FISH and FISHERIES

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Etymology of Ghoti

George Bernard Shaw (1856–1950), polymath, playwright, Nobel prize winner, and the most prolific letter writer in history, was an advocate of English spelling reform. He was reportedly fond of pointing out its absurdities by proving that 'fish' could be spelt 'ghoti'. That is: 'gh' as in 'rough', 'o' as in 'women' and 'ti' as in palatial.

Bait worms: a valuable and important fishery with implications for fisheries and conservation management

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Abstract

Bait is an integral part of coastal life, but is perceived as a low-value resource as fisheries are data-limited, locally focussed and largely unregulated even though the ecological impacts of collection are considerable. An empirical assessment of three UK-based ragworm fisheries combined with an analysis of published literature has produced the first global assessment of polychaete bait fisheries. The five most expensive (retail price per kg) marine species sold on the global fisheries market are polychaetes (*Glycera dibranchiata*, *Diopatra aciculata*, *Nereis* (*Alitta*) *virens*, *Arenicola defodiens* and *Marphysa sanguinea*). We estimate that 1600 t of *N. virens* per annum (worth £52 million) are landed in the UK with approximately 121 000 tonnes of polychaetes collected globally valued at £5.9 billion. Using remote closed circuit television (CCTV) cameras to monitor collectors, activity at local sites is considerable with a mean of 3.14 collectors per tide (day and night) at one site and individuals digging for up to 3 h per tide, although intensity differed seasonally and between sites. Collectors removed on average 1.4 kg of *N. virens* per person per hour, walking a considerable distance across the intertidal sediment to reach areas that were usually already dug. The implications of these human activity and biomass

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removal levels are explored in the context of fisheries and conservation management. At local, regional and national scales, polychaete bait fisheries are highly valuable, extract significant biomass and have considerable impacts; therefore, they urgently require governance equivalent to other fisheries.

Keywords *Arenicola marina*, bait collection, invertebrate fishery management, marine protected areas, *Nereis (Alitta) virens*, polychaete

Introduction

The harvesting of marine invertebrates for fishing bait has been an integral part of global coastal life for thousands of years (Byrd 1996). Collectors are a diverse set of individuals including anglers collecting for personal use to those, sometimes organized in groups, who sell via tackle shops or online. Bait is, therefore, a spatially and temporally intermittent fishery involving a diverse set of participants who are difficult to engage (Watson *et al.* 2015). Like many data-poor invertebrate fisheries (e.g. Leiva and Castilla 2002; Berkes *et al.* 2006; Anderson *et al.* 2008), managers have found bait collection extremely challenging to regulate and manage resulting in a persistent and widely held view that it is a low-value fishery of very limited (i.e. local) extent. The absence of data has ensured that outdated estimates of collection effort and biomasses extracted circulate freely leading to highly spurious or non-existent local, national and global fishery estimates. Bait collection is often located in areas designated as marine protected areas (MPAs) so the lack of data is also a highly significant gap in conservation management. Ultimately, without these data, fisheries management and habitat conservation of coastal soft sediments cannot be implemented with any confidence.

A wide range of marine invertebrates can be used for bait depending on season, personal preference and the species to be caught, but in nearly all locations, intertidal soft sediment polychaetes are the dominant group collected (Olive 1994). Whilst a minority of fisheries use a hand pump (Fowler 1999), boat-mounted rake (Birchenough 2013), or dredge (Beukema 1995), the vast majority collect through manual turning of the sediment with a fork or similar implement (e.g. Fowler 1999; Sypitkowski *et al.* 2009). By acting as ecosystem engineers or as dominant invertebrate predators, these polychaetes are keystone benthic species (e.g. Ambrose 1984; Caron *et al.* 2004; Volkenborn *et al.* 2007). Many are also prey for wading birds (often directly protected under conservation legislation) and commercially important fish and crustaceans (McIntosh 1908–1910; Ambrose 1986).

Using a global analysis of bait collection studies and underpinned by empirical research of UK polychaete fisheries in the Solent European Marine Site (SEMS), we make the case to overturn the existing paradigm that bait fisheries are low catch and value fisheries that are *only* ancillary to 'traditional' fisheries. Due to value, extent, productivity and impacts, we contest that they should urgently be given equivalent status. Finally, we set out the issues surrounding the management of bait collection providing fisheries specialists, conservation practitioners, scientists and policy-makers with a 'road map' for appropriate management.

Materials and methods

Retail value

To assess their value, we collated the retail prices (January 2015 exchange rates [UK£ 1: US$ 1.55; UK£ 1: €1.26]) of a range of polychaete species used for bait. Prices (UK pounds sterling per kilogramme) are presented for live bait with values extracted from online sites (available to purchase directly by the public) and from the primary literature. Some polychaete baits (e.g. *A. defodiens*) can also be sold frozen, but as the retail price for this species is very similar, we have not included a separate analysis.

Assessing bait collection activity

Three popular sites (Fowler 2001) within the SEMS (Fareham Creek, Portsmouth Harbour; Dell Quay, Chichester Harbour and Pagham Harbour) were surveyed over spring tides in August and

September 2011. A biotope survey assessment was conducted and bait-collected areas mapped using differential global positioning system (DGPS), in conjunction with hand-drawings of habitat boundaries on aerial photographs (scale 1: 10000). Points were recorded by walking along the outer boundary of dug areas, and any polygons considered too small to be mapped with DGPS were numbered on the aerial photograph. Bait dug areas matched in the field were then digitized in GIS (ArcMap).

