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Defining and estimating global marine fisheries bycatch

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ABSTRACT

Unselective fishing catches non-target organisms as 'bycatch'—an issue of critical ocean conservation and resource management concern. However, the situation is confused because perceptions of target and non-target catch vary widely, impeding efforts to estimate bycatch globally. To remedy this, the term needs to be redefined as a consistent definition that establishes what should be considered bycatch. A new definition is put forward as: 'bycatch is catch that is either unused or unmanaged'. Applying this definition to global marine fisheries data conservatively indicates that bycatch represents 40.4 percent of global marine catches, exposing systemic gaps in fisheries policy and management.

1. Introduction

One of the most urgent threats to the world's remaining fish stocks is commercial fishing [1–3], especially the indiscriminate capture [4] of non-target organisms, typically referred to as 'bycatch'. Whilst bycatch may be sold, it may also be unusable or unwanted for a variety of regulatory and economic reasons and subsequently thrown back to sea, often dead or dying [5,6]. This unutilised sub-set of bycatch is known as 'discards'. Bycatch is so pervasive that it spans the spectrum of marine fauna and fishing gear including turtles on hooks, juvenile fish in nets, and benthic invertebrates in trawl and dredge gear. The role of bycatch in degrading marine ecosystems has made this one of the most significant nature conservation issues in the world today [5,7,8], with serious food-security implications for up to 1 billion people who depend on fish as their principal source of protein [9].

However, a consistent understanding of bycatch is lacking due to several unresolved issues: definition, measurement and quantification. To date, bycatch has largely been determined by establishing that element of the catch which is not targeted. The fundamental problem is that differing value judgements lead to differing perceptions of what is considered a non-target catch, especially with the emergence of fisheries where no specific species appear to be targeted. For example, in many tropical shrimp trawl fisheries, much of the catch other than shrimp has traditionally been considered as bycatch and was usually discarded. However, socio-economic factors and an eroding resource base meant a use was created for this bycatch and therefore discarding in these fisheries has been reduced (a trend identified by Kelleher [10]). From the viewpoint of the fishers, these former discards are now considered less as bycatch, but rather an important part of what should more accurately be described as a multi-species fishery. Murawski [11] succinctly summarised this shift with the slogan "yesterday's bycatch may be tomorrow's target catch". However, management, where it is in place, has not re-classified the bycatch as targeted catch. Further, in most cases there is little or no effective regulation on the use of indiscriminate fishing gear, thus creating an incentive to use such gear to maximise the catch.

Due to the changes in the value and use of bycatch over time, the term bycatch is interpreted in numerous ways based on arbitrary assessments of catch usage. This prevents a consistent and widespread agreement of what constitutes target and non-target catch. Further, this results in fisheries where fishermen consider a very large proportion of their catch to be targeted, but a management plan—if one exists—often considers only a small portion of the catch to be targeted, leading to a substantial amount of the catch being ineffectively measured or documented. These inconsistencies are now having profound implications on ocean governance the world-over. A failure to clearly define bycatch leads to a failure to fully appreciate the impact this often unmanaged, undocumented, biomass removal is having on the marine environment. The term bycatch as currently applied has thus been ineffective, leading to questions as to the usefulness, applicability and relevance of the term in today's fisheries.

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A different approach is to redefine the term so that it prescribes what should and should not be considered a target and non-target catch, specifically in relation to managed and unmanaged/unused catches, respectively. This would provide a baseline standard for guiding sustainable fisheries management the world-over, making the bycatch definition consistent and therefore unaffected by changes in the operational practice of the fishing industry. Moreover, by applying such an approach to existing fisheries data, bycatch becomes a proxy to measure the global extent of unmanaged fishing effort. Such an application can therefore reveal a potentially substantial amount of 'invisible' and indiscriminate fishing effort, the impact of which cannot be determined in currently published fisheries statistics.

Using two important discard studies as a springboard [10,12], this paper proposes a new bycatch definition that defines what should be considered bycatch in the context of sustainable fisheries management. The new definition has been applied to a selection of global fisheries data (representing at least two-thirds of global marine fisheries) to estimate bycatch as a percentage of total catch (for the data analysed), simultaneously estimating the global extent of unmanaged fisheries and unused catches.

2. Discards—our current understanding

Although the overall global bycatch situation is not well understood, two studies commissioned by the United Nations Food and Agricultural Organisation (FAO) have furthered our understanding of the discarded element of bycatch. In 1994, Alverson [12] estimated that between 17.9 and 39.5 million tonnes (averaging 27 million tonnes) of fish are discarded each year in commercial fisheries. Ten years later, a second estimate by Kelleher [10], applied a different methodology and estimated the weighted average rate of discards in the world's fisheries to be substantially lower at 7.3 million tonnes. Recognising that differences in methodologies meant the two studies were not directly comparable, Kelleher put forward three reasons for a discard decline: (1) decrease in effort and change of target species in some major trawl fisheries, (2) changes in regulatory regimes that required greater selectivity in fishing, and (3) changes in regulatory regimes leading to a greater incentive to utilise what would otherwise be discarded.

When examining Kelleher's [10] three factors, especially with respect to the first and third point, it appears that yesterday's bycatch has indeed become today's target catch. What proportion of the overall reduced discard estimate, then, is due to an increased utilisation of the catch? More importantly, of this increased utilisation, what proportion of the catch is managed to ensure the harvest is within safe biological limits? Answering this is fundamental as it will indicate the degree of fishing effort that could be accounting for an unknown volume of potentially unmanaged biomass removal; one that a clearer approach to bycatch could highlight and help address.

3. Redefining bycatch

In seeking a term that defines what should be considered bycatch, this paper viewed the issue through a management lens. If one expects management plans to help fisheries achieve sustainability, then one must look at what the management plan considers to be target and non-target catches. From this, those parts of the overall catch that are managed and unmanaged and/or unused, respectively, can be determined. The critical underlying assumption is that in the interests of sustainable fisheries utilisation, a global standard needs to be adopted stating that a well-managed fishery is one that does not target unmanaged stocks or waste natural resources through unused catches.

The new bycatch definition is therefore defined in its simplest form as

Bycatch is catch that is either unused or unmanaged

where

- Unused catch is that which is not used for consumption, sold for any purpose, or reused by the fisher as bait. It includes discards (that portion of the catch that is thrown overboard) and wasted catch after landing that is neither sold nor directly consumed.
- Unmanaged refers to catch, whether categorised as individual species or groups of different species, that does not have specific management to ensure the take is sustainable (in keeping with the FAO's Code of Conduct for Responsible Fishing [13]). The effectiveness of any management to ensure the fishery is responsible is a related but separate issue to the current definition of bycatch. To qualify as managed there must be clearly defined measures specifically intended to ensure the sustainable capture of any species or groups of species within any fishing operation.

This bycatch definition can be expressed simply as

$$B = C_t - C_{lm}$$

where B is the bycatch biomass; C_t the total catch biomass of all species; C_{lm} the total managed catch landed and/or utilised.

