LETTER

Global estimates of shark catches using trade records from commercial markets

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Abstract

Despite growing concerns about overexploitation of sharks, lack of accurate, species-specific harvest data often hampers quantitative stock assessment. In such cases, trade studies can provide insights into exploitation unavailable from traditional monitoring. We applied Bayesian statistical methods to trade data in combination with genetic identification to estimate by species, the annual number of globally traded shark fins, the most commercially valuable product from a group of species often unrecorded in harvest statistics. Our results provide the first fishery-independent estimate of the scale of shark catches worldwide and indicate that shark biomass in the fin trade is three to four times higher than shark catch figures reported in the only global data base. Comparison of our estimates to approximated stock assessment reference points for one of the most commonly traded species, blue shark, suggests that current trade volumes in numbers of sharks are close to or possibly exceeding the maximum sustainable yield levels.

Keywords

Bayesian, extrapolation, fin, fishery, sampling, species, sustainable yield, wildlife.

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INTRODUCTION

Quantitative assessment of the status of exploited animal populations usually requires accurate counts of individuals harvested over time (Schaefer 1954; Lande *et al.* 2003). However, when a substantial portion of the population off-take is illegal, unregulated or unreported, actual harvested numbers are highly uncertain, and intervention for conservation purposes may be hampered by calls for collection of better data. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) has recognized that trade monitoring is critical in protecting biodiversity, but most trade data remain decoupled from population models used to estimate sustainable yields for

management. There is a growing body of research aimed at determining the origin of animal products suspected to derive from illegal harvests (Birstein *et al.* 1998; Roman & Bowen 2000; Wasser *et al.* 2004; Shivji *et al.* 2005) but only a few studies (Baker *et al.* 2000; Dalebout *et al.* 2002) have obtained sufficient market access to allow conclusions regarding population impacts.

Reported declines in shark populations (Baum *et al.* 2003; Ward & Myers 2005) and a shark fin trade driven by rapid economic growth in China (Clarke 2004a) make sharks an especially relevant example of the need for trade studies. Despite their vulnerability to overfishing (Walker 1998; Castro *et al.* 1999), and the listing by CITES of some shark species, i.e. basking (*Cetorhinus maximus*), whale (*Rhincodon*

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typus) and great white (*Carcharodon carcharias*), sharks are generally ignored or given a low priority in most fisheries management organizations due to their characterization as bycatch and low value per unit weight (Shotton 1999; Fowler *et al.* 2005). The resulting lack of catch or landings data for sharks severely inhibits the types of assessments conducted for more data-rich fishery species. However, shark fins are a highly valued commodity and are being sourced globally through market channels concentrated in a handful of Asian trading centres (Clarke 2004b). Notwithstanding the secretive and wary nature of the shark fin trade, monitoring these markets may currently be the best option for determining shark exploitation levels and species pressures worldwide.

This study extends our previous work to assess the impact of the shark fin trade on shark species using data collected in Hong Kong, the world's largest shark fin entrepôt. In an earlier study we estimated the total traded fin weights in Hong Kong auctions for 11 common Chinese trade name categories (comprised of fins from one or more species), each classified according to four different fin positions: dorsal (first only), pectoral, caudal (lower lobe only), and other (Clarke *et al.* 2004). Our empirical data included records from at least one auction held by each trader during the period October 1999 to March 2001 and overall comprised 29% of the total number of auctions. We used Bayesian imputation methods (Little & Rubin 1987; Rubin 1996) to probabilistically simulate missing data while taking into account uncertainty in model formulation and parameter values. Once the total weight of auctioned fins over the 18-month period was estimated, we found that fins in the 44 studied product type-fin position categories jointly represented *c.* 46% of the total (Clarke *et al.* 2004).

In a subsequent study (Clarke *et al.* 2006), we produced taxon-specific fin weight estimates, and described species composition, in the Hong Kong auctions. This was accomplished by combining market sampling and genetic methods (Shivji *et al.* 2002) to derive concordances between Chinese trade names and taxa. These species-specific adjustments reduced traded weight quantities in each category by 0–35%, but typically resulted in < 1% change in the percentage distribution of fin weights among species-specific categories for the entire market.

Building upon these previous studies, we now convert species-specific fin weights in the Hong Kong market to worldwide estimates of shark catch in numbers and biomass. Our Bayesian modelling framework accounts for joint uncertainties arising from each step and the resulting probability intervals (PIs) for estimated quantities thus summarize the total uncertainty in the estimates, providing an objective means of judging the overall reliability of the estimation. Our results represent the first fishery-independent estimate of the global shark catch for the shark fin trade,

and allow us to contrast this estimate with existing shark catch records and assess the potential impacts on one commonly traded shark species, the blue shark. In addition to its application to sharks, the combined trade-based quantitative and genetic forensic approach used here to assess global exploitation levels provides a framework applicable to other heavily traded, but largely unregulated animal products (Vincent 1996; Thorbjarnarson 1999; Milner-Gulland & Bennett 2003).

METHODS

Estimation of the number of sharks represented

To relate estimates of auctioned fin weights (Clarke *et al.* 2004) to whole shark equivalents, a series of conversion factors was applied in an integrated Bayesian estimation framework using WinBUGS software (Anon. 2004). To produce estimates of the number of sharks present, we estimated the mean weight of a single fin in each species-fin position category (e.g. blue shark-dorsal fin) and used it as the divisor for the total weight of fins in that category (Clarke *et al.* 2004). The resulting estimate of the number of fins present in each category was assumed to be equivalent to the number of sharks for either dorsal or caudal fins, or twice the number of sharks for pectoral fins.