To analyse collection activity, two Sanyo HD 4600 cameras with external hard drives were used for direct recording and were rotated amongst the sites. Cameras were set up twice at each site during 2011 and 2012 with the expectation that they would record continuously for one tidal cycle (approximately 14 days) for each run. However, battery failure and other circumstances meant that some periods were not recorded (Watson *et al.* 2015). Video starting 1 h before the predicted low tide time from the nearest tidal station until 2 h after low tide was viewed during which time the number and location of collectors were recorded. A one-hectare grid was overlaid on the aerial view of each site and the time spent by each collector (digging, walking and boating) in each hectare recorded and whether they were digging in areas mapped as dug. Both day and night tides were analysed as collecting is only dependent on the tide. Although the cameras have near-infrared capability and can record in low light conditions, records of activity in the dark were reliant on a collector's head torch. If this made the precise location of the collector difficult to ascertain, data were excluded from any spatial analysis. Using the video footage collected, it was also possible to analyse individual bait collectors (approximately 20 collectors [721 minutes of collection activity from Dell Quay and Fareham Creek]) and record the number of times they placed a worm in their bucket over a given period to calculate biomass extraction rates. Correspondence with the UK Government's Information Commissioner's Office confirmed that personal data legislation did not apply to the collected images.

Bait-use survey

As the majority of bait purchased is from retailers and it is also estimated that 75% of anglers are not affiliated to any angling association (Fowler 1999), the most appropriate way of assessing bait choice was to visit/contact 20 coastal fishing shops. To prevent the questionnaire becoming interrogative, there was no formal discussion structure, but notes were taken and a series of questions were broached including the amount of bait used during an angling trip. To explore bait choice further, we also asked editors/moderators of UK-based sea angling magazines and online fora/websites which they believed to be the most popular baits, with one asking their social media group directly.

Bait storage

To see how long *N. virens* could be stored alive and in a reasonable condition to be used as bait, we simulated a variety of storage methods obtained from searches of the Internet and discussions with collectors and anglers (Table S1). Plastic seed trays were used for all treatments except the Bucket Simulation and the Experimental Control. A biomass of 300 g (of freshly dug worms) was randomly allocated to treatments (three replicates), and the experiment ran for one month. All trays were maintained in a dark temperature-controlled room set at 8 °C. As the Bucket Simulation and Experimental Control treatments needed the flow-through seawater system, they were maintained in a separate aquarium facility (12:12 LD photoperiod with ambient [UK summer] seawater temperature). All treatments were checked daily or every other day for one month during which time the number of dead worms and the condition of those alive were recorded.

Landings (productivity)

For estimates of landings and monetary value at the different spatial scales (e.g. site, UK, USA, Europe and global), we have provided not only the realistic (median values), but high and low scenarios. For each of these output calculations, the median, maximum and minimum of the component values were combined with the mean, minimum and maximum 95% CIs of the weight of *N. virens*, collector rates, biomass removal rates and weight of polychaetes used per fishing trip. Details of the data sources for each are given in Tables S2 and S3. To calculate the mean biomass removal rate per person per minute/hour, the direct measurements of removal rates from the closed circuit television (CCTV) footage and the mean weight of over 1500 *N. virens* collected by an experienced commercial collector were combined. This also enabled us to calculate the annual biomass removed from each site by using the collector activity data, assuming that collectors utilize two tides per day for 365 days. For UK, European, USA and global landings, we used the estimates of people engaged in sea angling at the different spatial scales, the number of fishing days per angler per year for the UK and the amount of bait used in a single fishing trip (defined as someone who is fishing for 3–4 h or one tidal cycle) from the bait-use survey (Tables S2, S3). All five editors/moderators of the online fora contacted agreed that live ragworms and lugworms are the most popular polychaetes. S. Craig (a polychaete aquaculture industry consultant) also agreed via a personal communication and even indicated that this would hold true globally with nereids being used most often in S. Korea, Vietnam, Thailand, Iran, Canada, Tunisia, S. Africa, Indonesia, Malaysia, Mexico and most coastal European countries. Davies *et al.* (2008) also reported that the three most popular species sold in Australian bait shops were polychaetes, and Cohen (2012) showed that polychaetes were stocked most frequently in bait shops in California, USA. Finally, respondents of the social media survey also placed ragworms as the most popular live bait. Whilst it would be true to say anglers use numerous types and species of bait and there will be significant regional differences, based on this evidence we believe that many anglers use polychaete bait, specifically ragworms. Nevertheless, we have also incorporated estimates of the proportion of fishers that use ragworms and polychaete worms into the output calculations (Table S3) based on our social media survey, data from AFBI (2014) and Armstrong *et al.* (2013) for the UK and these plus data from Font and Lloret (2011) for Europe, USA and global estimates.