There are several critical boundary points to this definition:

- Though damaging to the stock, catch landed from a managed but over-fished fishery (e.g. catch levels set above scientific advice) would not be considered as bycatch and is a different issue to the current definition of bycatch.
- With respect to IUU (illegal, unreported and unregulated) fishing, the scope of the definition as outlined above is not intended to include the bycatch from fishing occurring without a permit and the catch of which is unreported. That is an issue of ocean governance, not of bycatch. However, there is an overlap with the 'Unregulated' portion of IUU and the 'Unmanaged' part of the current bycatch definition. Rather than cause any conflict between the two definitions, it is hoped that this bycatch definition could actually shine the spotlight on existing unregulated fisheries and help identify additional unregulated fisheries.
- Certain types of fishing gear, such as bottom trawls and dredges, are known to cause considerable damage to marine habitats and the species within them [14–16]. Currently it is difficult in practical terms to measure the 'collateral' damage caused by the destruction of habitats and species that are not actually caught, but which are left dead or damaged *in situ*. Although the physical impact of fishing gear is fundamental to understanding the overall impacts of fishing on the marine environment, this is a different issue to the current definition of bycatch.

An illustration of the application of this definition to different catch elements is shown in Fig. 1, demonstrating those catch elements that should be considered bycatch.

4. Methodology

To provide indicative bycatch estimates for global fisheries based on the new definition, this research concentrated mostly on the global trawl fleet due to the availability of data and because a

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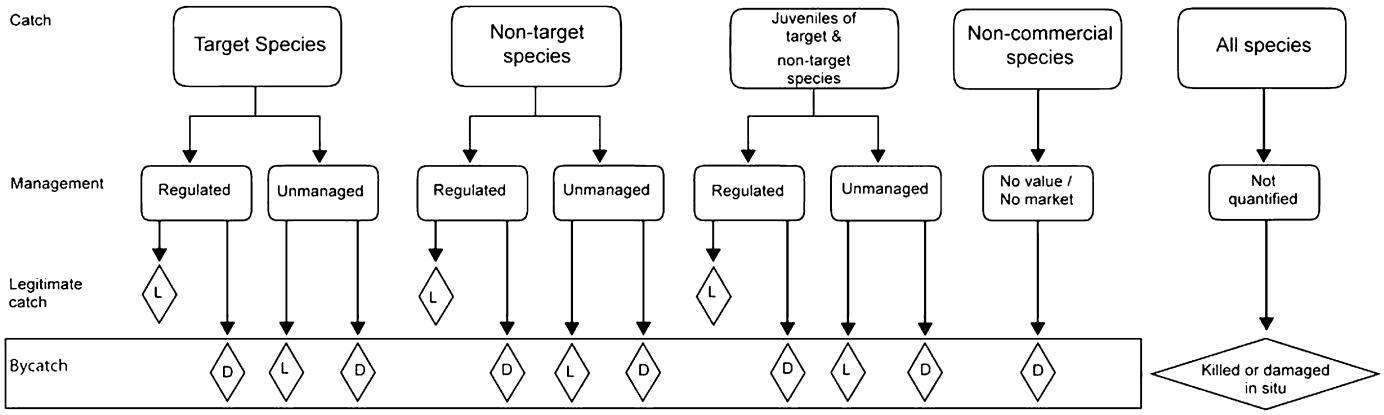

Fig. 1. Applying $B = C_t - C_{lm}$ to various fisheries catch elements to determine bycatch. L = landed catch; D = Discarded catch.

global examination of all types of fishery/fishing methods was beyond the scope of this paper. To determine bycatch according to that which was unused, all discards were considered bycatch. To determine bycatch according to that which was unmanaged, any catch caught in fisheries where the regulations on net mesh size was either too permissive to prevent damaging juvenile catch, or was generally ignored by the fishers, or which the government failed to regulate effectively, was considered to be bycatch. Consequently, in some cases the entire catch complex from such indiscriminate fishing activities is unmanaged, according to the criteria established in this paper and therefore, by default, is considered bycatch.

The estimate of bycatch in global fisheries has been constructed by aggregating estimates of those fisheries for which bycatch-related data were available for 23 major fishing countries as well as for 8 countries in Central America and the Caribbean and 13 African countries. This estimates presented in this paper mainly refer to the period 2000–2003, though where necessary data slightly earlier and slightly later than this range has been used. For Western Europe (FAO Statistical Area 27) overall published estimates from the literature was used, and for the Mediterranean and Black Sea (FAO Statistical Area 37) estimates for specific fisheries for which data was available were aggregated. For a few countries with limited bycatch data (i.e. New Zealand, Myanmar and four Central American countries), estimates were based on the similarities between their fisheries to similar fisheries in countries for which more data was available.

The total marine catch for each fishery, country or regional grouping analysed was estimated by adding the discard data to the data on landings. This made it possible to estimate bycatch as a percentage of the actual total catch. In addition to this, Kelleher's [10] estimates on global shark fin and tuna discards were also included. Unless otherwise indicated, data on marine landings for individual countries are from the *Sea Around Us* database maintained by the fisheries centre of the University of British Colombia [17].

5. Country estimates

5.1. Argentina

Estimating bycatch in Argentina's marine fisheries for the 1999–2003 period is complicated by the instability of the hake (*Merluccius hubbsi* [Marni, 1933]) fishery and the unreliability of nominal (i.e. official landings data) statistics on hake catch, which dominates the country's marine catch. The hake stock was already in danger of collapsing by the late 1990s, as it had been overfished to the point that the catch was increasingly relying on the youngest fish [18]. Much of the catch had to be discarded because the fish were so immature. In 1997, the National Institute for Fisheries Research & Development of Argentina, reported that 149,000 tonnes of hake, consisting entirely of juvenile fish, were discarded by the hake trawl fleet, out of a total estimated hake catch of over 800,000 tonnes [18].

Although both quota, geographical, and fishing gear restrictions on the hake fleet were tightened in the wake of the 1998 near collapse of the hake stock, these measures had no effect on the proportion of captured juveniles [19,20]. According to Kalikoski [19], the industry now uses substantially more of the immature fish than in the past because fewer adult fish have caused the fishery to be more dependent on juveniles. Kalikoski [19] cites an estimate that 40 percent of the catch of the southern hake stock and 70 percent of the catch of the northern stock consisted of juveniles, and that most of the catch of juveniles is now landed and marketed. The mid-point of those two estimates is 55 percent, meaning that the average of 273,000 tonnes of hake caught annually would yield 150,150 tonnes of juvenile hake bycatch annually. In the absence of any definitive landing data other than the range given by Kalikoski [19], for the purposes of this estimate it was assumed that two-thirds, or 67 percent, was landed.

The Argentine shrimp fishery also generates a large amount of bycatch. Kelleher [10] indicates that the shrimp beam trawl fishery generates 50 percent discards. In 1997, however, that fishery generated 40,000 tonnes of bycatch on a shrimp catch of only 5500 tonnes [20]. That 7.3:1 ratio of bycatch to target catch, when applied to the 2000–2003 average shrimp catch of 50,000 tonnes annually, would have generated a total shrimp beam trawl fishery bycatch of 365,000 tonnes. Of that estimated total, 30,000–40,000 tonnes were Hake, all of which was discarded [21].