Three data sets were required to estimate the mean weight of single fins in a species-fin position category. First, data on fin sizes provided on each auction sheet in qualitative categories were translated into six arbitrary, numerical classes (c). Auction records, consisting of numbers and often weights of bags of fins by size class, were sorted by species-fin position (s, p) category (11 species by three fin positions) and the proportion of fins (by number of bags, see Clarke *et al.* 2004) in each of the six size classes was obtained. Second, each size class in each species-fin position category was assigned a fin length midpoint and range based on observations of each category-class at 17 Hong Kong auctions over a 4-month period ($n = 179$). Informal interview information from cooperative traders was also used to assign the fin length midpoints for each class size. The assigned midpoint lengths of dorsal, pectoral and caudal fins for each species were cross-checked using ratios (each fin's length as a proportion of pre-caudal length) from taxonomically accurate drawings and observed whole length ranges (Compagno 1984) to ensure they were realistic. Third, a cooperative trader allowed length–weight measurements to be taken for 10–20 fin samples from each species-fin position category ($n = 397$) thus providing the basis for conversion from fin length to fin weight.

Prior probability distribution functions were assigned for the average number of fins per bag and fin lengths. A log-linear relationship between fin length and fin weight was

used to obtain mean fin weight for each species-fin position category (see Appendix A). In the final step, for each species-fin position category the annual total auctioned weight ($W_{s,p}^{\text{tot}}$) was divided by the mean fin weight $\bar{W}_{s,p}$ to produce an estimate of the number of fins and corresponding number of sharks ($N_{s,p}$):

$$N_{s,p} = \frac{W_{s,p}^{\text{tot}}}{\bar{W}_{s,p}}. \tag{1}$$

Results for dorsal, pectoral and caudal fins provided independent estimates of the number of sharks represented.

Estimation of shark biomass represented

Estimates of shark biomass were developed using an algorithm which converted the mean dry fin length estimate used in the previous algorithm to a mean wet fin length, then related the mean wet fin length to the mean whole length of the shark and then to the shark's mean whole biomass. In the final step, mean whole shark biomass for each species-fin position ($\bar{B}_{s,p}^{\text{f}}$) was multiplied by the number of sharks estimated for that species-fin position combination ($N_{s,p}$) to produce an estimate of the total biomass of sharks supplying the fin trade ($B_{s,p}^{\text{tot}}$). Although this algorithm requires a greater number of steps, and thus incorporates a greater potential for uncertainty, estimates in units of biomass facilitate comparison with landed weights reported in fisheries statistics. The model equations for the steps outlined here are given in Appendix B.

In order to obtain shark biomass estimates, three additional conversion factor data sets were required. First, published data were sought on the relationship between dry fin length and wet fin length as rehydration experiments using Hong Kong fins would have been prohibitively expensive. The only available data were based on 28 blacktip shark (*Carcharhinus limbatus*) individuals (Fong 1999), but as the purpose of this conversion was merely to account for the change in fin length due to moisture loss during drying, results were not expected to vary considerably across species.

Second, data on the relationship between fin length and body length were compiled at the port of Su'Ao in eastern Taiwan. Data collection was constrained by the species composition of landings, occurrences of partial processing (e.g. heads removed and tails cut), and difficulties in accessing large sharks for measurement. Seven of the 11 species groups were sampled ($n = 79$) for fork length and length of all three fin positions. The remaining four species were assigned the parameters of the most appropriate sampled species, usually within the same genus, based on similarities in fin morphology. Dusky (*Carcharhinus obscurus*) and bull (*Carcharhinus leucas*) sharks were assigned the sandbar shark (*Carcharhinus plumbeus*) parameters, and the

great hammerhead (*Sphyrna mokarran*) was assigned the jointly estimated parameters from smooth and scalloped hammerheads (*Sphyrna zygaena* and *Sphyrna lewini*). Tiger sharks (*Galeocerdo cuvier*) are arguably most similar in fin morphology to sandbar or silky (*Carcharhinus falciformis*) sharks, but given the small size of silky shark individuals in the sample, and the relatively large size of tiger sharks, the sandbar shark parameters were believed to provide a better representation.

Third, published length–weight conversion factors, based on measurements of 5065 sharks from the western North Atlantic, were applied using fork length as the measurement standard (Kohler *et al.* 1995). All *Sphyrna* spp. conversions applied the published factors for *Sphyrna lewini* and all *Alopias* spp. conversions applied the published factors for *Alopias superciliosus*. Species-specific conversion factors for bull shark and oceanic whitetip (*Carcharhinus longimanus*), which were not included in Kohler *et al.* (1995), were drawn from Bonfil *et al.* (1990) and Lessa *et al.* (1999) respectively. As these latter length–weight relationships were based on total length, to convert from fork length, specific-specific conversion factors from Branstetter & Stiles (1987) for bull shark, and from Compagno (1984) for oceanic whitetip, were applied. Because there was insufficient information in these references to quantify error in the total length–fork length conversion factors, we assumed that they were precisely estimated.

Extrapolation to global trade volumes

Estimates of the annual number and biomass of sharks represented in the global shark fin trade (G) were obtained as follows:

$$G = N_p \times \frac{1}{k} \times \frac{1}{i} \times \frac{1}{w}, \tag{2}$$

where N_p is the sum of estimated fins over all species for a given fin position (or for biomass substitute B_p^{tot}, the biomass of sharks over all species for a given fin position); k is the proportion of auctioned fins included in the studied species categories (i.e. accounts for 'other' fins of unknown type which could not be fully modelled due to morphological uncertainties); i is the proportion of Hong Kong imports that were auctioned; and w is the proportion of global shark fin imports that passed through Hong Kong. When computing species-specific global totals, we assumed that all individuals of the given species were identified in the auction records as the market category corresponding to that species, and thus set the value of k to 1.