Retail value

Limited studies (Cunha *et al.* 2005; Sypitkowski *et al.* 2009; Carvalho *et al.* 2013) have indicated that the economic value of bait, specifically live polychaete worms, may be considerable at the local level, but a wider assessment of popular species is absent. Table 1 shows that generally, retail prices for polychaetes are high, but with considerable variation between species and source countries. Trade in marine products is characterized by consumers with different requirements who are constrained within social and economic frameworks. The five most valuable species (*M. sanguinea, D. aciculata, G. dibranchiata, N. virens* and *A. defodiens)* are not rare (Bass and Brafield 1972; Creaser and Clifford 1986; Paxton 1993; Cadman 1997; Garcês and Perreira 2011), but retail prices between species will always vary, driven by supply and demand from specific consumer groups and the economic conditions (e.g. labour costs) within a country. The price differential of closely related species is also likely to be underpinned by a higher cost (i.e. difficulty) of capture. For example, in the UK, *A. defodiens* has a much more limited distribution compared to *A. marina* and as it is found lower down the shore, hand collection is restricted to good spring tides only (Cadman 1997). Over twenty years ago, Olive (1994) stated that there was an urgent need to assess bait fisheries globally. As they are some of the most expensive products extracted from the sea, this is now economically as well as ecologically imperative.

Extent

The close proximity of intertidal soft sediment shores to multiple conurbations in the SEMS means it supports numerous polychaete bait fisheries. Using the remote CCTV deployed at the three sites, the number and location of collectors, time spent on the shore and the activities they performed were recorded. These data (mean number of collectors per tide and mean number of minutes per collector), in addition to a meta-analysis of other studies, have provided the first global assessment of the extent of polychaete fisheries at various spatial scales (Table 2).

Unlike many subtidal invertebrate fisheries (e.g. Anderson *et al.* 2011), the spatial extent of intertidal bait collection (area of dug sediment) is generally low. Recorded bait collection areas from the biotope surveys for both Dell Quay and Fareham Creek in the SEMS were only 0.16 km^2, reflecting other bait fisheries, for example *H. diversicolor* and *D. neapolitana* from Portugal (Cunha *et al.* 2005; Carvalho *et al.* 2013). Nevertheless, the 18 km^2 reported by Sypitkowski *et al.* (2009) is approximately 25% of the US state of Maine's 80 km^2 of suitable habitat. Low values could be explained by temporal variability of collection and the timings of surveys (Blake 1978). For example, 48% of the

Table 1 Retail prices of polychaete species used for bait.

Common name	Species	Price (UK £) kg^{-1}	Source country	Price reference and method of calculation
Blood worm	*G. dibranchiata*	153	USA	www.bloodwormdepot.com/products.html mean worm weight: 4.22 g (Sypitkowski *et al.* 2009)
Tube worm	*D. aciculata*	97	Australia	Davies (2013)
Sand worm	*N. virens*	62	USA	www.youtube.com/watch?v=tsWWrZAXE-Q mean worm weight: 6.11 g (this study)
Ganso	*M. sanguinea*	55	Portugal	www.valbaits.com/index.php?route=product/
Black lugworm	*A. defodiens*	53	UK	www.seafishingbaits.com/ mean worm weight: 6 g (Watson *et al.* 1998)
Lugworm	*A. marina*	40	UK	www.hookersbaits.com/
King ragworm	*N. virens*	33	UK	www.baitsrus.com/
Tremolina	*Hediste diversicolor*	31	Portugal	www.valbaits.com/index.php?route=product/
Lugworm	*Perinereis aibuhitensis*	10	China	www.ruiqingbait.com/products.html
Polychaete	*D. neapolitana*	6	Portugal	This is not retail price, but first sale (wholesale) (Cunha *et al.* 2005)
Green worm	*P. cultrifera*	6	Algeria	Younsi *et al.* (2010)
Mud worm	*H. diversicolor*	6	Algeria	Younsi *et al.* (2010)
Sand worm	*Scolelepis squamata*	6	Algeria	Younsi *et al.* (2010)

sediment surveyed in 2004 by Sypitkowski *et al.* (2010) was dug, but this fell to 24% the following year. Our own data from Dell Quay and Fareham Creek also confirm much higher levels of activity in the summer than winter. Underreporting of the full extent of bait fisheries may also occur because of logistical and financial constraints on the surveys. We estimate that 7.5% and 8.4% of the mapped intertidal sediment was dug at Dell Quay and Fareham Creek, respectively, and Sypitkowski *et al.* (2010) calculated from aerial observations that an average of 43.6% of the mud flats surveyed were dug in Maine, USA. For both data sets, the areas surveyed were only a small proportion of the intertidal mudflats present in these regions. If the surveyed areas are scalable across the representative habitat in a region, then the full extent of collection would be considerable.

Even though the mapped extent of the dug areas is small, the total number of collectors per site and mean number of collectors per tide utilizing Dell Quay and Fareham Creek confirm high levels of exploitation (Table 2). Dell Quay had the highest mean number of collectors per tide (3.14), but with 14 recorded as the maximum number of different collectors on one tide and none recorded on other days, variation between tides is high. Both cameras at Fareham Creek recorded fewer collectors per tide with none recorded at Pagham Harbour. Once onsite collectors at Dell Quay spent on average 93 min digging per collector per tide compared with 19 min for Resident 1 and 54 min for Resident 2 viewpoints at Fareham Creek. The maximum amount of recorded time spent by collectors was 180 min at Dell Quay, 124 min from Resident 1 and 114 min from Resident 2 viewpoints. Although a small number were also recorded at each site for only a few minutes, these most likely moved out of the field of view, or were not effectively tracked (e.g. during low light levels) rather than left the site. Differences in emersion time combined with moving out of the fields of view are probably the main reasons for the lower activity times at Fareham Creek. Different levels of activity between sites are also partly due to the camera deployment times and the seasonality of bait collection (Blake 1978). Site-specific densities of size-appropriate *N. virens* as shown by Watson *et al.* (2007) might also explain divergent fishery intensities, but other important factors are shore access and distance to collection areas, for example Pagham Harbour is much more difficult to access (Watson *et al.* 2015). Our study confirms the high level of exploitation at two of the most popular sites in the UK, and these levels of exploitation are comparable with activity levels (e.g. number of collectors and time spent collecting per tide) reported from across the globe for other polychaete fisheries (Blake 1978, 1979; Harvard and Tindal 1994; Fowler 2001; Cunha *et al.*