The sum of bycatch for the hake and shrimp trawl fisheries is therefore estimated at 515,150 tonnes annually (150,150 from the hake fishery and 365,000 from the shrimp fishery) for 2000–2003. The total nominal catch for the period averaged 870,000 tonnes annually, to which 415,000 tonnes (50,000 tonnes from the hake fishery, i.e. 33 percent of 150,000—the amount that would not have been recorded as catch) and 365,000 tonnes from the shrimp fishery, is added as discards giving a total estimated actual marine catch of 1,285,000 tonnes. Thus the 515,000 tonnes of bycatch represents 40 percent of the estimated total marine annual catch for the 2000–2003 period.

5.2. Australia

This paper took Kelleher's [10] discard totals for several Australian trawl fisheries totalling 113,000 tonnes annually. These discards were added to the average nominal landings of 347,000

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tonnes for the 2000–2004 period, giving a total estimated actual catch of 460,000 tonnes, to calculate the bycatch percentage of 24.6 percent.

5.3. Bangladesh

The Bangladesh trawl fishery has regulations that limit the percentage of finfish caught, prescribe minimum mesh size, prohibit commercial trawlers in waters less than 40 m deep and prohibit discards. But Rahman [22] notes that the trawl fisheries do not observe these regulations and even operate in waters of as little as 10 m depth. Kelleher [10] uses a 4:1 ratio of shrimp trawl catch to discards. But according to Rahman [22], shrimp represents just 4.8 percent of the total catch composition in the fishery in waters deeper than 30 m, which is accounted for entirely by commercial trawlers. That figure is close to the figure given by Ahmad [23] based on a survey of 44 commercial trawlers. However, shrimp represent only 1.5 percent of the total catch in waters less than 30 m, which is partly commercial catch and partly artisanal catch. Bycatch is thus more than 20.8 times greater than the catch of shrimp in deeper waters and 67 times greater than the shrimp catch in shallower waters.

The industrial trawl shrimp catch in 2004 was approximately 3000 tonnes [23]. A large artisanal shrimp trawl fleet operating in estuaries and coastal waters contributes five times more shrimp than do the industrial trawlers [22]. The artisanal shrimp trawl catch is estimated at 15,000 tonnes annually for the period 2000–2003. Assuming, conservatively, that all of the industrial trawl shrimp catch is caught outside 30 m depth, and that all the artisanal catch is caught in water less than 30 m depth, the bycatch from the industrial fleet would have been an estimated 60,000 tonnes (3000×20), and the bycatch from the artisanal fleet would have been an estimated 930,000 tonnes ($15{,}000 \times 62$). The total estimate for bycatch in the shrimp trawl fishery, according to these figures, was 990,000 tonnes.

For the finfish trawl fleet, Kelleher's [10] 4:1 ratio of discards to target catch was used. This sector grew from 21 to 49 trawlers between 1999 and 2001 and accounted for 23,000 tonnes of finfish catch in 2003–2004 [23], for a bycatch total of 92,000 tonnes (calculated by applying the 4:1 ratio). The marine set bag-net fisheries represented 20 percent of total marine catch and the estuarine set bag-net 10 percent of the totals, as of 2004 [24]. The two set bag-net fisheries thus account for 30 percent, or 138,600 tonnes, of the total marine catch of 462,000 tonnes in 2004. Mazid [24] observes that the catch in the bag-net fisheries are "mostly juvenile" with the giant prawn *Penaeus monodon* (Fabricius, 1798), target species constituting less than 1 percent of the catch. A 1993 study in the Bay of Bengal program found that only 10 percent of the push-net and bag-net catch consisted of shrimp, whereas 90 percent—or 124,740 tonnes of the total set bag-net fisheries—consisted of finfish larvae and plankton [10] leaving a target catch estimated total of 13,860 tonnes.

Thus the totals for the shrimp trawl for 2000–2003 (990,000 tonnes), finfish trawl (92,000 tonnes) and bag-net fisheries alone (125,000 tonnes, respectively) add up to 1,207,000 tonnes of bycatch. The target catch is estimated at only 54,860 tonnes (based on target catches of 3000 and 15,000 tonnes from the industrial and artisanal prawn trawl fleet, respectively, 23,000 tonnes from the finfish fleet and 13,860 tonnes from set bag-net fishing), so bycatch in Bangladesh fisheries appears to account for 95.7 percent of the actual catch of 1,261,600 tonnes.

5.4. Brazil

Alverson [12] cited the Brazilian shrimp trawl fleet as having a ratio of 9.3 kg of discards to 1 kg of landed shrimp. However, Brazilian shrimp fishery discard rates of 7.2:1 and 10.5:1 have been recorded [25]. This estimate uses the mid-point between these two more recent estimates to generate a bycatch to shrimp catch ratio of 8.9 to 1. These bycatch ratios indicate that Brazil shares the indiscriminate character of other tropical shrimp fisheries and therefore the entire catch of the Brazilian shrimp trawl fishery is considered as unmanaged and therefore bycatch, according to the criteria in this paper.

The Brazilian shrimp and prawn catch during 2000–2003 was 51,000 tonnes annually. At a rate of 8.9:1, the shrimp and prawn fisheries alone would have generated an estimated 453,900 tonnes of bycatch annually. According to Clucas [26], 10 percent of the bycatch in Brazil was being utilised, so 45,300 tonnes of bycatch is estimated to have been used, while 408,600 tonnes is assumed to have been discarded.

Kelleher [10] cites discard rates of 22–33 percent for trawl fisheries off central and southern Brazil, which were landing a total of 122,000 tonnes of non-crustacean catch annually during the same period. With that discard rate, 26,840–40,260 tonnes of discards would have been generated by the non-shrimp trawl fisheries of Brazil. Taking the mean average value of 33,550 tonnes for the non-shrimp discards and adding it the 453,900 tonnes of shrimp bycatch gives the total of 487,450 tonnes of bycatch in the trawl fisheries sector, of which 442,150 tonnes was discarded (408,600 tonnes from shrimp trawling plus 33,550 tonnes from non-shrimp trawling). Adding the discard total of 442,150 tonnes to the average total landed catch of 400,000 tonnes for 2000–2003 gives an average estimated total of marine catch of 842,150 tonnes annually. The total of 487,450 tonnes of bycatch thus represents 57.9 percent of the total annual marine catch.

5.5. Canada

Kelleher [10] estimates discard amounts in the Canadian Atlantic scallop dredge, groundfish, lobster/crab fisheries of 23,000; 11,000; and 25,000 tonnes, respectively. For Canada's Pacific fisheries, 9000 tonnes were discarded in the British Columbia Pacific hake demersal trawl fishery [10]. In addition, however, more than 13,000 tonnes of cod bycatch and other high-value commercial species were reported to have been caught by Canadian and other trawlers in the Grand Banks off Canada's east coast [27]. The total of 81,000 tonnes of bycatch derived from these four totals represents 8.1 percent of the annual total landings of 1,000,000 tonnes.