Due to the lack of information on product types not examined in this study, extrapolation by weight from studied to unstudied product types (k) assumed that the fin sizes and shapes represented in the 11 studied product types were representative of the unstudied product types. Based on

model-estimated proportions of unstudied fins (treated as a single, undifferentiated class), the median and 95% PI of the percentage of studied fins by weight were 45.9 and 43.7–48.2 respectively (Clarke *et al.* 2004). The percentage of auctioned fins within the total quantity of Hong Kong imports, i (median 17.4, 95% PI 16.3–18.6) was estimated using the posterior distribution for the total weight of auctioned fins per year (Clarke *et al.* 2004) and a uniform distribution representing the total quantity of fin imports to Hong Kong as recorded in government customs statistics for 2000 adjusted for water content of frozen fins. The range of this uniform distribution was specified by allowing the water content of frozen fins to vary between 70% and 80% (Clarke 2004b). Parameters k and i were formulated as random variables (RVs) using appropriate distributions based on these observed mean and variance values. The final extrapolation from Hong Kong quantities to the global trade, w, was based on ratios of the quantity of shark fins traded through Hong Kong to the sum of quantities traded through the major markets of Hong Kong, Mainland China, Singapore, Taiwan and Japan over the years 1996–2000 (Table 1; *sensu* Clarke 2004b). This analysis showed that Hong Kong's share of global imports varied between 44% and 59% with a mean of 52%, and thus values of w were drawn from a uniform distribution limited between 0.44 and 0.59. For deterministic calculations, the three extrapolation factors were combined into a base scenario formed from the midpoint of the range of each factor.

When combining results across fin positions to estimate totals in numbers and biomass, a mixture distribution was computed with the density function for each fin position weighted proportional to its precision. The use of a mixture distribution accurately accounts for uncertainty as it presumes that the actual value for abundance or biomass may come from any of the three fin positions with credibility proportional to the precision obtained for each fin position.

RESULTS AND DISCUSSION

Estimates of shark numbers and biomass

Model results were checked at two critical steps in the conversion factor algorithms to verify the reliability of the results for total numbers and biomass. As estimates of the number of sharks represented were strongly influenced by the estimates of mean single fin weights, estimated values of $\bar{W}_{s,p}$ were checked against deterministic estimates and empirical observations (Table 2). In seven of 33 instances, the deterministic values fell outside of the 95% PIs; in six of these cases, the deterministic values were higher than the 95th percentile. The largest outlier was observed for bull shark dorsal fins where the average deterministic fin weight value was 83 g higher than the 95th percentile. This was primarily because 76% of all bull shark dorsal fins were observed in the largest size class and unlike the Bayesian estimation, the deterministic computation ignored sampling error. All other outlying deterministic values were within ± 25 g beyond the PI.

Another critical step in the algorithm was the conversion from fin length to whole length and weight. Estimates of whole length and weight from the model were thus assessed against maximum and minimum values observed in nature to gauge the reliability of the algorithms (Table 3). This comparison revealed that caudal fin estimators usually produced the lowest 2.5th percentiles of whole length (in 91% of 22 length and weight predictions) and dorsal and pectoral fin estimators usually produced the highest 97.5th percentiles (in 45% and 55%, respectively, of 22 predictions). None of the model predictions exceeded the observed length or weight in nature. Comparisons between 2.5th percentiles and empirical values are not particularly useful as modelled length values below observed minimums may be accurate due to observed trading of fins from unborn sharks (S.C. Clarke, personal observation).

Table 1 Estimates of the traded quantity of shark fins (tonnes) based on national customs statistics and adjusted for observed under-reporting of Mainland China, Singapore, Taiwan and Japan relative to Hong Kong

Country	1996	1997	1998	1999	2000
Share of Mainland China, Singapore, Taiwan and Japan corrected for double-counting among these countries*	4690	4601	4399	4311	4637
Above share inflated by 1.3158 to adjust for 24% under-reporting*	6171	6054	5788	5672	6101
Hong Kong share corrected for double-counting*	4061	4414	4086	4489	5501
Estimate of total global trade	10 232	10 468	9874	10 161	11 602
Hong Kong imports without correction for double-counting*	4513	4868	5196	5824	6788
Hong Kong percentage of total (%)	44	47	53	57	59

As the purpose of the calculation is to determine the proportion of the total trade passing through Hong Kong, the total quantity traded through Hong Kong (regardless of whether these fins were enumerated in other countries; fifth row) is used as the numerator, and an accurate estimate of the total global trade (free of double-counting bias; fourth row) is used as the denominator.
*Data from Clarke (2004b).

Table 2 Posterior median and 95% probability intervals for weight of single fin (g) for each species-fin position combination, $\bar{W}_{s,p}$

Product type	Predominant species or genus	Dorsal (n = 125; min = 22; max = 305)		Pectoral (n = 127; min = 22; max = 643)		Caudal (n = 148; min = 14; max = 354)	
		Probabilistic	Deterministic	Probabilistic	Deterministic	Probabilistic	Deterministic
Ya Jian	*Prionace glauca* (blue)	41 (37–45)	43	138 (124–153)	114*	30 (24–36)	37*
Qing Lian	*Isurus oxyrinchus* (shortfin mako)	159 (118–210)	149	127 (109–151)	140	170 (142–200)	167
Wu Yang	*Carcharhinus falciformis* (silky)	190 (159–228)	202	139 (124–155)	135	54 (45–62)	59
Hai Hu	*Carcharhinus obscurus* (dusky)	198 (153–232)	229	174 (153–199)	172	63 (45–75)	96*
Bai Qing	*Carcharhinus plumbeus* (sandbar)	197 (173–224)	217	139 (115–165)	139	51 (40–61)	56
Ruan Sha	*Galeocerdo cuvier* (tiger)	189 (113–253)	230	117 (93–153)	122	30 (13–50)	44
Chun Chi	*Sphyrna* spp. (except *Sphyrna mokarran*) (hammerheads)	79 (62–98)	88	93 (80–107)	125*	60 (52–67)	62
Gu Pian	*Sphyrna mokarran* (great hammerhead)	166 (103–239)	137	138 (111–166)	160	59 (36–76)	76
Wu Gu	*Alopias* spp. (threshers)	117 (92–142)	134	194 (165–228)	190	22 (17–27)	19
Sha Qing	*Carcharhinus leucas* (bull)	245 (198–281)	364*	220 (185–258)	196	66 (41–82)	85*
Liu Qiu	*Carcharhinus longimanus* (oceanic whitetip)	189 (163–213)	172	84 (75–94)	119*	48 (39–58)	52

Weights deterministically calculated using the fin length midpoints ($\mu_{\bar{L}_{s,p|c}}$), the mean slopes ($\mu_{a1_{s,p}}$) and intercepts ($\mu_{b1_{s,p}}$), and the observed proportions in each size class ($b(c)_{s,p}$), are also shown. Deterministic values lying outside the predicted 95% probability intervals are marked with an asterisk.

