0.125	(0.056–0.254)	0.11	(0.058–0.180)
PPMO	0.044	(0.017–0.072)	0.024	(0.000–0.062)	0.051	(0.000–0.129)
Pj	0.405	(0.363–0.471)	0.377	(0.296–0.447)	0.371	(0.311–0.449)
Pe	0.502	(0.453–0.547)	0.507	(0.442–0.594)	0.499	(0.450–0.556)
CPD	0.144	(0.123–0.171)	0.150	(0.115–0.183)	0.164	(0.141–0.186)
CTR	0.217	(0.158–0.281)	0.168	(0.074–0.252)	0.228	(0.149–0.280)
CPU	0.591	(0.486–0.671)	0.633	(0.569–0.730)	0.538	(0.444–0.642)
CFW	0.312	(0.284–0.336)	0.311	(0.277–0.356)	0.336	(0.305–0.403)
CPV	0.481	(0.401–0.538)	0.452	(0.375–0.545)	0.442	(0.340–0.544)

Table 6.4 Morphological variables identified by SIMPER as typifying the fin morphology of the carcharhinid species from the *oceanic epipelagic*, *neritic epipelagic*, and *benthopelagic* functional groups (shaded boxes) and as distinguishing between the fin morphology between the pairwise comparisons of each of the groups (open boxes).

	oceanic epipelagic	*neritic epipelagic*	*benthopelagic*
oceanic epipelagic	PAM D1AM CPU D1PMO PH Pe CTR		
neritic epipelagic	$D1PMO^{OE}$ PH^{OE} $PPMI^{NE}$ $D1PMI^{NE}$ $D1AM^{OE}$ CTR^{OE} Pj^{OE}	Pe PPMI D1PMI Pj CPD PAM D1j	
benthopelagic	PH^{OE} $D1PMO^{OE}$ $D1AM^{OE}$ CPD^{BP} CPV^{OE} $D1H^{OE}$ CFW^{BP} Pj^{OE}	CPU^{NE} CFW^{BP} CTR^{BP} $PPMO^{BP}$ $PFRT^{BP}$ $D1H^{NE}$ $D1j^{NE}$ CPD^{BP}	D1e CPV D1FRT PPMO PFRT D1j PAM

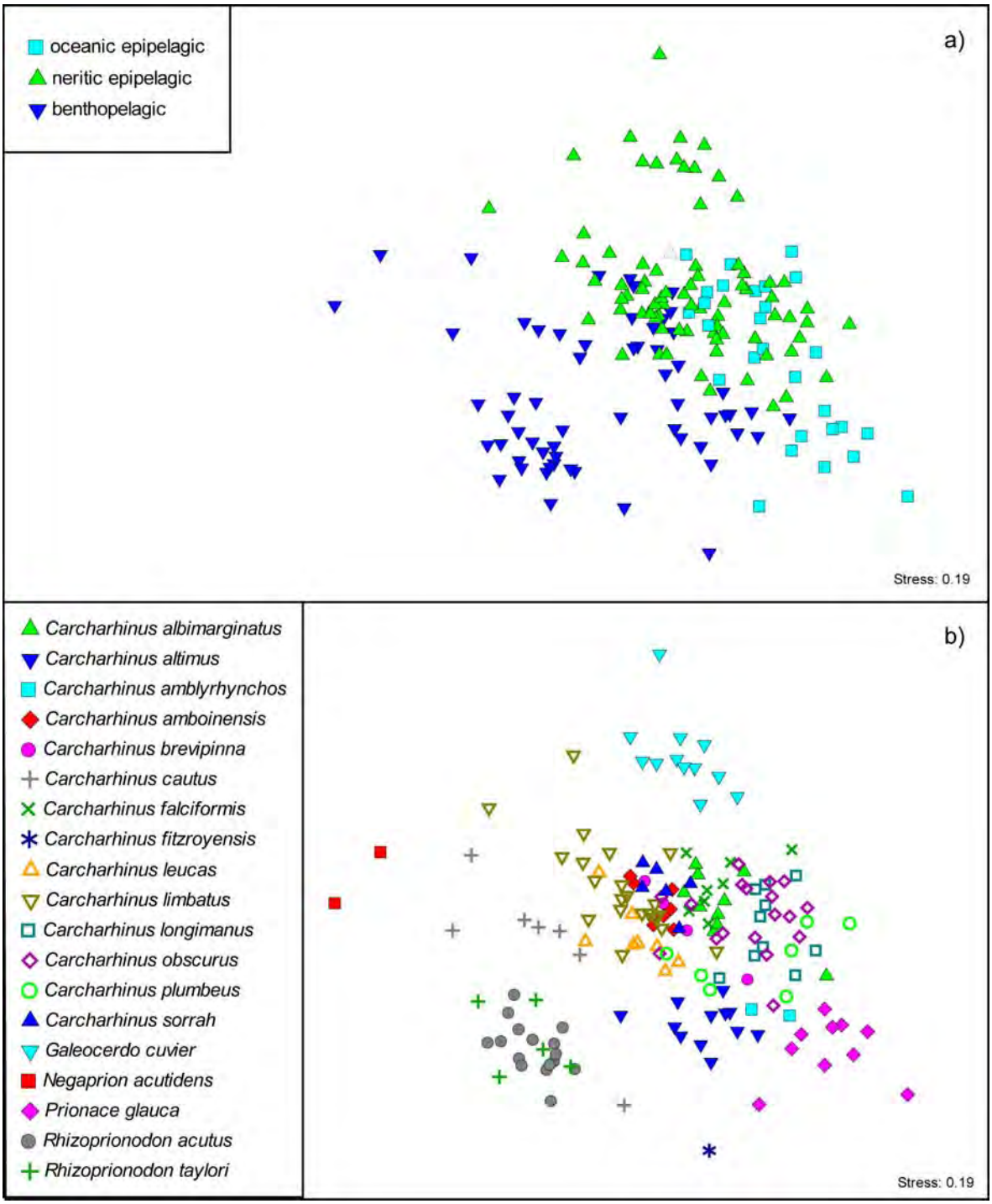


Figure 6.3 A non-metric multidimensional scaling (MDS) ordination derived from morphological data (consisting of 20 morphological variables) from the dorsal, pectoral and caudal fins of each of the 167 specimens from 19 shark species (family: Carcharhinidae). The same MDS ordination is shown twice, indicating a) the factor 'functional group', and b) the factor 'species'.