5.6. Chile

In Chile, the minimum cod end mesh has been shown to be too small to protect the spawning fraction of the hake stock needed to maximise biomass [28]. As a consequence, many juveniles were caught and discarded. By 2004, discards of undersized hake were five times greater than the recorded catch [29]. Because cod-end mesh size was, effectively, unregulated in the hake fishery, this study considered the entire catch to be unmanaged and therefore bycatch, according to the criteria in this paper.

Average southern hake (*Merluccius australis* [Hutton, 1872]) catch during the 2000–2003 period was 123,000 tonnes, so the 5:1 rate of discards to landed catch would have represented 615,000 tonnes. Average nominal marine catch in Chilean waters during the 2000–2003 period was 2,644,000 tonnes, so discards of 615,000 tonnes would have made the actual total marine catch 3,259,000 tonnes. Thus the estimated 615,000 tonnes of discarded bycatch represented 18.9 percent of the total catch.

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5.7. China

Official Chinese statistics for 2003 show a catch of low value and trash fish of 2,160,000 tonnes, out of a total marine catch of 9,730,000 tonnes [30]. However, as much as 5,000,000 tonnes of fish were being used for fishmeal, livestock and aquaculture feed by 2001 [30] so these figures appear to understate the level of low value and trash fish. That figure includes the entire catch of small pelagic fish used for fishmeal which is considered bycatch because they are caught indiscriminately with extremely high rates of juveniles in the catch. By 1999, the catch of low-value pelagic fish consisted primarily of juveniles, and the biomass was reported to be in very serious decline [31].

By 1990, trash fish and low value fish, including juveniles of commercial species, were already estimated by Chinese fisheries specialists to account for 70 percent of China's marine catch [32]. The evidence indicates that that the percentage of low value and trash fish has increased over the past two decades. Monitoring of catch composition in the East China Sea in 1994 showed that juveniles already represented more than 90 percent of the catch of the largehead hairtail (*Trichiurus lepturus* [Linnaeus, 1758], one of the major commercial species of the catch composition in the past [33,34].

Between 1990 and 1999, nominal Chinese marine catch increased from 5,500,000 tonnes to nearly 15,000,000 tonnes [35]. Serious questions have been raised, however, about the accuracy of this data because these figures could not, biologically, have supported such increases [36,37]. The FAO agreed that Chinese fisheries production figures were not consistent with data from household surveys (e.g. FAO [35]). Watson [37] suggests that the total landings for China for 1999 were only 5,600,000 tonnes.

That figure is taken as the minimum estimate for total Chinese marine catch. The upper boundary of 9,000,000 tonnes is taken from the nominal level of landings reported by China in 1994 [31]. This paper adopted that value because it was after this year that China began claiming such rapid growth in marine catch—a 55 percent increase in just 4 years [31]—as to strain credibility. Taking the mid-point between upper and lower boundaries (7,300,000 tonnes) the estimated bycatch of 5,000,000 tonnes used for non-human consumption as of 1999 would represent 68.5 percent of total Chinese marine catch.

5.8. India

A study of India's marine fisheries in the early 1990s found that the bulk of marine landings in all of its maritime states consisted of juvenile fish [38] due to the use of extremely small cod-end mesh size (as low as 8–10 mm—only one-fourth of the 35 mm size that is legally required [39,40]) Given that such a fishery cannot be considered managed, as defined in this paper, the entire catch of the Indian bottom trawl fleet is considered bycatch.

The earliest survey of bycatch in Indian marine fisheries, carried out in 1979, found that 79 percent of total landings in the shrimp trawl fishery consisted of non-shrimp catch [41] (giving a ratio of 4:1 non-shrimp to shrimp catch). In 1999, another study [39] estimated that bycatch ranged between 56 percent and 82 percent, respectively. In this paper, the 4:1 non-shrimp to shrimp catch were assumed to be maintained during the 2000–2004 period. Bhathal [40] estimates total shrimp catch as of 2000 at 450,000 tonnes, which would imply that the shrimp trawl fleet generates an additional 1,800,000 tonnes of bycatch (using the 4:1 ratio). The total catch of the shrimp trawl fleet would therefore be 2,250,000 tonnes.

There is substantial evidence that the bulk of the catch of trash and low value fish—primarily juveniles—was being landed by the late 1990s, driven by rapidly growing demand beginning in the late 1980s from the fishmeal industry, which increased prices for such catch [42]. Chandrapal [43] estimates that total landed non-shrimp catch was 1,300,000 tonnes annually—more than two-thirds of the non-shrimp catch. Combined with the shrimp catch of 450,000 tonnes, this would give a total landed trawl catch of 1,750,000 tonnes.

Bhathal [40] estimates total landings in 2000 at 3,400,000 tonnes, so trawl catch would be just over half of the nominal total marine catch. However, Bhathal [40] assumes virtually no discards in the trawl fishery, contrary to a number of other sources. If, as the data suggest, one-third of the 1,800,000 non-shrimp catch was discarded, the total discards would be about 600,000 tonnes. That figure is added to the total estimated nominal catch of 3,400,000 tonnes to get an estimated actual marine catch of 4,000,000 tonnes. The estimated total trawl catch of 2,250,000 tonnes, all of which is considered bycatch, thus represents 56.3 percent of the estimated total marine catch.

5.9. Indonesia

Trawling within Indonesia was officially banned in the 1980s, except for the Arafura Sea. The Indonesian Directorate General of Fisheries stated that there were 87 trawlers operated by joint venture companies (in the Arafura Sea), all equipped with bycatch excluder devices [44]. However, official time series data on Indonesian shrimp trawl catches indicate that the mean annual level of catch by bottom trawlers for 2000–2003 was 1,464,000 tonnes. The magnitude of this weight is a clear indication that bottom trawling is not simply targeting shrimp. Furthermore, Fegan [45] investigated the Indonesian trawl fishery and found that as many as 750 bottom trawlers, all foreign owned, have been operating in eastern Indonesia for many years, and that they had been reporting only one-third of their catch to the government.

The Indonesian bottom trawl fleet does not target any particular species but aims to maximise the catch in terms of biomass, catching everything from crabs to finfish to sharks and turtles [45]. Furthermore, the fleet operates outside the law, under-reporting its catch to a degree that makes the fishery unmanaged as defined in this paper. Therefore, the entire trawl catch in Indonesia is considered to be bycatch.

Multiplying the official mean trawl catch for 2000–2003 (1,464,000 tonnes) by three (to account for the two-thirds unreported catch), the actual estimate level of trawl catch for the period was 4,392,000 tonnes. Adding the previously unreported trawl tonnage (2.928 million tonnes = two-thirds of 4,392,000 tonnes) to the average reported total marine catch of 4,093,000 tonnes, the actual average marine catch of Indonesia for 2000–2003 is 7,021,000 tonnes. Therefore the bycatch represented 62.6 percent ($4{,}392{,}000/7{,}031{,}000 \times 100$) of the total marine catch in Indonesia for 2000–2003.