Table 2 Assessment of global polychaete bait fisheries in terms of biomass removed and value. Values in parentheses for the first four data columns are minimum and maximum 95% CIs. For the other columns, where data allow these to be calculated, values are realistic (median), low and high scenarios in parentheses (see tables S2 and S3 for details).

Site	Date	Species	Extraction area (km^2)	Mean number of collectors $tide^{-1}$	Minutes collecting $individual^{-1}$ $tide^{-1}$	Mean biomass (kg) $person^{-1}$ min^{-1}	Mean biomass (kg) removed m^{-2} $year^{-1}$	Total biomass (t) removed $site^{-1}$ $year^{-1}$	Retail price (UK £) kg^{-1}	Biomass value (£ thousand) removed $site^{-1}$ $year^{-1}$	Value (£) removed m^{-2} $year^{-1}$
Dell Quay	2012	*N. virens*	0.16[a]	3.14 (2.2–4.1)	93 (85–100)	0.023 (0.019–0.027)	0.031 (0.016–0.051)	4.9[a] (2.6–8.2)	33	164 (86–271)	1.02 (0.54–1.70)
Fareham Creek Res. 1	2012	*N. virens*	–	0.375 (0.1–0.65)	19 (5–32)	0.023 (0.019–0.027)	–	0.12[a] (0.007–0.42)	33	3.9 (0.24–13.8)	–
Fareham Creek Res. 2	2012	*N. virens*	–	0.78 (0.35–1.2)	54 (44–64)	0.023 (0.019–0.027)	–	0.72[a] (0.22–1.5)	33	23 (7.2–50.5)	–
Fareham Creek comb.	2012	*N. virens*	0.16[a]	–	–	–	0.005 (0.001–0.012)	0.84[a] (0.23–1.95)	33	27 (7–64)	0.17 (0.05–0.40)
Pagham Harbour	2012	*N. virens*	0.004[a]	0	–	–	–	–	–	–	–
Solent & Poole, UK	2001	*N. virens*	–	–	–	–	–	130[b]	33	4290	–
UK	2015	*N. virens*	–	–	–	–	–	1565[c] (179–19 741)	33	52 000 (6000–651 000)	–
USA	2013	*G. dibranchiata*	–	–	–	–	–	214[d]	153	33 000	–
USA	2013	*N. virens*	–	–	–	–	–	116[e]	62	7000	–
Maine, USA	2006	*G. dibranchiata*	18[b]	–	–	–	0.009	169[f]	153	26 000	1.44
Portugal	2001	*D. neapolitana*	1.5[c]	–	–	–	0.030	45[g]	6	267	0.18
Portugal	2013	*H. diversicolor*	0.27[d]	–	–	–	0.017	4.6[h]	31	144	0.53
Australia	2008	*G. ovigera* *D. aciculata*	–	–	–	–	–	7[i]	97	679	–
UK	2015	All species	–	–	–	–	–	3372[j] (341–21 035)	42[a]	142 000 (14 000–883 000)	–
USA	2015	All species	–	–	–	–	–	19 258[k] (2803–48 831)	108[b]	2 080 000 (303 000–5 274 000)	–

Table 2 Continued.

Site	Date	Species	Extraction area (km^2)	Mean number of collectors $tide^{-1}$	Minutes collecting $individual^{-1}$ $tide^{-1}$	Mean biomass (kg) $person^{-1}$ min^{-1}	Mean biomass (kg) removed m^{-2} $year^{-1}$	Total biomass (t) removed $site^{-1}$ $year^{-1}$	Retail price (UK £) kg^{-1}	Biomass value (£ thousand) removed $site^{-1}$ $year^{-1}$	Value (£) removed m^{-2} $year^{-1}$
Europe	2015	All species	–	–	–	–	–	51 064[l] (7 432–129 480)	36[c]	1 838 000 (268 000–4 661 000)	–
Global	2015	All species	–	–	–	–	–	121 776[m] (17 725–308 782)	49[d]	5 967 000 (868 000–15 130 000)	–