The SIMPER analysis illustrated the morphological variables that typified each functional group, and that contributed most to the separation between functional groups (Table 6.4). The *oceanic epipelagic* group was most typified by the anterior margin of both the pectoral fin (PAM), and dorsal fin (D1AM) and the upper postventral margin of the caudal fin (CPU) (Table 6.4). The

neritic epipelagic group was most typified by both the pectoral fin angle *e* (Pe), and inner posterior margin (PPMI), and the inner posterior margin of the dorsal fin (D1PMI) (Table 6.4). The *benthopelagic* group was most typified by angle *e* on the dorsal fin (D1e), the caudal preventral margin (CPV), and the free rear tip of the dorsal fin (D1FRT) (Table 6.4). The *oceanic epipelagic* and *neritic epipelagic* categories could be distinguished by a larger outer posterior margin of the dorsal fin (D1PMO) and larger pectoral fin height (PH) for species in the *oceanic epipelagic* group, and by a larger dorsal (D1PMI) and pectoral (PPMI) inner posterior margin for those species in the *neritic epipelagic* group (Table 6.4). The *oceanic epipelagic* and *benthopelagic* categories could be distinguished from each other by a larger outer posterior margin (D1PMO) and anterior margin (D1AM) of the dorsal fin, and larger pectoral fin height (PH) for species in the *oceanic epipelagic* group, and by a wider caudal peduncle (CPD) for those species in the *benthopelagic* group (Table 6.4). The *neritic epipelagic* and *benthopelagic* categories could be distinguished by a larger caudal fin upper postventral margin (CPU) for the *neritic epipelagic* species, and by the greater width (CW), and terminal margin (CTR) of the caudal fin, and larger outer posterior margin (PPMO) of the pectoral fin of species in the *benthopelagic* group (Table 6.4).

Each of the four discriminant function analyses revealed significant differences in fin shape between functional groups (all $P < 0.001$), and exhibited high predictability (Table 6.5). That is, based on morphology, the majority of individual sharks could be correctly classified to their assigned functional group using each of the three fin types, and using all fin types combined. Of the four stepwise discriminant analysis models, the model that used morphological variables from all three fin types was the most successful at discriminating the three functional groups, 82% of all hold-out specimens identified correctly (Table 6.5). When ecological variables from all fin types were used, the discriminant index successfully distinguished between all three of the functional groups (Wilks' $\lambda = 0.364$; $\chi^2 = 11.048$, df = 8, $P < 0.001$) and nine variables were identified as being most important for classifying each group (Table 6.6). Two discriminant functions explained 100% of the morphometric variance (*f*1 canonical correlation = 0.835, *f*2 canonical correlation =

0.797). The discriminant scores for each specimen from function 1 were plotted against the discriminant scores from function 2 to visually represent how well these functions differentiated each of the specimens (Figure 6.4a). Function 1 differentiated the *oceanic epipelagic* group from the *benthopelagic* group, while function 2 differentiated the *neritic epipelagic* group from all other categories (Figure 6.4a).

When fin types were analysed separately, caudal fins were most successful in separating functional groups overall, with 80% of hold-out samples classified correctly, followed by pectoral fins (78%) and dorsal fins (72%) (Table 6.6). However, when the classification percentages for each ecological group were considered, pectoral fins gave more consistent results, despite having lower classification values (75, 71.4, and 100% correctly classified, for the categories *benthopelagic*, *neritic epipelagic*, and *oceanic epipelagic*, respectively).

Five morphological variables were identified as being most important for classifying the three functional groups using pectoral fin measurements (Table 6.6). The discriminant index successfully distinguished between all three categories (Wilks' $\lambda = 0.593$; $\chi^2 = 58.453$, df = 4, $P < 0.001$). Two discriminant functions explained 100% of the morphometric variance (*f*1 canonical correlation = 0.757, *f*2 canonical correlation = 0.638). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from functions 2 to visually represent how well these functions differentiated each of the specimens (Figure 6.4c). Function 1 differentiated the *oceanic epipelagic* group from all other categories, while function 2 differentiated the *neritic epipelagic* group from the *benthopelagic* group (Figure 6.4c).

Five variables (morphological variables) were identified as being most important for classifying the three functional groups using caudal fin measurements (Table 6.6). The discriminant index successfully distinguished between all three categories (Wilks' $\lambda = 0.661$; $\chi^2 = 46.4$, df = 4, $P < 0.001$). Two discriminant functions explained 100% of the morphometric variance (*f*1 canonical correlation = 0.748, *f*2 canonical correlation = 0.582). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from functions 2 to visually represent how

well these functions differentiated each of the specimens (Figure 6.4d). Function 1 differentiated the *neritic epipelagic* group from the *benthopelagic* group, while function 2 differentiated the *oceanic epipelagic* group from all other categories (Figure 6.4d).

Three morphological variables were identified as being most important for classifying the three functional groups using dorsal fin measurements (Table 6.6). The discriminant index successfully distinguished between all three categories (Wilks' $\lambda = 0.838$; $\chi^2 = 19.9$, df = 2, $P < 0.001$). Two discriminant functions explained 100% of the morphometric variance (*f*1 canonical correlation = 0.677, *f*2 canonical correlation = 0.402). The discriminant scores for each sample from function 1 were plotted against the discriminant scores from functions 2 to visually represent how well these functions differentiated each of the specimens (Figure 6.4b). Function 1 differentiated the *oceanic epipelagic* group from all other categories, while function 2 differentiated the *neritic epipelagic* group from the *benthopelagic* group (Figure 6.4b).

Table 6.5 The classification results for hold-out samples of each of the four stepwise discriminant analyses using 1) all morphological variables (all fins), 2) morphological variables from the dorsal fin only (dorsal), 3) morphological variables from the pectoral fin only (pectoral), and 3) morphological variables from the caudal fin only (caudal). Results show the percent of samples classified in each category, with correct classifications shown in bold. The number of samples used (*n*) is shown. Analyses were conducted with the aim of discriminating between the three functional groups, *benthopelagic* (BP), *neritic epipelagic* (NE), and *oceanic epipelagic* (OE).

		BP	NE	OE	*n*	Global Accuracy %
all fins	*benthopelagic*	**80**	20	.	20	**82**
	neritic epipelagic	14.3	**85.7**	.	21	
	oceanic epipelagic	.	22.2	**77.8**	9	
dorsal	*benthopelagic*	**60**	35	5	20	**72**
	neritic epipelagic	19	**81**	.	21	
	oceanic epipelagic	.	22.2	**77.8**	9	
pectoral	*benthopelagic*	**75**	20	5	20	**78**
	neritic epipelagic	23.8	**71.4**	4.8	21	
	oceanic epipelagic	.	.	**100**	9	
caudal	*benthopelagic*	**85**	10	5	20	**80**
	neritic epipelagic	4.8	**85.7**	9.5	21	
	oceanic epipelagic	.	44.4	**55.6**	9	