5.10. Japan

The estimate for Japan is based on Kelleher [10], which gives a total of 900,000 tonnes of discards on total marine landings of 6,000,000 tonnes, apparently for 1997. Based on these figures, total marine catch has been calculated by adding discards to total landings for a total of 6,900,000 million tonnes. Thus the bycatch rate for Japan is 13 percent.

5.11. Malaysia

Stobutzki [46] cite Malaysian Department of Fisheries figures indicating that landings of trash fish in Malaysia had increased

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from 318,695 tonnes in 1995 to 353,810 tonnes in 2003. But bycatch in Malaysian fisheries is not limited to trash fish. Malaysia produced 46,000 tons of shrimp in 2003. However, although the government intended in the 1980s to require a 40 mm minimum mesh size for the cod end of trawl nets, it relented and allowed trawlers to continue to use 25 mm meshes, leading to a high proportion of juvenile fish [47,48]. As is the case in the Philippines and Vietnam, the absence of meaningful regulation on the fishing gear used effectively makes Malaysia's trawl fisheries catch unmanaged and therefore, by default, bycatch (as defined in this paper).

Malaysia's trawl fleet accounts for 56 percent of the total marine catch [49]. Using the official total for marine catch in 2004 of 1,283,000 tonnes [45], at 56 percent of the catch, bycatch in Malaysia would represent 718,480 tonnes.

5.12. Mexico

Kelleher [10] cites estimates of bycatch in the form of discards in the Mexican shrimp trawl fishery of 119,000 tonnes, based on ratios of bycatch to target catch of 3:1 in the Gulf of California fishery, and 2:1 elsewhere. Those figures would only have been accurate if bycatch reduction devices had been installed throughout the shrimp fishing industry. By the end of 2005, however, only 7 percent of shrimp trawlers were reported to have adopted the BRD on a voluntary basis [50].

From the 1960s to the 1980s, the size of net mesh was reduced from 64 to 38 mm, and the size of the shrimp captured was reduced on average by 21 percent [51]. Although a larger cod-end mesh size was recommended by scientists, an even more serious problem was the increased use of diamond-shaped meshes that close tight when tension from the tow is applied [52]. As of the late 1990s, for example, the shrimp trawl fleet was catching 34,000,000 tonnes of red snapper under the age of 1 year, which was more than 11 times more than the catch of the red snapper fishery [53].

For the 2000–2003 period, the estimate of 10 lb (by weight) of bycatch for every pound of shrimp caught was deemed applicable to the Mexican shrimp industry [54]. Because of the unregulated mesh net used, which causes severe over-fishing of commercial fish stocks, the entire production of the Gulf of California shrimp fishery, for that period, is regarded as bycatch as the fishery cannot be considered to have been managed effectively, in accordance to the criteria outlined in this paper. An estimate of marketed non-shrimp bycatch was not found, so all but the shrimp catch is considered to be discarded.

Mexico's shrimp production averaged 57,000 tonnes from 2000 to 2003, so the average annual bycatch for Mexico is estimated at 570,000 tonnes. That represents 38 percent of average total marine catch (including discards) of 1,500,000 tonnes.

5.13. Myanmar

Myanmar has allowed Thai trawlers to operate in its waters without any limitation on catch [55]. In this regard, Myanmar appears to be very similar to the Indonesian case, where foreign trawlers report only a fraction of their total catch. Therefore, Myanmar bycatch is estimated by using the bycatch percentage of the Indonesian case to adjust the official Myanmar data. That would therefore assume actual trawl catch is three times greater than the nominal level of 290,000 tonnes, giving 870,000 tonnes for the 2000–2003 period. Adding the additional 580,000 tonnes (to account for the two-thirds unreported catch) to the nominal total catch of 1,210,000 tonnes annually, a new total of 1,790,000 tonnes is reached, of which 870,000 or 48.6 percent is estimated to be bycatch.

5.14. New Zealand

Due to data limitations, the New Zealand bycatch estimate is based on that of Australia's, which has similar fisheries and management practices. This paper therefore assigns New Zealand the same rate of bycatch as that of Australia (24.6 percent [10]) by inference. Using the annual average 497,000 tonnes of marine catch per year, we get an estimated 122,262 tonnes of bycatch for the 2000–2003 period.

5.15. Pakistan

According to Pitcher [56], at the Karachi fish harbour, which handles 90 percent of Pakistan's marine catch, more than 60 percent of landings consist of bycatch, supposedly because of a three-fold increase in bycatch of non-target species in the shrimp trawl fishery. But the shrimp catch in Pakistan has fallen from only 5900 tonnes in 2000 to 5100 tonnes in 2003, so these shrimp trawlers are likely fishing for more than shrimp. As in Indonesia and elsewhere in East Asia, bottom trawlers appear to land the maximum volume of fish possible, which means that the fishery is, effectively, unmanaged as defined in this paper. Based on the 2003 level of total marine catch of 320,000 tonnes, a 60 percent bycatch rate would put total bycatch at 192,000 tonnes.

5.16. Peru

In Peru, anchovies (*Engraulis ringens* [Jenyny, 1842]) and other small pelagics have accounted for an average of 7.4 million tonnes annually over the past 14 years, representing 90 percent of Peru's total marine landings. But high percentages of juveniles in the catch over many years have reduced the potential biomass of Peru's anchovy [57]. In June 2001, a new regulation required that the minimum size of net mesh be 26 cm for anchovy, and allowed only 10 percent of the fish caught to be smaller than that [58].

However, statistics on the catch of juvenile anchoveta at the 14 major ports during the April–June 2005 fishing season shows that about one-third of the catch consisted of juveniles [59]. The total anchoveta landings from 2000 to 2004 (averaging 8,230,000 tonnes annually) were used to calculate the one-third of the catch consisting of juveniles—2,743,000 tonnes of bycatch in the anchoveta fishery. In this case, a regulation was in place (though it was not effective), so only the 2,743,000 tonnes of juvenile catch in violation of the regulation is considered as bycatch, according to this paper's definition of bycatch.

In the past, horse mackerel (*Trachurus murphyi* [Nichols, 1920] has been fished for the fishmeal industry, along with anchovies. In a June 2001 regulation, however, only horse mackerel of at least 31 cm in length and mackerel of at least 32 cm in length could be landed [58]. The law also allowed the trawlers to have up to 30 percent of their catch volume to consist of fish that were smaller than that requirement, but only a few months later that 30 percent limit was lifted. In the absence of any regulation limiting the catch of juveniles, Peru's horse mackerel fishery is considered unmanaged, as defined in this paper. Therefore the entire annual average total of 245,000 tonnes of landings from 2000 to 2004 is considered as bycatch.

Peru's shrimp trawl fishery generates 74,000 tonnes of bycatch annually, according to Kelleher [10]. Total shrimp catch in the 2000–2004 period averaged 7000 tonnes. Given the unregulated use of fine mesh nets which catch largely juveniles, the entire catch of this shrimp trawl fishery is considered bycatch as defined in this paper. Therefore the total bycatch is 81,000 tonnes.