Extraction area: [a](from Watson *et al.* 2015); [b](from Sypitkowski *et al.* 2009); [c](from Cunha *et al.* 2005); [d](from Carvalho *et al.* 2013). Mean collectors $tide^{-1}$: Mean number of collectors per tide recorded at each site per camera view over 51 (Dell Quay), 54 (Fareham Creek Resident 1), 56 (Fareham Creek Resident 2), 39 (Pagham Harbour east facing) and 37 (Pagham Harbour west facing) tides. Minutes $collector^{-1}$ $tide^{-1}$: number of minutes recorded for each activity per tide for all collectors divided by the total number of collectors for each camera view. Biomass $person^{-1}$ min^{-1}: biomass removed per person combined with biomass extraction rate. Biomass removed m^{-2} y^{-1}: biomass removed per person combined with biomass extraction rates and extraction area. Total biomass removed $site^{-1}$ y^{-1}: [a](biomass removed per person combined with biomass extraction rate and extraction area, two tides per day, 365 days per year; [b](from Fowler 2001); [c](Percentage of sea anglers in UK population combined with number of fishing trips per angler per year, proportion of bait as *N. virens* and weight of *N. virens* used per trip; [d,e](from http://www.st.nmfs.noaa.gov/); [f](from Sypitkowski *et al.* 2009); [g](from Cunha *et al.* 2005); [h](from Carvalho *et al.* 2013); [i](from Davies 2013); [j](Percentage of sea anglers in UK population combined with number of fishing trips per angler per year, proportion of bait as polychaetes and weight of *N. virens* used per trip; [k](Percentage of sea anglers in USA population combined with number of fishing trips per angler per year, proportion of bait as polychaetes and weight of *N. virens* used per trip; [l](Percentage of sea anglers in Europe combined with number of fishing trips per angler per year, proportion of bait as polychaetes and weight of *N. virens* used per trip; [m](Percentage of sea anglers globally combined with number of fishing trips per angler per year, proportion of bait as polychaetes and weight of *N. virens* used per trip. Retail price: from Table 1; [a](mean price of UK species); [b](mean price of US species); [c](mean price of European species); [d](mean price of all species). Biomass value $site^{-1}$ y^{-1}: Table 1 combined with total biomass removed per site per year. Value removed m^{-2} y^{-1}: Biomass value per site per year combined with area of site.

2005; Younsi *et al.* 2010; Carvalho *et al.* 2013). As the requirement for bait is intimately linked to all coastal communities, it is, therefore, highly likely that these values are replicated at numerous sites around the UK and beyond, although it is clear that there will be considerable variation in bait choice especially in tropical countries where polychaetes may be hard to collect compared to fish.

Landings (productivity)

From the direct measurements of collector removal rates, we also determined a mean collection rate per person per hour of 228 worms $\pm$ 64 SD. Fowler (2001) reported that commercial collectors harvest as much as 4.5–9 kg per day in summer, but she did not specify the number of hours collecting or the location. We are confident that our value is robust as our data were from over 12 h of direct video recordings of multiple collectors from two sites. Site-specific differences, season and collector efficiency will be important, but our value corresponds to a number of studies of other species (Blake 1979; Harvard and Tindal 1994; Miller and Smith 2012; Carvalho *et al.* 2013).

Using the mean weight of *N. virens* collected by a commercial collector of 6.11 g $\pm$ 4.11 SD gives a mean biomass removal rate of 1.4 kg per person per hour resulting in a substantial quantity (4.9 t) of *N. virens* biomass removed per year from Dell Quay (Table 2). Values for Fareham Creek are much lower reflecting the lower number of collectors per tide and less time spent collecting per individual. Nevertheless, just over 0.8 t are still extracted each year from an equivalent area. Both sites have lower biomass removal rates than the fisheries of either *D. neapolitana* from Portugal or *G. dibranchiata* from the USA; however, production values of the sediment (biomass removed per m^2 per year) for Dell Quay are comparable. The differences in total biomass removed are because the fisheries of *D. neapolitana* and *G. dibranchiata* are much more spatially extensive.

At the local scale, bait fisheries are highly productive, comparable to other intertidal bivalve fisheries (e.g. Ambrose *et al.* 1998) that have significant quantities extracted from relatively small areas of sediment. Site productivities (biomass removed per m^2 of sediment) are orders of magnitude greater than many of the large marine ecosystem (LME) areas used to demarcate the global fished area with the productivity of Dell Quay for *N. virens* 20 times greater than the most productive subtidal bivalve fishery (0.00153 kg m^{-2}; North East US continental shelf LME) and 775 times that of the subtidal bivalve fishery of the Patagonian shelf LME (0.00004 kg m^{-2}) (Anderson *et al.* 2011). Not only does this emphasize polychaete bait's exceptional yield/value ratio, but understanding the true value of a habitat (i.e. intertidal sediment) as a fisheries resource will enable managers to better balance economic activity, conservation planning and multiple stakeholder use (Rodwell *et al.* 2014).

In 2001, Fowler estimated that 130 t of *N. virens* were extracted per annum from the Solent and Poole Harbour combined with Dell Quay and Fareham Creek accounting for 4% if this catch has remained constant. Comparing fisheries at this larger scale indicate that this is a very productive region; extraction rates far exceed the 7 t Australian fishery for *D. aciculata*, the official figures for the *N. virens* USA fishery and approaching those of the biomass of *G. dibranchiata* extracted from the US state of Maine (Table 2). It would be virtually impossible to provide a direct global assessment of all bait collection with the resources and management frameworks available to fisheries agencies. However, where ancillary data are available, our local data can be scaled up resulting in the first national assessments. For the UK (and countries within), a number of studies (Tables S2, S3) have estimated both the number of people engaged in sea angling and the number of fishing days per angler per year. Using the medians of these values, the mean amount of bait used per angling trip, the median percentage of polychaetes used as bait and fishing type (shore or boat) gives a UK fishery landing nearly 1600 t per annum of *N. virens* and 3400 t of polychaetes. To put the UK ragworm and polychaete bait fisheries in context, in 2013 only 800 t of bass (*Dicentrarchus labrax*), 1600 t of pollack (*Pollachius pollachius)*, 3000 t of lobsters (*Homarus gammarus*); 10 000 t of cockles (*Cerastoderma edule*) and 13 000 t of cod (*Gadus morhua*) were landed in the UK by UK-registered vessels (UK Sea Fisheries Statistics 2013).