Table 3 Comparison between estimated whole shark lengths, $\bar{T}_{s,p}$ (cm, fork length) and weights $\bar{B}_{s,p}$ (kg), and observed maximum and minimum shark lengths and weights

Product type	Results from model				Predominant species or genus	Observed		
	Minimum length	Maximum length	Minimum weight	Maximum weight		Length at birth	Maximum length	Maximum weight
Ya Jian	141 (C)	201 (P)	17 (C)	52 (P)	*Prionace glauca* (blue)	30–38	334	206
Qing Lian	160 (P)	219 (D)	43 (P)	119 (D)	*Isurus oxyrinchus* (shortfin mako)	54–63	370	506
Wu Yang	124 (C)	247 (D)	20 (C)	158 (D)	*Carcharhinus falciformis* (silky)	45–70	274*	205*
Hai Hu	138 (C)	181 (P)	30 (C)	63 (P)	*Carcharhinus obscurus* (dusky)	56–81	350	347
Bai Qing	132 (C)	169 (D)	26 (C)	57 (D)	*Carcharhinus plumbeus* (sandbar)	48–64	207	118
Ruan Sha	100 (C)	175 (D)	9 (C)	51 (D)	*Galeocerdo cuvier* (tiger)	31–78	468*	–
Chun Chi	127 (C)	174 (P)	23 (C)	57 (P)	*Sphyrna* spp. (except *S. mokarran*) (hammerheads)	36–48	420*	–
Gu Pian	111 (C)	224 (P)	16 (C)	128 (P)	*Sphyrna mokarran* (great hammerhead)	45–53	458	450
Wu Gu	100 (C)	215 (D)	13 (C)	133 (D)	*Alopias* spp. (threshers)	50–89	423	364
Sha Qing	107 (C)	192 (D)	17 (C)	86 (D)	*Carcharhinus leucas* (bull)	49	287	317
Liu Qiu	128 (C)	173 (P)	25 (C)	56 (P)	*Carcharhinus longimanus* (oceanic whitetip)	49–53	326	167

Model results columns list the 2.5th percentile (minimum) or 97.5th percentile (maximum) values of the lowest or highest estimate among the three fin positions for the given product type; figures in parentheses indicate whether the estimate is for dorsal (D), pectoral (P) or caudal (C) fins. Most observed values were taken from Froese & Pauly (2006) and converted from total length using factors given in that data base for each species. Observed values marked with an asterisk were taken from Compagno *et al.* (2005) and converted to weight using factors from Kohler *et al.* (1995), except in cases where the maximum observed length greatly exceeded the range of lengths observed by Kohler *et al.* (1995) in which case no conversion was performed. No minimum weights or weight at birth data were available.

Estimates of the total number of sharks traded annually worldwide, based on all fin positions combined, ranged from 26 to 73 million year^{-1} (95% PI), with an overall median of 38 million year^{-1}. Pectoral- and dorsal-based estimates were relatively similar with median values of 29–38 million year^{-1} (95% PIs of 25–36 and 30–47

million year^{-1}, for pectoral and dorsal respectively) but caudal estimates indicated a considerably higher median of 62 million year^{-1} (95% PI of 50–79 million year^{-1}). Application of point estimate (e.g. mean) conversion factors from the same data sets produced estimates of the numbers of sharks represented in the fin trade of 30–52 million year^{-1} over the three fin positions for the base extrapolation scenario. The shark biomass represented by the global fin trade, based on all fin positions combined, is estimated to lie between 1.21 and 2.29 million tonnes year^{-1} (95% PI) with a median of 1.70 million tonnes year^{-1}. Estimates by individual fin positions produced a similar PI with medians ranging from 1.37 to 1.91 million tonnes year^{-1} and 95% PIs ranging from 1.13 to 2.38 million tonnes year^{-1}. Calculations based on point estimates from the conversion factor data bases resulted in estimates of 1.39–1.73 million tonnes year^{-1}. Species-specific estimates by number and biomass are shown in Fig. 1.

The deterministic estimates for the total number and biomass of sharks do not show marked differences from the Bayesian posterior medians but, as expected, results by individual species showed some larger deviations. This is because the additional information included in the Bayesian analysis provides the largest relative gains in accuracy at the species level, whereas the total number and biomass estimates show the averaging effect of combining results across species. Where differences do occur, they are likely to arise from the sparse data available for some conversion steps. Deterministic methods rely heavily on the sample mean to represent the best parameter estimate, but this can be problematic when the sample size is low or the sample is otherwise unrepresentative, and offer no reliable approach to assessing the uncertainty in the estimates. In contrast, the Bayesian methodology incorporates the same data but also sampling theory and probabilistic auxiliary information, e.g. on the mean and variance in the number of fins per bag, to estimate the mean fin length traded by species and fin position. The Bayesian method also utilizes a hierarchical model structure (Gelman *et al.* 1995) to combine data from a set of sampled shark species to estimate the variance in key parameters (i.e. fin to body length conversion factors) across the species, and provides reliable estimates of uncertainty in the estimated quantities, as well as considerably improved parameter estimates.

Comparison with other estimates of global shark catches

Our trade-derived figures provide a basis for evaluating the quality of chondrichthyan (sharks, skates, rays and chimaeras) capture production data compiled by the Food and Agriculture Organization (FAO; Anon. 2005a), currently the only data base attempting to encapsulate global catches. The data base indicates that in 2000 the capture production for chondrichthyans totaled 869 544 tonnes. However, of this amount 386 547 tonnes is reported in the undifferentiated 'sharks, rays, skates, etc. not elsewhere indicated' category, and thus may contain rays, skates and chimaeras that do not contribute to the shark fin trade. Of the FAO data that are differentiated, 218 080 tonnes (45%) are types of chondrichthyans used or potentially used in the shark fin trade, i.e. shark species or guitarfish or sawfish (Rose 1996). This figure (0.22 million tonnes) may be assumed to represent a low-end estimate. Applying the percentage (45%) to the undifferentiated capture production suggests that 174 531 tonnes of the undifferentiated capture production is used in the shark fin trade. Therefore, a reasonable, mid-range estimate of the total FAO capture production supporting the shark fin trade is *c.* 0.39 million tonnes. If we assume the shark fin trade utilizes all undifferentiated capture production, the estimate is *c.* 0.60 million tonnes (Fig. 2a).