The sum of the estimates for these three fisheries is 3,069,000 tonnes of bycatch. Total marine catch from 2001 through 2004

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averaged 7,800,000 tonnes, so bycatch from these three fisheries represents 39.3 percent of the total marine catch.

5.17. Philippines

Trawlers accounted for an estimated 6,157 tonnes of shrimp annually—about 15 percent of the total shrimp catch [60]. Total catch of trawlers associated with the shrimp trawl fishery, however, averaged about 115,000 tonnes from 1992 to 1995 [60]. Those data imply that, overall, the shrimp trawl fleet was catching 5.4 percent shrimp and 94.6 percent bycatch. Dickson [60] observes that the bulk of the bottom trawl fleet catch consists of juveniles of commercial species. The mandatory minimum mesh size for the cod-end of trawlers in the Philippines, at 27.5 mm, is too small to prevent the capture of (primarily) juveniles [61]. The optimum mesh size for inshore fisheries in the Philippines is roughly twice as large [62]. Therefore, in light of this lack of management, the 280,000 tonnes annual average (for the period 2000–2003) of trawl catch in the Philippines is regarded as bycatch.

The push-net accounted for about 14,000 tonnes of shrimp catch as of 1995 [60]. This method is highly unselective and uses a very small mesh net to catch the small shrimp *Aceties*, which represented 90 percent of the industrial shrimp catch in 1997 [63]. In India and Bangladesh, where such small mesh push-nets are used to catch the fry of the *Aceties* shrimp, 90 percent of the catch is post-larvae of other species [64] giving a 9:1 ratio. Using this 9:1 ratio, the shrimp push-net fishery accounted for roughly 126,000 tonnes of bycatch.

The sum of the estimates of bycatch in the bottom trawl fisheries and the shrimp push-net fishery is 406,000 tonnes (280,000 from the trawl fleet and 126,000 from shrimp push-net fleet). Total landed catch in Philippines marine fisheries from 2000 to 2003 averaged 1,300,000 tonnes, so this bycatch estimate represents 31.2 percent of the total marine catch.

5.18. Russian federation (Barents Sea)

Matishov [65] give an estimate of 10–15 percent of the cod (*Gadus morhua* [Linnaues, 1758]) catch as being discarded in the Barents Sea. However, non-target species undoubtedly have a higher discard rate in the cod fishery and also other fisheries in the Barents Sea. Discards of other commercial species ranged from 10 to 25 percent of total catches: 15–20 percent for redfish and wolfish, 10–20 percent for plaice, and 5–25 percent for black halibut [66].

In the northern Bering Strait, the Russian fishery for Alaska pollock (*Theragra chalcogramma* [Pallas, 1814]) was believed by the United States National Marine Fisheries Service (USNMFS) scientists in the mid-1990s to be taking an excessively high rate of juveniles, which would reduce the yield of pollock throughout the northern Bering Sea [67]. Discards in some parts of the Alaskan pollock fishery are as high as 45 percent [10].

Based on the midpoint in the range of estimates from the Barents Sea fisheries (i.e. 5–45 percent), and the indications of high rates of juvenile bycatch in the Bering Sea and the driftnet fishery in the Russian Far East, this paper uses an estimate of 957,000 tonnes, or 25 percent of the official total catch in Russian Federation marine fisheries of 3,828,000 tonnes in 1999. With discards added to the total landed catch, however, the actual marine catch comes to 4,785,000, of which the bycatch represents 20 percent of the total.

5.19. Sri Lanka

The Sri Lankan shrimp trawl fishery was estimated by Alverson [12] to have a bycatch to shrimp catch ratio of 11:1. Applying that ratio to the shrimp catch for Sri Lanka for 2000–2003, which averaged 6000 tonnes annually, gives a total of 66,000 tonnes of non-shrimp bycatch, of which none is apparently discarded [68]. Given the pattern in South-Asia of using very small mesh nets for shrimp trawling, the entire catch of the shrimp fishery (72,000 tonnes) is considered as bycatch, given the fishery must be considered as unmanaged in accordance with this papers criteria. The total marine catch for Sri Lanka averaged 140,000 tonnes during the same period, so bycatch represented at least 51.4 percent of the total marine catch.

5.20. Thailand

In Thailand, trawlers use cod end meshes as small as 25 mm for fish and 15 mm for shrimp on otter board trawlers [69]. As noted by Pauly [62], the minimum appropriate net cod end mesh size for the inner Gulf of Thailand, where the bulk of the catch is made, is 45–55 mm. The push-net fleet in Thailand, which usually has a cod end of only 5–15 mm, catches three-quarters trash fish, juveniles of commercial species and other undesirable species [70,71].

These small mesh sizes results in the capture of a very large proportion of juveniles of commercial species. Roughly 25 percent of the trash fish catch is said to consist of juveniles of commercially important species, while the rest are very small adults and juveniles of other species [69]. In the absence of effective regulation of net mesh size, therefore, the entire catch of the trawl and push-net fleets is therefore considered unmanaged and is thus considered bycatch (as defined in this paper).

The trawl catch represented 63 percent of the total marine catch of Thailand of just over 2,600,000 tonnes annual average for the 2000–2004 period, or 1,638,000 tonnes [72]. The push-net catch has been estimated at 26,000 tons [70]. The total trawl and push-net catch, which is considered as the bycatch for Thailand, is therefore estimated at 1,664,000 tonnes. That figure represents 64 percent of the total marine catch.

5.21. United States

The estimate for US bycatch is based on a review by Harrington [73], which used estimates of discarded bycatch of finfish and fishable vertebrates in US fisheries totaling 1.06 million tonnes of fish discarded annually [73]. The estimated discards represent 22.3 percent of the 4,760,000 tonnes of total annual marine catch for 2002 (calculated by adding the 1,060,000 tonnes of discards to the 3,700,000 tonnes landed in US marine fisheries).

5.22. Venezuela

Venezuela's shrimp trawl fleet is estimated to generate 9 kg of bycatch species per 1 kg of shrimp catch, with industrial fisheries having a rate of 94 percent bycatch while artisanal fisheries have rates varying from 47 to 90 percent of the catch [74]. About 20 percent of the bycatch is landed—virtually all by the industrial shrimp fleet [74]. For the purpose of this paper the entire shrimp trawl catch is considered to be bycatch (on the basis that it does not meet adequate management requirements).

Shrimp catch from 2000 to 2003 averaged 12,000 tonnes annually, which is estimated to have generated 108,000 tonnes of bycatch (calculated by applying the 9:1 ratio), of which about 21,600 tonnes was landed (calculated by applying the 20 percent landed rate) and the rest discarded (86,400 tonnes). Total bycatch is estimated at 120,000 tonnes (12,000 shrimp plus 108,000 non-shrimp). Total nominal catch in Venezuela for that period averaged 500,000 tonnes annually. Adding the 86,400 annual discards from the shrimp fishery gives a total catch of 586,400

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tonnes of which the 120,000 trawl catch, which is considered bycatch, represents 20 percent.