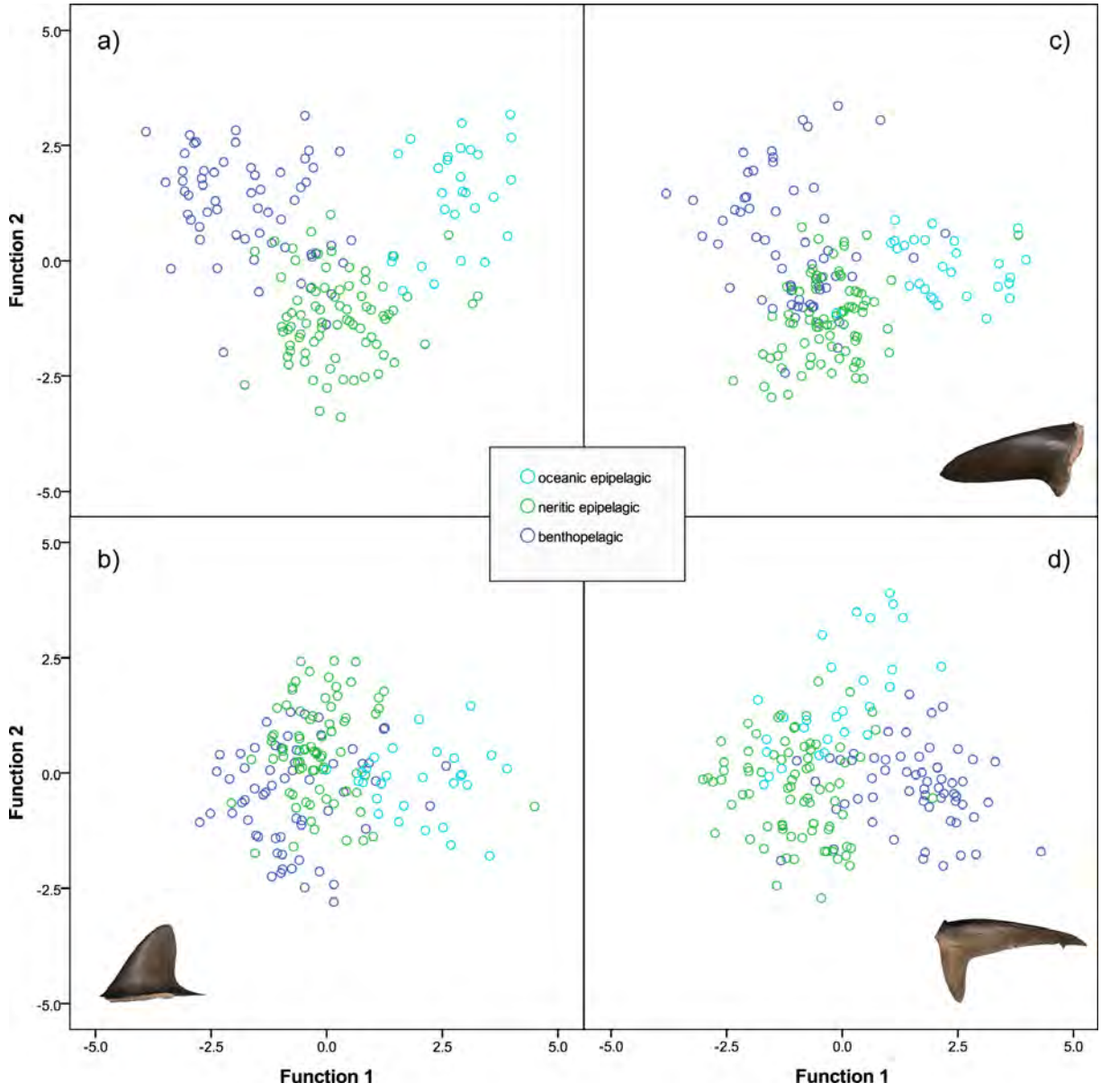


Figure 6.4. Three-dimensional plot of the results of four stepwise discriminant analyses using a) all morphological variables, b) morphological variables from the dorsal fin only, c) morphological variables from the pectoral fin only, and d) morphological variables from the caudal fin only. Each plot shows the first two discriminant functions from each discriminant analysis from the fins of 117 specimens from 19 carcharhinid species, where each species is assigned to one of the three functional groups *oceanic epipelagic*, *neritic epipelagic*, and *benthopelagic*.

Table 6.6. Classification function coefficients derived from Fisher's linear discriminant functions for each of the three functional groups *benthopelagic*, *neritic epipelagic*, and *oceanic epipelagic*. Classification functions are given for each of the four discriminant analyses.

	FP	*benthopelagic*	*neritic epipelagic*	*oceanic epipelagic*
All fins	D1AM	44.146	66.188	100.813
	D1PMI	11.296	34.621	23.385
	D1PMO	-13.188	0.824	62.755
	PFRT	49.266	43.484	23.585
	PH	8.210	11.029	15.810
	PPMO	190.353	154.161	266.076
	CPD	163.953	158.069	-18.634
	CTR	107.249	50.940	97.906
	CFW	1276.560	1155.487	1251.678
	(Constant)	-276.891	-235.145	-259.683
Dorsal	D1AM	22.050	31.016	61.825
	D1H	75.860	84.106	86.443
	D1PMO	85.253	80.346	156.315
	(Constant)	-37.412	-45.803	-57.447
Pectoral	PFRT	22.097	12.163	-3.739
	PAM	348.909	317.636	385.959
	PH	29.769	32.224	40.214
	PPMI	297.003	332.247	341.865
	PPMO	438.944	413.699	531.911
	(Constant)	-90.890	-89.737	-114.653
Caudal	CPD	-123.963	-100.202	-220.758
	CTR	1318.744	1295.634	1388.971
	CPU	994.155	1017.475	1033.611
	CFW	1521.030	1397.128	1435.455
	CPV	-84.770	-71.403	-53.205
	(Constant)	-645.657	-624.648	-655.599

6.4 Discussion

Although species-specific identification is the ultimate goal for morphological shark fin methods, this is not always practical. Despite the 80% success rate of the morphological identification technique developed in Chapter 4, other approaches are warranted. Often, gaining an insight into the broad ecosystem or habitat from where sharks have been captured provides useful information for the management of key habitats and regions. This study has revealed that carcharhinid sharks exhibit variations in fin morphology corresponding to function and ecology. As such, fin shape can be used to predict functional group with accuracy (80%), thus indicating that these findings have implications for fisheries management by enabling the identification of functional groups that are

most exploited in the shark catch. Furthermore, as the group of species investigated is known to be very morphologically similar, the results suggest that these methods can be successfully applied to other, more morphologically diverse, shark groups.

6.4.1 Shark Fin Ecomorphology

The Carcharhinidae are known to be a very morphologically similar group of shark species, however differences in fin morphology between each of the three functional groups were found during this study. These morphological differences could be related to the hydrodynamic role of each fin type and the swimming requirements associated with each habitat type.

Dorsal fins for sharks in the *oceanic epipelagic* group generally had a larger anterior margin, and inner posterior margin. A large inner posterior margin may act like a rudder and give added thrust during swimming, the trade-off of being an increase in drag during sharp turns. Conversely, the hydrodynamic sickle-shape of the dorsal fin of the *neritic epipelagic* species, compared to the *oceanic epipelagic* species, may provide greater manoeuvrability through a smaller turning radius achieved by reduced drag. As there is less chance of roll at slower swimming speeds there is less need for more upright, roll-stabilising fins. The *benthopelagic* species were found to have dorsal fins that were lower and more raked back than the *neritic epipelagic* or *oceanic epipelagic* species.

In terms of pectoral fin morphology, *oceanic epipelagic* species had longer, more outright, fins than *neritic epipelagic* or *benthopelagic* species. *Oceanic epipelagic* sharks such as *Prionace glauca* and *Carcharhinus longimanus* may have evolved long pectoral fins in response to a need to maximise hydrodynamic lift at slow cruising speeds in vast open water habitats (Fish & Shannahan 2000). Conversely, the hydrodynamic sickle-shape of the pectoral fins of the *neritic epipelagic* species, compared to *oceanic epipelagic* species, may reduce drag and therefore be more suitable for faster burst swimming and manoeuvrable turns, as opposed to slow cruising. The pectoral fins of the *benthopelagic* sharks were characterised by larger free rear tips and outer posterior margins,

which may aid in turning and manoeuvrability, as the posterior margins of the pectoral fins may aid in turning and breaking through differential drag (Lauder & Drucker 2004).