Value of bait fisheries

Combining the retail value for each species with the biomass removed enables a number of fisheries at different spatial scales to be assessed. The value per annum for Dell Quay and Fareham Creek combined is approaching £200 000. This is close to the value of *D. neapolitana* from Portugal, although the £6 kg^{-1} is the first sale price (presumably equivalent to wholesale), suggesting that the retail value is much greater for the Portuguese fishery. As the spatial extent is increased, the value of each fishery increases concomitantly. For example, *N. virens* worth £4.3 million per annum are extracted from the Solent and Poole Harbour region. Nationally, the values in the USA are substantial with *N. virens* and *G. dibranchiata* fisheries officially reported to be worth close to £40 million. Calculating these values is a significant step forward, but inconsistencies due to the self-reporting process highlighted by Sypitkowski *et al.* (2009) combined with a lack of a direct demand estimate reduce precision considerably. In the UK, assessments of sea angling participation, days spent fishing, use of polychaetes as bait and fishing type (shore or boat) (Table S2) provide an estimate that the *N. virens* fishery alone is worth £52 million per annum with the polychaete fishery worth £142 million per annum. As a comparison using a retail price of £35 per kilogram, the UK lobster fishery in 2013 was only worth £105 million (UK Sea Fisheries Statistics 2013).

In the UK, approximately 10% of an angler's expenditure is on bait (Radford *et al.* 2009; Armstrong *et al.* 2013; Monkman *et al.* 2015) and using the combined estimates from these studies gives a total UK spend of £169 million per annum, which is very close to our calculated value for all polychaete species within the UK. However, as these studies included all bait types (e.g. artificial and non-polychaete), a full assessment of the bait market is urgently required to understand any disparity, even though the combined value is well within the low and high scenario polychaete fishery range (£14 to 883 million).

At the large spatial scale (Europe, USA and globally), estimates are less secure, but the approximate values are very substantial. Using the mean price of bait species reported in Table 1 for each area, combined with 0.32 kg used per fishing day per person, the proportion that uses polychaetes as bait (Tables S2, S3) and that 0.913% (Cisneros-Montemayor and Sumaila 2010) of the global population go sea fishing, then 121 000 tonnes of polychaete bait are collected each year with a retail value of approximately £5.9 billion. This is comparable to many of the world's most important fisheries, but these data also highlight the current landings records for marine worms as being completely erroneous. For example, the National Marine Fisheries Service (2015) recorded only 290 t landed in 2014 for the USA (we estimate a median of nearly 19 000 t), whilst the FAO database has a global mean of only 439 ± 23.7 SEM tonnes per annum from 2000–12 (FAO 2014).

Impacts

The impacts of bait collection have received considerable attention over the last 30 years. Physical characteristics of the shore are altered with topographical changes redistributing organic material, loss of the finer grained particles and changes in bioavailability of sediment-bound pollutants (e.g. Howell 1985; Watson *et al.* 2007). Not surprisingly, bait collection also results in changes in the size-/age-structure of exploited populations (e.g. Watson *et al.* 2007) as well as significant and long-lasting reductions of other invertebrate species (e.g. Jackson and James 1979; Beukema 1995; Brown and Wilson 1997; Ambrose *et al.* 1998; Watson *et al.* 2007; Masero *et al.* 2008; Carvalho *et al.* 2011; Winberg and Davis 2014). There is also evidence that wading bird populations are disturbed by collectors on the shore (Townshend and O'Connor 1993) and are affected indirectly by reductions in prey densities (Shepherd and Boates 1999; Masero *et al.* 2008). Bait collection can also adversely affect many other shore users. Unfilled holes are a hazard causing injury, whilst moorings, jetties and boats can be damaged or undermined (Fowler 1999). There are even conflicts with other fisheries as has occurred for clam fishing in the USA (Ambrose *et al.* 1998). As so many studies based on different species, regions and methods of extraction have shown significant effects, we believe that the impacts of collection are comparable to many of the traditional fisheries in terms of habitat modifications, biodiversity changes and effects on stakeholders, adding further weight to the need for management corresponding to fisheries of equivalent impact.

Management methods

We believe there is a robust case to bring bait collection in line with other fisheries in terms of management and governance at all spatial scales. The challenge is to develop the regulatory, policy and governance frameworks and provide the resources necessary to do this when fisheries and conservation budgets are already under significant pressure. The final section summarizes some of the current options for management and their limitations.

Any decision to manage bait collection at a location must first scientifically assess the site-specific collection level and not rely on anecdotal evidence or historical activity. For example, Pagham Harbour was thought to be popular, but this is not corroborated by our data (Table 2). The implementation of the correct level and extent of any management must be tailored to the local need and ideally linked to a regional approach.