5.23. Vietnam

Vietnam's Research Institute of Marine Fisheries estimates the annual total of "trash fish" caught by the Vietnamese fleet at 930,000 tonnes, all of which is used for aquaculture feed or feed ingredients [76]. However, the entire Vietnamese trawl fleet is geared to catch very small shrimp and immature fish in ways that fail to conform to the regulation minimum net mesh size [76]. Therefore, the catch from this trawl fleet is considered unmanaged and therefore as bycatch (in accordance to the criteria defined in this paper). Bycatch in the shrimp fleet, which accounted for 100,000 tonnes of shrimp in 2004, varies from 60 to 80 percent [75]. Trash fish is now between 50 and 60 percent of the trawl catch in many areas but up to 80 percent in at least one province [74].

Vietnam's average annual trawl catch of 1,339,000 tonnes accounted for 81.5 percent of Vietnam's average official annual marine catch of 1,643,000 tonnes from 1999 through 2004. However, according to the Research Institute for Marine Fisheries (RIMF) the total marine catch for 2001 was actually 2,600,000 tonnes [75]. Assuming that the higher estimate represents a more accurate total for trawl catch, the total trawl catch is estimated at 80 percent of that figure, or 2,080,000 tonnes.

5.24. North-east Atlantic (FAO statistical area 27) estimates

Many north-east Atlantic fisheries have extremely high discard rates, particularly from the bottom trawling fleet which generates far more bycatch than marketable fish [77,78]. The Commission of the European Union did not require member states to collect discard data until 2002 [79]. However, Megapesca [78] cites an estimate of 2,700,000 tonnes of discards in the north-east Atlantic. The total nominal catch for the north east Atlantic in 1999 was 10,920,000 tonnes, but adding the 2,700,000 tonnes of discards increases the estimated actual total catch to 13,620,000 tonnes. The estimate bycatch level (in the form of discards) is thus 19.8 percent of the actual marine catch.

5.25. Mediterranean and Black Sea (FAO statistical area 37) estimates

Kelleher [10] assigns the Mediterranean and Black Sea a discard rate of 4.9 percent, based on data covering 24 percent of the total catch. But if landed bycatch and catch of juveniles are taken into account, the overall rate of bycatch, as defined in this paper, is higher. Tudela [80] indicates that the problem of demersal fish populations (which represented 40 percent of the total catch) being trawled by using small mesh nets, is widespread in the Mediterranean. Most of the species caught are discarded, and estimates of the ratio of discards to the total catch in most trawl fisheries have been in the range 45–50 percent of the catch [80,81].

Trawling for hake, which has been the most important demersal species in the Mediterranean in the past, has resulted in catches that consist almost entirely of immature fish [82]. However, in the absence of any specific figures, and in the knowledge that hake account for the majority of the trawl catch in addition to the fact that this catch are juveniles, this paper estimated that 85 percent of the demersal trawl catch consisted of juveniles.

In 2003 bottom trawling by all the Mediterranean fishing countries in the Mediterranean Sea accounted for 153,000 tonnes, of which 143,000 tonnes was accounted for by the Greek and Italian fleets [83]. The discard rate in the bottom trawl fisheries of the Mediterranean has been estimated at 45–50 percent [80,81]. This high discard rate is used to estimate an actual trawl catch that was roughly 306,000 tonnes, of which 260,100 tonnes (85 percent) are assumed to be juvenile bycatch.

Total nominal landings for the Mediterranean and Black Sea in 2000 were 1,300,000 tonnes. Adding the discarded bycatch of 153,000 (50 percent discard rate applied to 153,000) to that total gives a total estimated marine catch of 1,453,000 tonnes. Bycatch of 306,000 would have represented 21.1 percent of the total catch.

5.26. Central America and Caribbean estimates

The marine catch of eight Central American and Caribbean countries is dominated by shrimp trawl fisheries which have high rates of discards. The discard rate for Costa Rica and Cuba are estimated in studies sponsored by the FAO [10,61]. A rate of bycatch similar to Costa Rica and Cuba was inferred from shrimp trawl fisheries in four other Central American countries (Nicaragua, El Salvador, Honduras and Guatemala) for which no independent data were available. These estimates are for the 2000–2003 period. Data used to derive these estimates can be seen in Table 1.

5.27. African estimates

The overwhelming majority of EU non-tuna vessels operating in African waters chose shrimp licenses, which allowed them to use small mesh (25 mm) nets, instead of the 65 mm net which is authorised for finfish catch, in order to maximise their catch of

Table 1
Estimated annual bycatch in Central America and the Caribbean for the period 2000–2003.

Country	Shrimp bycatch/ discards (tonnes)	Total nominal landed catch (tonnes)	Total catch in tonnes (shrimp bycatch/discards+total nominal landed catch)	Shrimp bycatch (as % of total catch)
Suriname	130,000	25,000	155,000	83.9
Costa Rica	11,000	14,000	25,000	44
Nicaragua	33,000	17,500	50,500	65.3
El Salvador	10,000	25,000	35,000	28.6
Cuba	10,000	34,000	44,000	22.7
Trinidad and Tobago	7000	7000	14,000	50
Honduras	32,000	9000	41,000	78
Guatemala	9000	2000	11,000	81.8
Total	242,000	133,500	375,500	64.4

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Table 2
Estimated average annual trawl, shrimp and cephalopod catch of selected African coastal states for the period 1999–2004.

Country	Reported total trawl catch (tonnes)	Shrimp catch (tonnes)	Cephalopod catch (tonnes)	Reported total marine catch (tonnes)
Mauritania	146,000	3500	34,000	615,000
Guinea	32,000	1300	4000	109,000
Gabon	14,000	2000	–	36,000
Angola	131,000	6000	–	249,000
Morocco	390,000	8000	76,000	872,000
Nigeria	120,000	25,000	–	264,000
Senegal	64,000	6000	20,000	349,000
Republic of Congo	8000	500	–	22,000
Mozambique	15,000	12,000	–	16,000
Tanzania	6000	2000	–	28,000
South Africa	132,000	–	7000	669,000
Namibia	180,000	–	–	499,000
Madagascar	90,000	12,000	1000	121,000
Total	1,328,000	78,300	142,000	3,849,000

demersal fish [84,85]. Many indigenous African shrimp trawlers also justify the use of the smaller-mesh nets by claiming to target shrimp when their actual objective is to maximise their finfish catch [86]. By 2000, industrial trawlers in Ghana had begun to use cod-ends with a mesh size of only 20 mm—half the size of the mesh used in the 1960s [87]. Although 30 percent of the shrimp trawl fishery landed catch in Ghana is shrimp, the mean ratio of non-shrimp: shrimp catch overall was reported to be 23:1 during the day, 9:1 at night [88]. Any trawling in African waters that uses unregulated indiscriminate fishing gear, and therefore unsustainable catch of juveniles of finfish species, are considered bycatch as defined in this paper.