The caudal fin morphology of *benthopelagic* sharks was characterised by a larger caudal peduncle, a generally wider caudal fin, and a proportionally smaller lower caudal lobe. Such morphology is associated with the high acceleration (thrust) requirements more suited to burst swimming (Webb & Keyes 1982). Fish inhabiting more complex habitats, such as these *benthopelagic* sharks species, may require the ability for bursts of speed in order to capture prey that may escape into cryptic habitat refuges. In contrast, *oceanic epipelagic* sharks require continuous thrust in order to chase down fast moving prey in the open ocean.

Of the 19 species investigated, not all species fit discretely into their assigned functional group. While some species (*e.g. Prionace glauca*, *Rhizoprionodon* spp., and *Galeocerdo cuvier*) appeared to typify their group, there were a number of species that were found in an intermediary position between all habitat types (*e.g. Carcharhinus albimarginatus*, *C. amboinensis*, *C. leucas*, and *C. sorrah*). This is expected, as carcharhinid species tend to exploit a range of habitats, prey types and swimming styles resulting in a more generalist, and less specified, morphology. Indeed, many studies of form and function describe a continuum between one extreme to another, *e.g* the pectoral fin locomotion of labrid fishes (Wainwright, *et al.* 2002). The lack of distinction between groups may also be compounded by improper group assignment. As each species was assigned to one of the three functional groups based on their life history description in the literature, the habitat use of these species may not be entirely understood or accurately reflected. For example, *Carcharhinus falciformis* was assigned to the *oceanic epipelagic* group as it is widely considered to be an open ocean ranging shark (Compagno 2008). However, this species also frequents the edges of continental shelves and makes excursions into neritic habitats (Last & Stevens 2009). Consequently, *C. falciformis* was positioned between the oceanic and neritic types on the MDS plot. *Carcharhinus plumbeus* and *C. obscurus* were expected to fall in the *neritic epipelagic* section of the plot, however they were found toward the more *oceanic epipelagic* section. Although these two

species are common in inshore waters, they are also known to inhabit oceanic habitats off the continental shelf (Last & Stevens 2009). *Carcharhinus altimus* is known to be benthopelagic on the open ocean, therefore, although it was characterised as *benthopelagic,* it featured on the *oceanic epipelagic* side of the *benthopelagic* group on the multivariate plot (Figure 6.4).

This study has found differences in the fin morphology between carcharhinid species from diverse habitat types, which can be correlated with the functional requirements of living in those habitats. As habitat preference will influence many aspects of shark biology, such as diet, range or reproduction, these factors will affect ecosystems differently, which has implications for conservation and management.

6.4.2 Ecomorphology: Implications for Management and Conservation

Hundreds of thousands of species, in millions of transactions per year, are potentially encountered as part of the task of monitoring the international trade in wildlife (Fragoso & Ferriss 2008). Customs usually plays a prominent role in the implementation of both national and international policies for regulating wildlife trade across boarders, and as such, has an important responsibility in the quantification of such trade (Fragoso & Ferriss 2008). However, wildlife trade control comprises only a small fraction of the duties of customs officials (Fragoso & Ferriss 2008). Both effort and expertise are required to identify most animals to species, due to the inherent nomenclatural complexity involved. The difficulty of this task makes collection of the species-specific trade information required by conservation officials time consuming and unrealistic (Fragoso & Ferriss 2008). This problem is compounded when species are reduced to parts for trade (*e.g.* shark fins, herbal remedies, pelts, feathers). Nonetheless, a practical solution is required to monitor international trade of wildlife at a level of resolution that is useful for conservation assessment. While many complex morphological measurements were required in order to identify sharks to species using dorsal fin morphology (Chapter 4), only a few (5–9) measurements were needed in order to identify carcharhinid species to one of three functional groups with a high level

of accuracy. Although species-specific data is preferable, fisheries managers can use such functional groups in ecosystem models to predict the outcomes of changes to ecosystems. Indeed, if exploitation information is easier to identify at the functional group level, it is more likely that such data will be collected.

This study has demonstrated predictable differences in fin morphology between carcharhinid sharks from different ecological groups. It is therefore suggested that, in some circumstances, this may be a more effective method to assess the impact of exploitation on ecosystems as it requires less monitoring effort. Furthermore, as the methods were developed on such a morphologically similar group of sharks, it is expected that they can be applied successfully to other more diverse groups.

7

General Discussion: the triumphs and trade-offs of trade monitoring

7.1 Monitoring the Trade in Wildlife

The world is facing a large loss of wildlife due to overhunting (Bennett, *et al.* 2002, Robinson & Bennett 2000) and overfishing (Pauly, *et al.* 2003, Pauly, *et al.* 2005). The importance of these wild harvests for human food security is considerable (Allison, *et al.* 2009). Compounding this issue is that overexploitation is often interlinked between both terrestrial and marine ecosystems. In Ghana,

for example, years of poor fish supply coincided with increased hunting for bushmeat in nature reserves, resulting in sharp declines of 41 mammal species (Brashares, *et al.* 2004). The international trade in bushmeat and fisheries is estimated to be worth in excess of US$60 billion per year (Baker 2008) and ample profits can be made from selling endangered and vulnerable wildlife on the black market. For example, a vulnerable Komodo Dragon (*Varanus komodoensis*) can fetch around US$30,000, while a critically endangered Lear's Macaw (*Anodorhynchus leari*) can fetch up to US$90,000 (Wyler & Sheikh 2008). A significant portion of this trade is illegal and unregulated.

INTERPOL has estimated the global illegal wildlife trade to be worth between $ 7 billion and $20 billion annually, making it the second largest underground economy after the smuggling of drugs (Baker 2008). Indeed, the illegal wildlife trade and the drug trade are often interlinked, exemplified by a particularly shocking case that occurred in a Miami airport in 1993, where drug enforcement agents found 36 kilos of cocaine stuffed into 312 live Boa constrictors (*Boa constrictor*) imported from South America (Hoser 1994). Given the illicit nature of illegal trade, it is difficult to accurately assess and monitor the volumes and species involved (Chomel, *et al.* 2007, Eaton, *et al.* 2010). As the extent of exploitation is not quantified, the illegal wildlife trade undermines a number of nation's efforts to manage their natural resources sustainably. Quantifying illegal trade is therefore crucial to the effective management of natural resources, and conservation of vulnerable species or populations.

Often when animals are traded, they are reduced to parts, such as skins, paws, claws, skulls, teeth, powder, *etc*., which are distributed separately. Identifying these parts to species, size, number and geographic origin are major challenges when assessing the nature and scale of the illegal wildlife trade — this is especially true for developing protocols to enforce bans on the trade of protected species (*e.g.* CITES). Despite these challenges, trade markets represent the end-point of a supply chain and surveying products which originated from both regulated and unregulated sources can be the most effective means of estimating true levels of exploitation (Baker 2008). The biggest hurdle lies in developing reliable and standardised methods of estimation. Such methods should aim

to not only identify the species involved, but also gather data on the number of whole animals, the size and maturity status of the animal, and the overall biomass of that exploited resource. As such, this thesis focused predominantly on developing morphological techniques to achieve the aforementioned goals in one highly exploited group, coastal and oceanic sharks.