Our video observations show that many collectors were willing to walk a considerable distance (up to 1.6 km) across intertidal shores to reach their collection areas. Not only will this increase the spatial extent of trampling impacts (e.g. Chandrasekara and Frid 1996), but studies (e.g. Cox and Ravenscroft 2009; Liley and Fearnley 2012) have shown that bait collection is amongst many activities that disturbs birds due to the presence of people within/near the intertidal zone. The extent of any management implemented in relation to bird disturbance must, therefore, ensure that these access movements are incorporated into MPA plans.

Using biotope maps of dug areas combined with the video footage for Fareham Creek and Dell Quay, we recorded whether individual collectors were digging in sediment already classified as dug or undug (Fig. 1). A Mann–Whitney U-test confirms that for Dell Quay, a very significant majority of the digging occurred in dug areas (W_{51}=3301, $P < 0.001$). The majority of the collectors recorded from Resident 2′s viewpoint at Fareham Creek were in areas already dug, but this contrasts with Resident 1′s viewpoint; however, neither of these differences were significantly different. From Fig. 1, it is clear that most collectors were digging in areas that were already dug. Although counter-intuitive, Watson *et al.* (2007) showed that *N. virens* are more numerous at dug sites, probably due to reduced competition and increased food availability for the smaller worms. If recruitment to the exploited area is maintained by subtidal populations, some of these fisheries may be more resistant to over-exploitation. This 'self-limiting' of the spatial extent of a fishery could lead to a much reduced level of management and enforcement if collectors select for repeatedly dug areas. However, it must be recognized that repeated digging can lead to local depletions (e.g. Olive 1993) and those fisheries that collect polychaetes from the subtidal region will be more vulnerable to over collection.

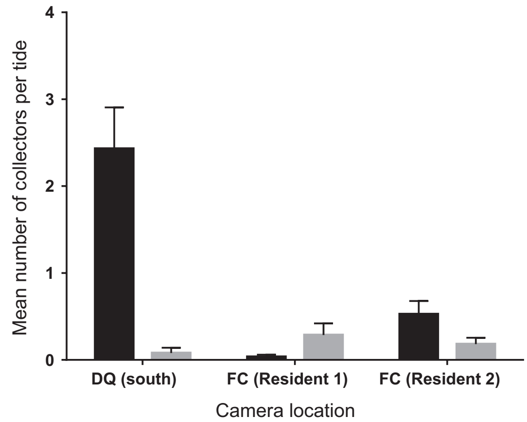

Figure 1 Mean number of collectors (± SEM) per tide recorded from the video footage as digging in areas defined as dug (black) or undug (grey) from the biotope walkover survey at Dell Quay (DQ) and at Fareham Creek (FC) for both residents. Data are from 51 tides (DQ); 56 tides (FC Resident 1); and 55 tides for (FC Resident 2).

Current management of bait collection often focuses on the commercial collector with those collecting for personal use exempt from MPA or fishery stock management. It is, therefore, critical to see whether it is possible to categorize commercial collection by quantifying what is a reasonable amount to be collected for personal use. Understanding commercial versus non-commercial activity is also important in being able to target conservation management (Watson *et al.* 2015) and ensuring that any tax on income is declared as for other regulated fisheries. Combining the mean number of times sea anglers go fishing and the mean amount of bait used per fishing session as 0.32 kg enables us to calculate that the average sea angler going on an average shore-based fishing trip once per week would use 0.33 kg of *N. virens* per week. The bait storage experiment data confirmed that with simple cooling (a household fridge) and either coral sand or seawater in shallow trays, *N. virens* could be maintained for at least 2 weeks. Using the mean removal rate per collector, two weeks' worth of *N. virens* could be collected with only 28 min of digging. It is clear from Table 2 that many collectors spend considerably longer digging with the mean collection time for Dell Quay enough for nearly four weeks of 'average' fishing. Storage for this time period would still be easy to achieve with coral sand or seawater. The time spent digging is highly variable between collectors, and if this is combined with the ease of long-term (weeks) storage and significant variability in the number of times people go fishing (e.g. Drew Associates, 2004; Armstrong *et al.* 2013), it is impossible to separate personal from commercial collection. If management methods are designed to control commercial collection only, then we believe that they will fail as a suitable deterrent and will be ineffective for managing the fishery and its impacts as a whole.

Bait collection in the state of Maine on the east coast of the USA has a licensing programme with approximately 1000 licensed collectors who can dig worms (Sypitkowski *et al.* 2009). Licences for bait fisheries have some support from the industry and anglers; however, licences are unlikely to control the level of bait collection on the shore or the frequency of collection visits. Trying to match the number of issued licences to the 'correct' level of activity would be impossible considering the variability in the frequency of visits, time spent on the shore and the difficulties in assessing what is an appropriate level of activity for a site to maintain the conservation feature. Often associated with licensing and permitting are personal quotas (bag limits). The variability in digging effort between sites, dates and collectors and the long-term storage of bait make any limit unrepresentative of the full spectrum of fishing. What is an appropriate bag limit also suffers similar problems to how many licences can be issued to still meet the management objectives. These issues combined with the difficulties of enforcement as highlighted by Miller and Smith (2012) make quotas/licences challenging management tools to implement, although licences could provide a framework for the implementation of other management measures.