Hake trawl fisheries of South Africa and Namibia, accounting for 312,000 tonnes of reported trawl catch from 1999 through 2004, appear to be departures from the general rule that trawl fisheries in the region are unmanaged in regard to the use of unregulated indiscriminate fishing gear. Thus the total estimated landed trawl catch (1,328,000 tonnes) minus the nominal hake catch of 312,000 tonnes leaves 1,016,000 tonnes of landed bycatch.

The cephalopod fishery is a targeted fishery, with a landed catch of 142,000 tonnes of cephalopod, so this should also be subtracted from the total landed trawl catch to be considered as bycatch. Subtracting that total from the subtotal of 1,016,000 tonnes leaves 874,000 tonnes of landed trawl bycatch.

The next problem is estimating the discarded catch associated with this landed trawl bycatch. Clucas [24] estimates 85–90 percent of the bycatch in the shrimp trawl fisheries is discarded. Because of the absence of a clear delineation between the shrimp trawl and finfish trawl fisheries, it is assumed that this estimate applies to the broader finfish trawl catch also. Taking the midpoint of those two percentages, 87.5 percent, and applying it to the subtotal of 874,000 tonnes of landed trawl bycatch would give a total of 6,118,000 tonnes of discarded bycatch associated with the landed bycatch total.

Adding the 874,000 tonnes of estimated landed bycatch to the 6,118,000 tonnes of estimated discarded bycatch would yield a total of 6,992,000 tonnes of estimated bycatch for Africa. Adding the estimated discards of 6,118,000 tonnes to the total landed catch associated with the bycatch of 3,849,000 tonnes (see Table 3) would give a total estimated marine catch of 9,967,000 tonnes. The estimated bycatch for Africa of 9,967,000 tonnes would therefore represent 70 percent of total marine catch. Data used to derive these estimates can be seen in Table 2.

6. Results

Based on this definition of bycatch and its application to the studied data, 38.5 million tonnes of annual bycatch can be identified, representing 40.4 percent of the estimated annual global marine catch of 95.2 million tonnes from the data studied (see Table 3).

These figures should be seen only as indicative minimum bycatch estimates because several sources of potentially large amounts of bycatch have not been estimated due to six identified data deficiencies. Namely, (1) estimates in this paper were mostly derived from trawl fisheries and thus bycatch from other fishing gears, such as gill nets and long-lines, is missing. (2) Quantitative catch estimates from many artisanal fisheries around the world are virtually non-existent. (3) Juvenile catches in the industrial fisheries of the world, especially those for small pelagics, e.g. sardines (*Sardina pilchardus* [Walbaum, 1792]) have not been adequately reflected in the estimates of most countries. (4) Large-scale bycatch of turtles, cetaceans, pinnipeds, and seabirds are not usually quantified by existing systems of data and research [89]. Those figures that do exist are often estimated by numbers of bycaught individuals [89], rather than weight, and so cannot be applied to this estimate. In addition, even if weight estimates could accurately be determined for such bycatch, it may still fail to convey the impact of bycatch on these affected species because many are endangered to the degree that even mortality of a few individuals may have profound effects on the whole population. (5) Bycatch of invertebrates, such as crustaceans, echinoderms and molluscs was not estimated. Although invertebrate discarding is an important consideration [14,90], for the most part these are not quantified by existing systems of data and research [91]. (6) The so-called 'observer effect' was not taken into account. This occurs when observed fishers tend to follow best practice fishing principles, as opposed to un-observed fishers, and can skew discard rates by a factor of ten [92]. The main source of discard data in North American and European fisheries in this paper are derived through analyses of discard samples collected by on-board observers. The resulting bycatch may therefore be an underestimate.

It must also be noted that using the proportional weight of bycatch in the overall marine catch, which is currently the only meaningful way of giving relevance to the problem, fails to convey the true impact of this biomass removal. A large proportion of bycatch takes the form of juvenile fish, the average weight of

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Table 3
Summary of all bycatch estimate results.

Geographic area of estimates	Bycatch estimate (tonnes)	Estimated total catch (tonnes)	Percentage bycatch of total catch
23 Individual countries	27,453,242	63,291,770	43.4
North-east Atlantic	2,700,000	13,620,000	19.8
Mediterranean and Black Sea	306,000	1,453,000	21.1
Central America and Caribbean	242,000	375,500	64.4
Africa	6,992,000	9,967,000	70.2
Global shark fin	207,000	224,000	92.4
Tuna	605,000	6,300,000	9.6
Total	38,505,242	95,231,270	40.4

which is much lighter than the weight of the generally larger fish recorded in the statistics of fisheries landings. The ecological importance of these juveniles to the marine environment is therefore not adequately conveyed when expressed as a weight and thus the ecological impact of bycatch is potentially far higher than can be reflected even in this current estimate.

7. Conclusions

This paper shows that, when a rigorous definition of bycatch is applied in line with the principles of sustainable management, enormous quantities of biomass are being removed from the ocean without any form of effective management. The approach outlined in this paper therefore exposes bycatch as an insidious problem of invisible fishing resulting from widespread unmanaged fisheries. Further, the magnitude of the problem is probably higher than the current estimate of up to 38.5 million tonnes (40.4 percent of the estimated total marine catch from the studied data), given the six major elements not accounted for in the current study and due to the shortcomings of a weight estimate in conveying the biological importance of juveniles to the ecosystem. Quantification of these additional sources would indicate how much bycatch is being retained and which fisheries are causing the greatest impacts, thereby allowing an understanding of the effect this biomass removal is having on the marine environment.

Few industries would tolerate levels of wastage and/or lack of sustainable management of around 40 percent year-on-year. Such is the need for a solution that the efficacy of actions such as changing quotas and other forms of fishing effort limitation by only a few percentage points must be questioned. This action achieves limited outcomes if it occurs in isolation, without dealing with the major element of bycatch. There is an urgent need for fishery managers to take drastic action to redress this. There is also a need for the production of extensive and robust data quantifying bycatch, as defined here, by credible, independent organisations. In seeking solutions to the unused 'wasted' catch component (i.e. that which is mainly discarded), it is vital to emphasise, from a sustainability point of view, that solutions to minimise the capture of these species, when over safe biological limits, should be prioritised ahead of seeking new markets for them. Given the dynamic complexity of marine ecosystems and the often inter-mingling of various types of species, the practical reality, however, is that selecting and catching only that which is managed will not be solved solely though selective fishing gear. Consequently, in many cases the most pressing priority for bycatch reduction and, moreover, global over-fishing, should be one of reducing the amount of fishing by, in part, reducing the amount of invisible fishing.

The application of the definition of bycatch in this paper exposes major systemic gaps in fisheries policy and management which must be addressed so that fisheries can provide sustainable harvests long into the future. It will be virtually impossible to achieve sustainability if a huge proportion of fishing effort is uncounted when setting limits for sustainability. Consequently, the extent of bycatch, as defined here, is revealed as potentially so serious that it must become a major political, management, sectoral and environmental focus, bringing its implications to the fore as a conservation/food security imperative.

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