7.2 The Great Debate: Morphological or Molecular Species Identification?

Whole animals are typically identified to species using morphological characters, as found in many species guidebooks and keys, *e.g.* Last & Stevens (2009). However, animals exploited in the wildlife trade, particularity for food, medicine or clothing, are commonly traded as parts. In this case the traditional species guides are impractical and other identification methods must be employed. Molecular methods are commonly used, as the morphology of the animal does not need to be conserved, *e.g.* pinnipeds (Malik, *et al.* 1997), tigers (Wan & Fang 2003) and turtles (Roman & Bowen 2000). Indeed, the vast majority of solutions for identifying species in trade monitoring involve molecular methods, including the shark fin trade (Clarke, *et al.* 2005, Shivji, *et al.* 2008). However, genetic methods have numerous drawbacks and, given the already thin conservation resources, their use in favour of more simple morphological identification methods may not always be justified.

Molecular species identification methods are a relatively new tool in wildlife trade monitoring. These methods are particularly useful for identifying species that are traded when the original morphology of the animal is not conserved (*e.g.* bushmeat, ground powders), or when species are so morphologically similar that identification is extremely difficult, *e.g.* species of bluefin tuna (Viñas & Tudela 2009). Molecular methods produce species identifications with a high level of confidence, and as such they are useful as evidence in the prosecution of wildlife trade offences, such as CITES breaches (McDowall 2008). However, there are also considerable downfalls to molecular methods in the scope of trade management. Molecular methods are costly and, given the typically small budget allocated for conservation efforts, this makes it unfeasible for

quantifying large amount of trade data. Furthermore, these methods often require sequencing technology, which is a challenge for remote locations or third world countries that deal with wildlife trafficking (Cooper, *et al.* 2009). Degradation of DNA because of poor preservation and high bacteria levels, such as those onboard fishing vessels, can result in sequenceable product being unobtainable (Holmes, *et al.* 2009). In a study by Holmes *et al.* (2009), which attempted to use DNA barcoding to identify shark species from fins, 18 of the 211 pectoral fins examined did not provide a viable sequence. This is a real issue with traded animal parts, such as shark fins, as they are often stored and processed over a prolonged period in undesirable conditions. Although there are many benefits in using molecular based methods to identify species, they may not always be the most appropriate.

Identification of specimens based on morphology is more traditional, involving the use of visual characters, such as shape and colour. In many cases, this is the simplest solution as many species, even within genus, can be morphologically distinct (for example the Oceanic White-tip shark and the Blacktip Reef Shark). Morphological identification methods are cheap, fast, and do not usually require further lab analysis upon identification. As such, they are highly applicable for quantifying large volumes of trade data, a scenario often faced by trade monitors. Furthermore, morphological techniques can provide data resolution beyond identification alone, by providing information on the size, sex, number and volume of animals in a particular sample. This is critical when trying to quantify the impact of harvest on species and populations (see Chapters 1 and 5). In spite of this, successful use of morphological methods often requires a certain level of taxonomic expertise. Furthermore, morphological methods cannot be used when processing does not yield any conservable characters (*e.g.* multi-species powders). However, recent studies have aimed to address this problem by applying morphological techniques to the body parts of individuals further down the processing line *e.g.* hair (Espinoza, *et al.* 2008), bones (Cooper & Cooper 2008), and shark fins (Chapter 4).

7.3 Maximizing Information: Suggested Use of Identification Methods

To fully quantify trade, morphological and molecular methods may both need to be applied. The strengths and limitations of both techniques should be considered when quantifying trade data so that the most appropriate method is used, maximising conservation resources. When a trade-monitoring program is established, clear objectives should be outlined to both guide the data collection and maximise the efficiency of the program. It should be stressed that not every program or situation needs the application of all methods, and the use of the latest technology does not guarantee the best outcome. For example, Pank *et al.* (2001) used multiplex polymerase chain reactions (PCR) to distinguish tissue samples from the Sandbar Shark (*Carcharhinus plumbeus*) and the Dusky Shark (*C. obscurus*) as a 'rapid diagnostic method' for identifying traded fins of these two morphologically similar species. However, while studying these species during the course of my PhD research it was noted that the fins of these species can be easily distinguished by a simple investigation of the skin. The Sandbar Shark possesses skin that is covered in robust denticles, which is extremely difficult to cut with a knife, whereas the Dusky Shark has much weaker skin that is more easily pierced. In effect, the identification of their body parts can be more easily and cost-effectively solved using simple morphometric characters and techniques. Moreover, when faced with a pile of disassociated shark fins, it could be argued that the real problem is distinguishing that fins are indeed from these two species in the first place. In many monitoring programs, indeed most scientific undertakings, a key aim lies in collecting relevant, cost-effective data in short periods of time. Even though genetic methods provide very useful species identifications, the sample design must take into account how this data will be used and if the presence of a species in trade alone is sufficient to estimate the exploitation risk to that species (*i.e.* without size or biomass data).

Genetic and morphological methods should be implemented as a way to enforce trade bans and monitor the exploitation of species. Genetic methods are often considered more useful for prosecuting for the possession of protected species, identifying species from highly processed body

parts and assigning species or population origin. Morphometric methods are more useful for large-scale catch quantification (*e.g.* foreign fishing vessels (FFVs) and commercial catch verification), which can be used to assess population impacts as they can provide estimates of animal size, animal biomass and individual vessel catch data. Such information is highly relevant to fisheries management. Furthermore, morphometric methods may enhance the effectiveness of genetic applications by identifying appropriate samples for further analysis (*e.g.* identifying possible protected species from a pile of other specimens).

7.4 Morphological Approaches to Identifying Shark Body Parts

The goal of this study was to develop methods to quantify the catch composition of foreign fishing vessels, which can be used to estimate the impact of illegal fishing on shark stocks in northern Australia. One of the most significant outcomes of this study was the development of a protocol to identify sharks to the level of species using dermal denticles (Chapter 3) and dorsal fin morphology (Chapter 4).

Dermal denticles were found to vary markedly between species. These differences can be correlated with the different hydrodynamic requirements of the species. While they can sometimes prove difficult to see, and can not be viewed when skin is removed, the difference in denticle morphology can be used to discriminate between species, particularly in conjunction with other methods such as dorsal fin morphology. As fins are the primary locomotor and movement apparatus in sharks, various ecological requirements for each species manifest in a range of different fin morphologies. In this study, specific fin shapes were attributed to *oceanic*, *neritic* and *benthopelagic* functional groups (Chapter 6). Additionally, detailed morphological measurements and characteristics (*e.g.* fin-tip colour) of the dorsal fin were used to differentiate a number of Australian shark species (Chapter 4). Using these characters, a system was developed whereby isolated shark dorsal fins could be identified to species via a binomial key followed by discriminant analyses. The accuracy of this system was validated by concurrent genetic analysis of a subset of

FFV fins. Species-specific regression equations were also developed so that, once identified to species, the length of the original shark was estimated.