Our median biomass estimate for the global shark fin trade based on all fin positions combined (1.70 million tonnes year^{-1}) is more than four times higher than the mid-range FAO-based figure (0.39 million tonnes), and nearly three times higher than the high FAO estimate (0.60 million tonnes year^{-1}). Independent estimates for the three fin positions also indicate median values three to five times higher than the FAO-based figures (Fig. 2b). Differences between our estimates and the FAO figures may be attributable to factors suppressing FAO landings data such as unrecorded shark landings, shark biomass recorded in non-chondrichthyan-specific categories, and/or a high frequency of shark finning and carcass disposal at sea. Shark finning is prohibited by national bans in several countries including the USA, the European Union, South Africa, Brazil and Costa Rica (Fowler *et al.* 2005), and regulated through administrative measures in other countries including Australia and Canada. The practice of finning is also contrary to recommendations or resolutions agreed by the International Commission for the Conservation of Atlantic Tunas, the Inter-American Tropical Tuna Commission, the Indian Ocean Tuna Commission and the Northwest Atlantic Fisheries Organization. Despite several successful prosecutions for violations in the USA (Anon. 2005b), global enforcement of finning restrictions remains minimal and finning undoubtedly continues.

In addition, our trade-based biomass calculations may underestimate global shark catches. For example, due to the lack of data on domestic production and consumption of shark fins by major Asian fishing entities such as in Taiwan and Japan, unless exported for processing and then re-imported, these fins are not accounted for within our methodology (Clarke 2004b). Furthermore, shark mortality which does not produce shark fins for market, e.g. fishing mortality where the entire carcass is discarded, is also not included. These discrepancies suggest that world shark catches are considerably
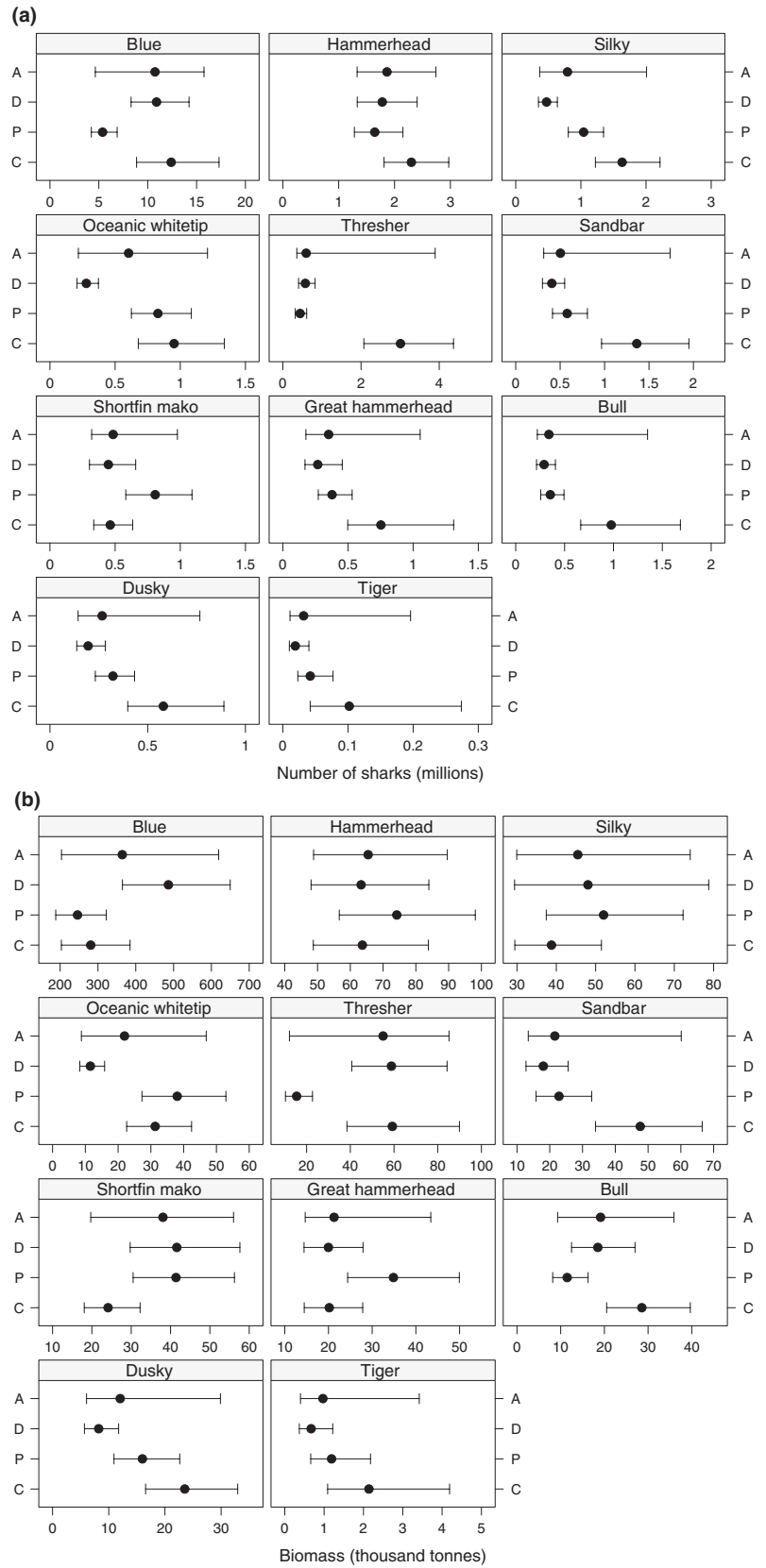
(a)