Education is aimed at increasing awareness, reducing impacts and increasing sustainability and can be approached actively, for example workshops, focus groups or passively such as signage or leaflets. Bait collection has often been managed passively (voluntary codes of conduct in the form of a leaflet are popular). To be successful, any education should induce the change in the target group's behaviour to meet the objectives of the original policy. As Watson *et al.* (2015) showed that a UK code restates standard practice or bait collectors ignore specific aspects completely, these passive educational methods have little demonstrable positive impacts for bait fisheries or conservation management.

Enforcement is critical to any management (e.g. Cooke *et al.* 2013), and the local management of bait collection is no exception. Community-based natural resource management (CBNRM) is a common method in tropical reef conservation devolving enforcement to the local community (Dressler *et al.* 2010). However, for CBNRM to be successful, the community should be identifiable and have unambiguous 'ownership/stewardship' of the protected resource (Rudd *et al.* 2003). For bait fisheries, the 'community' is often not obvious especially in multistakeholder areas, for example MPAs with competing requirements and diverse pressures. Often, the communities also lack the capacity to undertake adequate enforcement in the face of infringements (Ferse *et al.* 2010). For example, reliance on bait collectors only to manage the resource is unrealistic as they have low community capacity and social capital leading to a lack of coordination and cooperation needed to solve social dilemmas (Rudd *et al.* 2003).

Using technology to address the issues of enforcement and compliance is currently a hot topic in marine management, but intertidal areas often preclude current methods such as vessel monitoring systems. CCTV is now an everyday part of many people's lives and the recent step changes in technology and reduction in price mean this offers a cost-effective solution for bait collection, obviating the need for community involvement in enforcement. Incorporating these technologies (for example, via unmanned aerial vehicles [UAVs]) into a co-management approach that integrates decision-making/enforcement agencies with those stakeholders that use the resource could make management of bait fisheries affordable and effective. Nevertheless, 'surveillance conservation' has significant privacy and general public acceptance issues that would need to be urgently resolved.

Although the values presented in Table 2 are based on robust empirical data combined with evidence from selected literature (Table S3), the low and high scenarios cover a considerable range of values reflecting the limitations of data currently available. For example, the estimated biomass removed by the UK polychaete fishery with the low scenario (341 tonnes) is nearly two orders of magnitude lower than the high scenario (21 035 tonnes). This is driven by considerable variations in estimates from studies for the number of days fishing, percentage number of sea anglers within the UK and the percentage number of people using polychaetes as bait. Our data are the first to assess polychaete fisheries at a range of different spatial scales and are a substantial improvement on current national official landings data such as the National Marine Fisheries Service or the FAO, but the scenario ranges confirm high levels of uncertainty remain even for countries where the extent and quality of data are high (e.g. the UK). For countries to understand the value of a resource and, therefore, manage their own polychaete fisheries, site-level assessments combined with accurate data on sea fishing are essential. Identification of the types of bait used (and their value through the supply chain) is also critical as the species used by sea anglers are diverse and country/region specific, but also not limited to populations from within national borders. Saito *et al.* (2014) recorded 17 different species from fishing stores and wholesalers in Japan in just over 3 years, but only five species were exclusively supplied from Japanese populations. However, gathering the appropriate quantity and quality of data for bait species fisheries is a significant undertaking. Fujita *et al.* (2012) have designed a method to assess data-limited fisheries using productivity susceptibility analysis (PSA). Their PSA generated management guidance to reduce overfishing risk in coral reef marine ornamental fisheries so the applicability for benthic invertebrates might be limited. Nevertheless, it would be a logical next step for bait to use predictive tools for what will always be challenging fisheries to assess. An interim approach to inform local managers would be to perform an assessment of collector activity and bait-collected areas combined with the biomass removal data provided here or collected directly.

Conclusion

Coastal marine ecosystems face increasing threats from multiple anthropogenic activities and, although some countries (e.g. the UK) have belatedly recognized bait collection as a high priority due to its impacts on conservation features of MPAs, globally bait fisheries remain in the eyes of many low catch and value fisheries. We have shown that the significant value and biomass of polychaete bait fisheries demand urgent action to ensure that they are sustainable and the impacts are minimized for the future health of coastal regions. However, future demand for polychaetes is difficult to predict. Continued declines in fisheries stocks might lead to reduced demand for bait, but increasing disposable incomes in developing countries may see angling participation increase. Finally, the demand for wild-caught polychaetes could surge as an ever-expanding aquaculture industry increases polychaete consumption for use as maturation diets for broodstock and to offset stagnations in the supply of fish meal and fish oil. This has already led to a number of polychaete culture systems being developed (e.g. Bischoff *et al.* 2009), but more mechanized methods of collection (e.g. Beukema 1995 and Birchenough 2013) could make wild-caught polychaetes a cost-effective alternative to culture.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Sources of information for the *N. virens* storage method assessment.

Table S2. Data and sources of data for each component of the landings and value calculations for polychaete fisheries. Realistic, high and low scenarios for each output calculated in Table 2 were calculated using the mean, maximum and minimum value (where available) for each component of the calculation combined.

Table S3. Data and sources of data for each component of the landings and value calculations for polychaete fisheries. Realistic, high and low scenarios for each output in Table 2 were calculated using the median, maximum and minimum value (where available) for each component of the calculation combined. [1]Source providing the high scenario data; [2]source providing low scenario data. Data sources are: 1. Peer-reviewed publication; 2. government agency report/website; 3. social media survey.