To demonstrate the applicability of these protocols, the shark catch (as dorsal fins) of 15 FFVs from northern Australian waters was examined (Chapter 5). This yielded the first information on the length-frequency, maturity stage and biomass for individual species, as well as provided the first detailed data on the catch composition and impact of foreign fishing vessels in northern Australia. Such information highlighted the presence of high-risk species in the catch and highlighted that vessel type is a key factor to the impact of FFVs. Lastly, this is the first study to have quantified the shark catch of illegal Indonesian FFVs operating in northern Australian waters and as such, collected data and the application of methods developed by this project are fundamental to effective management of shark stocks in northern Australia.

7.5 Strengths and Limitations

A key consideration in this study was its cost-effectiveness. This is particularly important for future applications, as funding and resources are generally limited for the study and management of shark fisheries. Secondly, this project generated a large volume of accurate data that was largely collected *in situ* at fish markets and vessel apprehensions. The application of these methods can provide significant advances to assessments in both legal and illegal fisheries. Effective assessments of fishing impact are largely predicated upon the resolution of catch data. Comprehensive data (*e.g.* incorporating length and maturity, biomass, vessel type and location, gear type *etc.*) ultimately leads to the prioritisation of management strategies for at-risk species or populations. Advancing the proposed methods will allow such strategies to be implemented in a variety of fisheries, and this is the most significant outcome of this study. Methods were also validated using actual fins from real foreign fishing vessels.

Despite the importance of gaining high resolution catch data, not all species could be identified in this study. While the ideal is to identify each fin to a species, for some closely related

species this was not possible using the methods employed in this study. However, when this was the case these specimens could be identified to a smaller group of two or three species, called pseudo species. Although, ideally they should be identified to species, narrowing down to a smaller group of species still provides useful catch data for the majority of specimens and was adequate for the purpose of this study. Considering accuracy of of the catch data for many Australian commercial shark fisheries at present — where shark species are still reported in broad categories (such as 'black tip') and logbook data is questionable — the species identifications generated by the method in Chapter 4 represent a vast improvement. To further improve catch information, future studies should focus on designing ways to identify the species within the pseudo species groups.

In terms of limitations of the methods, there will be instances where the quality of the shark fin samples will hinder the identification process, *e.g.* where fins are highly dried or processed, or when fins are cut so that the fin origin and fin insertion are not preserved. There are also instances where quality of the sampling procedure will affect the success of the identification protocol, *e.g.* where photograph quality is affected by incorrect placement of the shark fin specimen. The level of access to specimens, *i.e.* whether samples are in the possession of the sampler, will also affect the ability to take adequate photos. The greatest limitation, in terms of the methods, is the complexity of the identification procedure. As the aim was to produce user-friendly methods, this represents a major shortcoming. Nevertheless, this represents the first study of its kind and has demonstrated that the methods developed are cost-effective, accurate, and can be used to generate a large amout of useful catch data for shark fisheries — particularily for the previously unaccounted for IUU component of the catch. The method represents a demonstration of the feasibility of using photographs to identify sharks to species using shark fins. In order for the method to be put into practice, it is suggested that it is expanded upon using outline shape analysis and then incorporated into an automated system such as a computer program.

A major challenge to the completion of this work was sample collection. Shark fins are extremely valuable, and thus, they could not be sourced from fishermen on a regular basis.

Therefore, specimens had to be obtained opportunistically from researchers, government initiatives (*e.g.* shark net beach protection programs) and photographing whole sharks in markets. As a result, the data consisted of samples of various origin and quality, and the desired number of specimens were not collected for all species. Because I did not collect all specimens myself, not all of them came with associated data, such as total length and sex. Future studies that use an opportunistic sampling method of similar high-value products should take into account the time required to collect an adequate amount of samples from a wide range of species.

Identification of species is possible using pectoral fins, and although the use of these fins was explored, it was not included in this thesis, as a single dorsal fin represents one animal and the similarity of the methods for fin identification made the inclusion redundant. However, in future, this should be applied to further advance the ability to quantify catch composition.

Robust stock assessments often require the sex-ratios of targeted species to be determined (Morgan & Burgess 2005). Although the identification of sex specific data was an aim of the project, quality data from known samples was lacking and could not be completed. However, it is clear that such data can be generated in future, especially through the analysis of excised pelvic fins as these can have key diagnostic features (*i.e.* claspers) attached.

Although the first estimates of the total biomass removed by FFVs were determined, a lack of quality data also hindered the ability to distinguish the catch of FFVs in terms of the varying gear types, vessel types, and fishing regions (Chapter 5). Understanding how catch can vary with respect to the aforementioned parameters will facilitate more accurate estimations of the impact of foreign fishing. Despite the variability surrounding the catch estimate that was made, it was nonetheless the first attempt to provide a figure for the illegal take of sharks in northern Australia. In this way, such an estimate provides a benchmark for assessing the real impact of this fishery on Australian shark stocks.

Perhaps the most significant challenge with respect to the effectiveness of these methods on the successful management of shark fisheries is in their adoption by fisheries managers. Aiding this

adoption is that the developed methods were applied to the highest number of species by any previous study investigating shark fins. However, as many of these species were morphologically similar, identification procedures remain complicated. As such, the obvious follow-up for this project is the incorporation of these results (or the further advancement of methods) into an integrated automated computer program, pending uptake of management.

7.6 Fins: The Future of Shark Management?

The recently released Australian Shark Report (Bensley, *et al.* 2010) identified a major need for alternative approaches to validate shark catch data in order to provide more reliable assessments and management strategies of shark species. The methods developed in this thesis fit this requirement: shark fins may offer the best estimate for total mortality to a shark population (Chapter 1).

The effect of illegal foreign fishing on the composition of shark and ray fauna in northern Australia cannot be quantified without also examining baseline data from which to gauge the level of change. It is a race to document the complex species assemblage before they are considerably affected by over-exploitation. This may have already occurred for northern Australian shark stocks, but without comprehensive collection of such data, this cannot be confirmed. As such, a fast, easy, and cost-effective method for collecting baseline data on species compositions is urgently needed. For example, botanists from the Smithsonian Institute are currently using a handheld plant identification system to achieve these objectives to document the complexity of the Earth's flora (Belhumeur, *et al.* 2008). The system captures an image of a plant leaf and, after a few seconds of shape analysis, provides the best matching species, along with descriptions and additional images (Belhumeur, *et al.* 2008). A similar system could be developed, from the methods in this thesis, to identify shark species from their fins. Indeed, Gaston & O'Neill (2004) believe that the greatest challenge to the development of rapid automated species identification from digital images is not due to practical considerations, but rather a lack of vision and enterprise.

8 References

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9 Appendices

9.1 Genetic Methods

Authors: Jenny Giles and Lindsay Marshall[5]

Validation of morphological methods to identify shark fins sourced from foreign fishing vessels ('unknown' category) was performed using mitochondrial DNA evidence in two ways. Firstly, a small subset of fins were identified using the COI region (Holmes, *et al.* 2009, Ward, *et al.* 2008) and morphological methods. Secondly, a larger subset of fins were identified using the control region (Ovenden, *et al.* 2007) and morphological methods. Both DNA regions have the capacity to identify shark tissues to species level for those species included in the study (Ovenden, *et al.* 2007), and each region has its own strengths and limitations. In addition to this, using the control region sequence to identify fins is part of an ongoing study by Jenny Giles for her current PhD thesis titled '*Population structure of Indo-West Pacific sharks and large batoids (< 10 spp), with forensic applications to the fin trade'*.