Figure 1 Estimates by species of the number and biomass of sharks utilized per year in the shark fin trade worldwide. Medians (circles) and 95% probability intervals (lines) are shown. Fin positions are abbreviated as: dorsal (D), pectoral (P), caudal (C) and all fin positions from a mixture distribution (A).
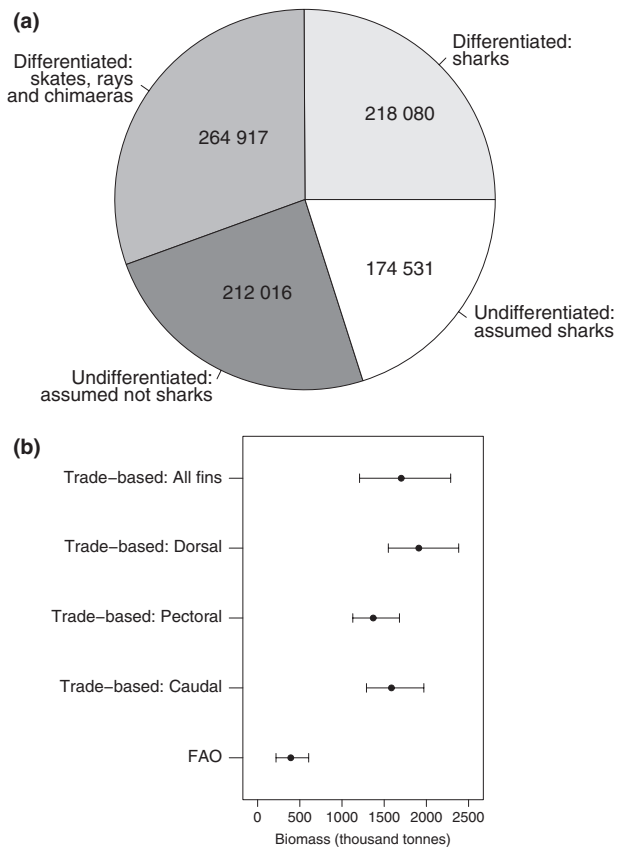
(a)

(b)

Figure 2 (a) FAO Capture Production for 2000 (Anon. 2005a) showing quantity (tonnes) of chondrichthyans reported in undifferentiated and differentiated categories; (b) adjusted FAO Capture Production data compared with estimates for shark biomass represented in the global shark fin trade by fin position [median (circle) and 95% probability interval (line) for fin estimates or range for FAO data].

higher than reported, and thus shark stocks are facing much heavier fishing pressures than previously indicated.

Comparison with species-specific reference points

Despite concerns regarding the potential overexploitation of sharks (Anon. 1999), only a small number of studies have produced estimates of maximum sustainable yield (MSY) or other reference points for sharks by species. These studies include stock assessments of blue sharks in the North Pacific (Kleiber *et al.* 2001), blue sharks and shortfin mako sharks in the North and South Atlantic (Anon. 2005c), and large coastal shark populations in the western Atlantic and Gulf Mexico with species-specific estimates for sandbar and blacktip sharks (McAllister *et al.* 2001; Cortés *et al.* 2002). As each study was conducted for an individual ocean basin, their reference points require extrapolation to a global value for comparison with global fin trade-based estimates.

We chose a wide ranging and continuously distributed species, the blue shark *Prionace glauca* (Compagno 1984; Nakano & Seki 2003), to illustrate our method. We made the simplifying assumption that although reproductive rates, natural mortality and fishing selectivity may vary among blue shark populations, MSY per unit area can be represented by a single value over the entire range of this species' habitat. Blue shark habitat was defined as the area between 50° N and 50° S latitude worldwide and extending to the coastline in each ocean basin (Compagno 1984; Nakano & Seki 2003). Using an equal area projection in a geographical information system, the North Pacific blue shark habitat was calculated at 75.35 million km^2, the Atlantic habitat at 72.16 million km^2, and the area of global habitat at 287.84 million km^2. The ratios used to extrapolate the regional MSY values were therefore set at 1 : 3.82 for the North Pacific : global extrapolation and 1 : 3.99 for the Atlantic : global extrapolation.

Based on the extrapolated North Pacific MSY estimate in number of sharks (Kleiber *et al.* 2001), the blue shark global MSY is 7.26–12.60 million sharks year^{-1}. The median global trade-based estimate for the number of blue sharks utilized each year based on all fin positions combined (10.74 million year^{-1}) is very similar to the MSY estimate, but the 95% PI (4.64–15.76 million year^{-1}) spans a broader range than the MSY estimate. Based on summing the minimum and maximum MSY biomass estimates for the North and South Atlantic basins (Anon. 2005c), the global MSY is 0.73–1.09 million tonnes year^{-1}, which exceeds the trade-based median catch biomass estimate for all fin positions (0.36 million tonnes year^{-1}) by *c.* 200–300% and also lies completely above the trade-based 95% PI of 0.20–0.62 million tonnes year^{-1}.

Acknowledging the margins of error, and the likely downward bias of trade-based estimates, our evaluation, using a Pacific numbers-based reference, suggests that blue sharks globally are being harvested at levels close to or possibly exceeding MSY. In contrast, our comparison with an Atlantic, biomass-based MSY reference point suggests catch levels may be less problematic. Given that we have no population estimate, we are not able to evaluate the actual sustainability of our estimated catch levels. The MSY reference point is the highest possible catch that could theoretically be sustainable, and thus any catch that approaches or exceeds this level is of concern.

CONCLUSIONS

As a result of the global nature of our assessment we cannot evaluate the exploitation status of individual populations. Furthermore, the blue shark is one of the most prolific and resilient of shark species (Smith *et al.* 1998; Cortés 2002) and thus our blue shark results cannot be used to make

inferences about other shark species. Conclusions regarding the sustainable or unsustainable use of other species, and thus the shark fin trade as a whole, will require more detailed species-based stock assessment reference points. However, given the lower productivity of the other species common in the fin trade (Smith *et al.* 1998; Cortés 2002), the large difference between trade-derived estimates of exploitation and the catch estimates reported to the FAO adds to growing concerns about the overexploitation of sharks.

Direct measures of catches will continue to be desirable for managing harvests of fish and wildlife populations. However, there are many situations for which the quality and quantity of harvest data are so poor that trade data provide equal or better opportunities for understanding whether species are threatened by exploitation. This is particularly the case for fisheries catching sharks, in which shark monitoring and management systems are only beginning to be implemented, and for which handling practices, such as finning, distort landings data. This study provides a quantitative characterization of the shark fin trade and a probabilistic linkage between trade volumes and sustainability reference points. To improve the accuracy of the algorithm, future research should focus on improving the estimates for those quantities that had the greatest uncertainty in this analysis due primarily to low sample sizes and possibly non-representative sampling (e.g. the length of fins in each auction size class and fin length to body length conversion factors).

On a broader level, this study illustrates a rigorous Bayesian statistical methodology, applicable across species and markets to high-value animal parts including ivory, and species traded for traditional medicine or as luxury foods. The methodology provides considerably more reliable estimates than simple deterministic estimates obtained from sample means and regression estimates of conversion factors. The Bayesian methodology is recommended for future trade applications as it offers more precise and reliable estimates by combining data with auxiliary information (e.g. auction structure), relating similar data sets (e.g. when sampling is constrained), and serving as a framework for incorporating new information as monitoring programmes develop.

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APPENDIX A: METHODOLOGICAL DETAILS FOR ESTIMATION OF SHARK NUMBER

For each species-fin position category s,p the chance that an auctioned bag of fins falls in bin c, $p(c)_{s,p}$, was assigned a relatively uninformative Dirichlet prior probability density function (pdf):

$$p(c)_{s,p} \sim \text{Dirichlet}(\alpha(c)_{s,p}), \tag{A1}$$

where $\alpha(c)_{s,p} = 1$ for all c.

The observed frequency of bags in the six length bins for each s, p category ($b(c)_{s,p}$) was given a multinomial likelihood function conditioned on the probabilities $p(c)_{s,p}$:

$$b(c)_{s,p} \sim \text{Multinomial}\left(p(c)_{s,p}, \sum_c b(c)_{s,p}\right). \tag{A2}$$

The Dirichlet prior pdf is conjugate to the multinomial likelihood function, and the Gibbs sampler in WinBUGS utilizes this conjugacy to form a highly efficient sampling algorithm (Spiegelhalter *et al.* 2002) to estimate the posterior pdf of $p(c)_{s,p}$ and other quantities of interest.

The mean fin length $\bar{L}_{s,p|c}$ in bin c was modelled as a normal random variable (RV), truncated at the lower ($y_{s,p|c}$) and upper ($z_{s,p|c}$) bin boundaries

$$\bar{L}_{s,p|c} \sim N(\mu_{\bar{L}_{s,p|c}}, \sigma^2_{\bar{L}_{s,p|c}}). \qquad (A3)$$

The mean ($\mu_{\bar{L}_{s,p|c}}$) was set equal to the available fin length midpoint while the variance ($\sigma^2_{\bar{L}_{s,p|c}}$) took account of the uncertainty in the number of fins falling within each bin ($F_{s,p|c}$) through the following equation

$$\sigma^2_{\bar{L}_{s,p|c}} = \frac{(z_{s,p|c} - y_{s,p|c})^2}{12 \times F_{s,p|c}}$$

where

$$F_{s,p|c} = p(c)_{s,p} \times \sum_c b(c)_{s,p} \times f_{s,p|c}. \qquad (A4)$$

Note that the variance of a uniformly distributed RV is equal to the squared difference between the upper and lower boundaries divided by 12.

The RV for the average number of fins per bag in each size bin c, $f_{s,p|c}$ is log-normally distributed:

$$f_{s,p|c} \sim \log \mathrm{normal}(\log(\mu_f), \sigma^2_{s,p|c}) \qquad (A5)$$

with

$$\sigma^2_{s,p|c} = \log\left(1 + \frac{var(f_{s,p|c})}{\mu_f^2}\right), \qquad (A6)$$

where

$$var(f_{s,p|c}) = \frac{var(f_b)}{p(c)_{s,p} \times \sum_c b(c)_{s,p}} \qquad (A7)$$

given that $var(f_b)$ is the variance in fins per bag, and μ_f is the average number of fins per bag.

Based on expert judgment gained through market observations, μ_f and $var(f_b)$ were given the following prior pdfs truncated at zero:

$$\mu_f \sim \mathrm{normal}(50, 14.14^2), \qquad (A8)$$

$$var(f_b) \sim \mathrm{normal}(500, 1000^2). \qquad (A9)$$

Sensitivity analyses proved the results to be insensitive to realistic changes in these priors. The RV for the probability that a fin falls into a particular bin c was computed as follows:

$$p^f_{s,p|c} = \frac{F_{s,p|c}}{\sum_{i=1}^6 F_{s,p|i}}. \qquad (A10)$$

The RV for the mean length across all bins was thus given by:

$$\bar{L}_{s,p} = \sum_{c=1}^6 (p^f_{s,p|c} \times \bar{L}_{s,p|c}). \qquad (A11)$$

The model used the fin length–weight data to estimate a joint posterior pdf for the slope ($a1_{s,p}$) and intercept ($b1_{s,p}$)

of a log linear relationship between RVs fin length ($\bar{L}_{s,p}$) and fin weight ($\bar{W}_{s,p}$) for each species-fin position category (s,p). The RV $\bar{L}_{s,p}$ was then used in conjunction with the RVs for these parameters to predict the RV mean fin weight:

$$\log \bar{W}_{s,p} = a1_{s,p} \times \log(\bar{L}_{s,p}) + b1_{s,p}. \qquad (A12)$$