The control region method for identification of shark fins from foreign fishing vessels was developed in direct comparison with COI methods, using tissue samples from whole elasmobranch specimens (Ovenden, *et al.* 2007). Corresponding elasmobranch specimens (n≤5 per species) were used to generate the reference sequences using both markers, including all species groups identified

[5] The author did not devise the methodology for, or carry out, the genetics component of this work, however it was integral for validating the morphological fin ID methods developed by the author. Therefore, it was decided that it was important to include a description of the genetic methods in this thesis as an appendix and the section was co-authored by Jenny Giles (who performed the genetic work) and Lindsay Marshall.

in Table 9.1 as morphological species categories in the current study, with the exception of *Alopias superciliosus* (Ovenden et al, 2007).

COI region

For each group of species that was identified using morphological methods in the 'unknown' category, a tissue sample was identified to species using the COI region (Holmes, *et al.* 2009, Ward, *et al.* 2008), resulting in 17 species identifications (17 species groups were identified at the time of testing). This served as a validation of the identity of fins representing the species categories as identified by morphological methods (Table 9.1). This work was performed by Jenny Ovenden and Jessica Morgan of the Molecular Fisheries Laboratory (Queensland Government).

Using the COI region, the 17 samples were each identified to species (Table 9.1). Sixteen of these samples correlated with the morphological identifications that were assigned. The remaining sample was identified as *Carcharhinus tilstoni* using the COI region, however this species could not be separated from *C. limbatus* using morphological methods.

Control Region

A subset of 197 dorsal fins from the 'unknown' category were sequenced using the control region method (Ovenden, *et al.* 2007), with subsequent assignments given in Table 9.1. Of the 197 specimens, 38 were assigned to a species complex rather than a single species, due to either incomplete sequences and/or previously unsampled haplotypes where species have very low interspecific variation in the control region fragment of interest.

Fourteen specimens were most similar to *Carcharhinus altimus* or *C. plumbeus*, seven specimens were most similar to *Carcharhinus amblyrhynchoides*, *C. limbatus* or *C. tilstoni*, and 15 specimens were most similar to *Carcharhinus limbatus* or *C. tilstoni*. Two specimens were assigned as *Rhynchobatus* spp. due to a recent redescription of the genus and need to review the status of the reference samples (Table 9.1). Three fins were categorised as 'No match'. FFVLM_3_006 was

most similar to sharks in the genus *Carcharhinus*, and FFVLM_14_009 and FFVLM_14_011 were most similar to, but different from, *Loxodon macrorhinus* in the reference database.

This work was performed by Jenny Giles (School of Biological Sciences, University of Queensland) as part of her ongoing PhD thesis work into population-level variation in a number of Indo-West Pacific shark species. Limitations in species coverage and sample size therefore reflect aspects of the current study that fell outside the scope of the PhD study.

To indicate the relationship between identifications produced by both DNA methods in the current study, samples were chosen for the COI sequencing that had already been sequenced for the control region where possible. Eight of the nine samples that were identified using both the COI region and the control region produced the same species identification using both methods, with the exception that the control region sequence for FFVLM_3_007 was most similar to either *Carcharhinus limbatus* or *C. tilstoni*, whereas the COI sequence was identified by the Ovenden lab as *C. tilstoni* (Table 9.2).

Table 9.1 Species identifications for 17 shark dorsal fin tissue samples using three different identification methods. 'COI' corresponds to molecular identifications using the COI region. 'LM Morphological ID' corresponds to samples that were identified using morphological techniques. . 'Control Region' corresponds to molecular identifications using the control region. *Not included in the Giles study.

Specimen ID	COI	LM Morphological ID	Control Region
FFVLM_1_0599	*Carcharhinus albimarginatus*	*C. albimarginatus*	*C. albimarginatus*
FFVLM_1_0678	*Carcharhinus altimus*	*C. altimus*	*C. altimus*
FFVLM_3_007	*Carcharhinus tilstoni*	*C. limbatus/tilstoni*	*C. limbatus/tilstoni*
FFVLM_1_1615	*Carcharhinus obscurus*	*C. obscurus*	*C. obscurus*
FFVLM_1_1760	*Carcharhinus plumbeus*	*C. plumbeus*	*C. plumbeus*
FFVLM_1_0551	*Prionace glauca*	*P. glauca*	*
FFVLM_1_0603	*Alopias vulpinus/superciliosus*	*A. superciliosus*	*
FFVLM_1_0786	*Isurus oxyrinchus*	*I. oxyrinchus*	*
FFVLM_1_1794	*Isurus paucus*	*I. paucus*	*
FFVLM_1_0584	*Sphyrna zygaena*	*S. zygaena*	*S. zygaena*
FFVLM_1_0592	*Galeocerdo cuvier*	*G. cuvier*	*G. cuvier*
FFVLM_1_0613	*Carcharhinus longimanus*	*C. longimanus*	*C.longimanus*
FFVLM_1_0673	*Carcharhinus falciformis*	*C. falciformis*	*C. falciformis*
FFVLM_1_1771	*Carcharhinus brevipinna*	*C. brevipinna*	-
FFVLM_19_006	*Carcharhinus leucas*	*C. leucas*	-
FFVLM_20_035	*Carcharhinus amblyrhynchos*	*C. amblyrhynchos*	-
FFVLM_6_001	*Carcharhinus melanopterus*	*C. melanopterus*	-

Table 9.2 Tally of specimens (n) assigned to species categories using control region sequences after Ovenden *et al.*, 2007.

Result	*n*
Carcharhinus albimarginatus	8
Carcharhinus altimus	16
Carcharhinus altimus/plumbeus	14
Carcharhinus amblyrhynchoides/limbatus/tilstoni	7
Carcharhinus amblyrhynchos	3
Carcharhinus brevipinna	4
Carcharhinus dussumieri	8
Carcharhinus falciformis	7
Carcharhinus leucas	1
Carcharhinus limbatus/tilstoni	15
Carcharhinus longimanus	5
Carcharhinus macloti	10
Carcharhinus obscurus	39
Carcharhinus plumbeus	8
Carcharhinus sorrah	25
Eusphyra blochii	1
Galeocerdo cuvier	2
Rhynchobatus spp.	2
Sphyrna lewini	6
Sphyrna mokarran	4
Sphyrna zygaena	9
NO MATCH	3
	197

9.2 Verification of Visual Identifications

In order to test the accuracy of the visual identification skills of the author, 198 samples from 'unknown' dorsal fins that were collected from illegal fishing vessels were identified using two methods and the results compared. First, each dorsal fin was identified visually by the author, then each dorsal fin was identified using the control region genetic method described in Appendix 9.1. The results are shown in Table 9.3. Of the 198 specimens tested, 191 (96.5%) were identified correctly by the author. That is, the visual identification was congruent with the species identification resulting from genetic methods.

Table 9.3 Species identification results for 198 samples from 'unknown' dorsal fins collected from illegal fishing vessels. First, each dorsal fin was identified visually by the author (LM ID), then each dorsal fin was identified using the control region genetic method described in Appendix 9.1.