APPENDIX B: METHODOLOGICAL DETAILS FOR ESTIMATION OF SHARK BIOMASS

Within the model, mean wet fin length ($\bar{L}^{\mathrm{wet}}_{s,p}$) was computed by estimating RVs for the slope ($a2_p$) and intercept ($b2_p$) of a linear relationship between mean wet fin length ($\bar{L}^{\mathrm{wet}}_p$) and mean dry fin length ($\bar{L}_p$) for each fin position, p, using diffuse priors and the Fong (1999) data. As the 95% posterior PIs of the intercepts for each fin position all overlapped with zero, the linear relationship was simplified to:

$$\bar{L}^{\mathrm{wet}}_{s,p} = a2_p \times \bar{L}_{s,p}. \qquad (B1)$$

Slopes ($a3_{s,p}$) and intercepts ($b3_{s,p}$) of the wet fin length ($L^{\mathrm{wet}}_{s,p}$) to whole shark length ($T_{s,p}$) linear relationship were estimated for each category (s,p) using a hierarchical model (Gelman *et al.* 1995) of the data collected in this study:

$$\log T^{\mathrm{obs}}_{s,p} = a3_{s,p} \times (\log(L^{\mathrm{wet,obs}}_{s,p}) - \log(\bar{L}^{\mathrm{wet,obs}}_{s,p})) + b3_{s,p}. \qquad (B2)$$

Due to high variances in some of the data, lengths were transformed to log space to avoid rare occurrences of negative values and individual fin lengths were standardized by the mean of all observed fins for each species – fin position combination. The RVs $a3_{s,p}$ and $b3_{s,p}$ were presumed to be drawn from normal distributions, each with a single global mean and variance across all species for each fin position:

$$a3_{s,p} \sim \mathrm{Norm}(\mu_{a3p}, \sigma^2_{a3p}), \qquad (B3)$$

$$b3_{s,p} \sim \mathrm{Norm}(\mu_{b3p}, \sigma^2_{b3p}). \qquad (B4)$$

Diffuse priors were assigned to the hyperparameters μ_{a3p}, σ^2_{a3p}, μ_{b3p}, and σ^2_{b3p}.

Random variables $a3_{s,p}$ and $b3_{s,p}$ were applied to the logged value of $\bar{L}^{\mathrm{wet}}_{s,p}$ (eqn B1), standardized by the mean of the observed fin lengths by species and fin position ($\log(L^{\mathrm{wet,obs}}_{s,p})$), to predict the RV for mean whole shark length ($\bar{T}_{s,p}$):

$$\log \bar{T}_{s,p} = a3_{s,p} \times (\log(\bar{L}^{\mathrm{wet}}_{s,p}) - \overline{\log(L^{\mathrm{wet,obs}}_{s,p})}) + b3_{s,p}. \qquad (B5)$$

The mean biomass per shark ($\bar{B}^f_{s,p}$) was modelled as a log normal RV:

$$\bar{B}_{s,p}^f \sim \log \text{normal}(\mu_{\bar{B}_{s,p}}, \sigma^2_{\bar{B}_{s,p}|\bar{T}_{s,p}}), \qquad (B6)$$

where $\mu_{\bar{B}_{s,p}} = \log(\bar{B}_{s,p})$, the natural logarithm of the mean biomass per shark by s,p was obtained by applying:

$$\log(\bar{B}_{s,p}) = a4_s + (b4_s \cdot \log \bar{T}_{s,p}). \qquad (B7)$$

The published values of the length–weight relationship are the mean values for normally distributed RVs $a4_s$ and $b4_s$. An approximation for the variance in the natural logarithm of mean weight per animal given the mean length $(\sigma^2_{\bar{B}_{s,p}|\bar{T}_{s,p}})$ was derived using properties of the linear regression model as follows:

$$\sigma^2_{\bar{B}_{s,p}|\bar{T}_{s,p}} \cong (1 - r_s^2)\frac{b4_s^2 \sigma^2_{T_{s,p}}}{r_s^2}\left[\frac{1}{n_s} + \frac{(\log(\bar{T}_{s,p}) - \overline{\log(T_{s,p})})^2}{\sigma^2_{T_{s,p}}(n_s - 2)}\right], \qquad (B8)$$

where $b4_s$ is the slope parameter, r_s is the correlation coefficient reported for the published values of $a4_s$ and $b4_s$ for species s, n_s is the number of samples used to estimate the published values of $a4_s$ and $b4_s$, and $\log(T_{s,p})$ and $\sigma^2_{T_{s,p}}$ are the mean and variance of the natural logarithm of input shark lengths used in the estimation of $a4_s$ and $b4_s$.

Conditional on the RVs $a2_p$, $b2_p$, $a3_{s,p}$ and $b3_{s,p}$ in the Monte Carlo Markov chain (MCMC) iteration, and presuming that the sample distribution of lengths of sharks is approximated by those whose fins were auctioned, it can be assumed that $\log(T_{s,p})$ is a normally distributed RV with mean $\log(\bar{T}_{s,p})$ and variance $\sigma^2_{T_{s,p}}/n_s$. This is because $\log(\bar{T}_{s,p})$ derives from the mean length of auctioned fins for the category s,p and given the above conditions, and in the absence of the length data used to estimate $a4_s$ and $b4_s$, the most suitable proxy for $\log(T_{s,p})$ is a RV with mean $\log(\bar{T}_{s,p})$ and a variance derived from sampling theory. The variance $\sigma^2_{T_{s,p}}$ was obtained in each MCMC iteration by a transformation of the variable for auctioned dry fin lengths modelled in eqns A1–A11. Mean dry fin length per bin c ($\bar{L}_{s,p|c}$, see eqn A11) is transformed to mean wet fin length for bin c ($\bar{L}_{s,p|c}^{\text{wet}}$) using eqn B1. Mean wet fin length per bin c is transformed to the natural logarithm of the mean whole shark length per bin c ($\log \bar{T}_{s,p|c}$) using eqn B5. The variance $\sigma^2_{T_{s,p}}$ is then approximated as follows:

$$\sigma^2_{T_{s,p}} = \sum_{c=1}^{6}\left(p_{s,p|c}^f \times (\log(T_{s,p|c}) - \log(\bar{T}_{s,p}))^2\right). \qquad (B9)$$