Sample Number	LM ID	Genetic ID
FFVLM_1_0599	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_1_0600	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_1_0602	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_1_1284	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_9_034	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_9_092	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_9_094	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_9_099	*Carcharhinus albimarginatus*	*Carcharhinus albimarginatus*
FFVLM_1_0671	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0672	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0678	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0684	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0705	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0794	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0795	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_0796	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1630	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1631	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1635	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1636	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1797	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1800	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1805	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1808	*Carcharhinus altimus*	*Carcharhinus altimus*
FFVLM_1_1633	*Carcharhinus altimus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1634	*Carcharhinus altimus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1796	*Carcharhinus altimus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1802	*Carcharhinus altimus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1804	*Carcharhinus altimus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1810	*Carcharhinus altimus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_5_009-10	*Carcharhinus amblyrhynchos*	*Carcharhinus amblyrhynchos*
FFVLM_5_009-7	*Carcharhinus amblyrhynchos*	*Carcharhinus amblyrhynchos*
FFVLM_5_009-8	*Carcharhinus amblyrhynchos*	*Carcharhinus amblyrhynchos*
FFVLM_5_009-3	*Carcharhinus amblyrhynchos*	*Carcharhinus sorrah*
FFVLM_1_0814	*Carcharhinus amboinensis*	*Carcharhinus obscurus*

Sample Number	LM ID	Genetic ID
FFVLM_9_118	*Carcharhinus amboinensis*	*Carcharhinus obscurus*
FFVLM_11_005	*Carcharhinus brevipinna*	*Carcharhinus brevipinna*
FFVLM_16_174	*Carcharhinus brevipinna*	*Carcharhinus brevipinna*
FFVLM_5_003	*Carcharhinus brevipinna*	*Carcharhinus brevipinna*
FFVLM_3_011	*Carcharhinus brevipinna*	*Carcharhinus limbatus/tilstoni*
FFVLM_10_017	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_10_023	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_10_024	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_12_003	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_16_018	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_16_019	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_16_023	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_16_035	*Carcharhinus dussumieri*	*Carcharhinus dussumieri*
FFVLM_1_0677	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_1_0690	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_1_0700	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_9_148	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_1_1696	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_1_1712	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_1_1745	*Carcharhinus falciformis*	*Carcharhinus falciformis*
FFVLM_9_052	*Carcharhinus leucas*	*Carcharhinus leucas*
FFVLM_5_009-11	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_006	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_008	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-10	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-5	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-9	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_009-5	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_16_164	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_009-12	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_009-13	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_002	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_002	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_004	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_007	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_007-1	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_011-1	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-1	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-2	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-3	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-6	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_3_017-8	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_5_009-9	*Carcharhinus limbatus/tilstoni*	*Carcharhinus limbatus/tilstoni/amblyrhynchoides*
FFVLM_1_0618	*Carcharhinus longimanus*	*Carcharhinus longimanus*
FFVLM_1_0619	*Carcharhinus longimanus*	*Carcharhinus longimanus*
FFVLM_1_0777	*Carcharhinus longimanus*	*Carcharhinus longimanus*
FFVLM_1_0781	*Carcharhinus longimanus*	*Carcharhinus longimanus*
FFVLM_9_153	*Carcharhinus longimanus*	*Carcharhinus longimanus*
FFVLM_10_013	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_10_015	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_10_016	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_10_022	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_16_037	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_16_038	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_16_175	*Carcharhinus macloti*	*Carcharhinus macloti*
FFVLM_1_0646	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0650	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0654	*Carcharhinus obscurus*	*Carcharhinus obscurus*

Sample Number	LM ID	Genetic ID
FFVLM_1_0655	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0659	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0667	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0811	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0812	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0813	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1281	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1600	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1601	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1602	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1603	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1614	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1615	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1616	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1617	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1619	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1620	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1621	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1622	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1623	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1624	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1626	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1628	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1629	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1780	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1781	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1783	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1784	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1786	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1787	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1788	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1789	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1791	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_1792	*Carcharhinus obscurus*	*Carcharhinus obscurus*
FFVLM_1_0806	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_0807	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_0808	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_0810	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1283	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_9_097	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_3_001	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_1759	*Carcharhinus plumbeus*	*Carcharhinus altimus* or *plumbeus*
FFVLM_1_0610	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_1_0804	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_1_0805	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_1_0809	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_1_0816	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_14_001	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_1_1758	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_1_1760	*Carcharhinus plumbeus*	*Carcharhinus plumbeus*
FFVLM_10_001	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_002	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_003	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_004	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_005	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_006	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_007	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_008	*Carcharhinus sorrah*	*Carcharhinus sorrah*

Sample Number	LM ID	Genetic ID
FFVLM_10_009	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_010	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_011	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_10_012	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_12_005	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_14_005	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_14_007	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_16_151	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_16_152	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_16_153	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_5_009-1	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_5_009-2	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_5_009-4	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_3_013	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_5_009-6	*Carcharhinus sorrah*	*Carcharhinus sorrah*
FFVLM_16_182	*Eusphyra blochii*	*Eusphyra blochii*
FFVLM_9_053	*Galeocerdo cuvier*	*Galeocerdo cuvier*
FFVLM_5_005	*Galeocerdo cuvier*	*Galeocerdo cuvier*
FFVLM_3_008	*Galeocerdo cuvier*	*Galeocerdo cuvier*
FFVLM_13_003	*Glaucostegus typus*	*Glaucostegus typus*
FFVLM_13_004	*Glaucostegus typus*	*Glaucostegus typus*
FFVLM_13_005	*Glaucostegus typus*	*Glaucostegus typus*
FFVLM_14_009	*Loxodon macrorhinus*	NO MATCH
FFVLM_14_011	*Loxodon macrorhinus*	NO MATCH
FFVLM_16_097	*Rhizoprionodon* spp.	*Carcharhinus macloti*
FFVLM_16_140	*Rhizoprionodon* spp.	*Carcharhinus macloti*
FFVLM_16_141	*Rhizoprionodon* spp.	*Carcharhinus macloti*
FFVLM_15_001	*Rhynchobatus* spp.	*Rhynchobatus* spp.
FFVLM_15_002	*Rhynchobatus* spp.	*Rhynchobatus* spp.
FFVLM_15_003	*Rhynchobatus* spp.	*Rhynchobatus* spp.
FFVLM_1_0802	*Sphyrna lewini*	*Sphyrna lewini*
FFVLM_12_017	*Sphyrna lewini*	*Sphyrna lewini*
FFVLM_9_029	*Sphyrna lewini*	*Sphyrna lewini*
FFVLM_9_126	*Sphyrna lewini*	*Sphyrna lewini*
FFVLM_5_001	*Sphyrna lewini*	*Sphyrna lewini*
FFVLM_1_1769	*Sphyrna lewini*	*Sphyrna lewini*
FFVLM_9_035	*Sphyrna mokarran*	*Sphyrna mokarran*
FFVLM_9_120	*Sphyrna mokarran*	*Sphyrna mokarran*
FFVLM_9_124	*Sphyrna mokarran*	*Sphyrna mokarran*
FFVLM_3_005	*Sphyrna mokarran*	*Sphyrna mokarran*
FFVLM_1_0584	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0585	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0588	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0589	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0789	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0790	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0791	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0792	*Sphyrna zygaena*	*Sphyrna zygaena*
FFVLM_1_0793	*Sphyrna zygaena*	*Sphyrna zygaena*