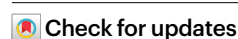


Small-scale octopus fishery operations enable environmentally and socioeconomically sustainable sourcing of nutrients under climate change

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David F. Willer¹✉, David C. Aldridge¹, Charlie Gough² & Kate Kincaid¹

Small-scale octopus fisheries represent an underexplored source of nutrients and socioeconomic benefits for populations in the tropics. Here we analyse data from global seafood databases and published literature, finding that tropical small-scale octopus fisheries produced 88,000 t of catch and processed octopus in 2017, with a landed value of US\$ 2.3 billion, contributing towards copper, iron and selenium intakes, with over twice the vitamin B12 content of finfish. Catch methods, primarily consisting of small-scale lines and small-scale pots and traps, produced minimal bycatch, and the fast growth and adaptability of octopus may facilitate environmentally sustainable production under climatic change. Management approaches including periodic fishery closures, size restrictions, licences and knowledge transfer of fishing gears can enable greater blue food supply and economic value to be generated while improving environmental sustainability.

Small-scale fisheries (SSFs) have been identified as an invaluable component in delivering food security, particularly in developing nations, and are vital to coastal economies¹. Worldwide SSFs make up 24% of the fishing sector (2017)², yet provide employment to over 113 million people, compared with just 7 million people for industrial fisheries³. SSFs play a key role in the delivery of essential micronutrients such as vitamins A, D and B12, calcium, iron and zinc, improving household nutrition for food security¹. They provide families with increased purchasing power through the sale of some of their catch, enabling the purchase of lower-cost staple foods¹. They enhance the economic status of women through their involvement in fishing gear manufacture, fish processing and trading, with women comprising 47% of the workforce employed in SSFs⁴. SSFs are able to thrive in regions and time periods where infrastructure is limited and governments unstable, while industrial food supply chains can be crippled by such conditions⁵. SSFs offer a route out of poverty and act as engines of socioeconomic growth on a local and national level⁵.

Here, we perform a review of tropical small-scale octopus fisheries (TSSOFs) and the major current and future role they can play in

global food security. TSSOFs are defined here as shallow soft-bottom or reef-associated fisheries, distinctly different from more industrial fisheries that target offshore species. Food security is a multi-dimensional concept, with many components from food supply variability to water scarcity. Here we place particular emphasis on the micronutrient component of food security. In the countries considered in this Analysis—those with TSSOFs—the prevalence of undernourishment can exceed 40%, the prevalence of stunting in children under five commonly exceeds 30% (Extended Data Table 1) and incomes are typically lower and food deficits more pronounced than in temperate regions⁶. In tropical countries, SSFs are especially important for delivering key micronutrients to people and tackling these issues. However, fisheries are under pressure, many finfish stocks are fully or overexploited, and large long-lived finfish species may struggle to cope under the pressure of a rapidly changing climate and continuous fishing pressure⁷. Octopus by comparison are shorter-lived, have high fecundity, are fast to adapt to environmental change and some species may benefit from warmer ocean temperatures under climatic change⁸. Small-scale

¹Department of Zoology, University of Cambridge, Cambridge, UK. ²Blue Ventures, Bristol, UK. ✉e-mail: Dw460@cam.ac.uk

octopus fishing is accessible, does not require expensive gear investments and does not have large bycatch or cause widespread seabed damage⁹. In 2017, catch from TSSOFs was around 88,000 t^{2,10}, representing 45% of all octopus caught in the tropics, with the remaining 55% being primarily industrial production. Catch volumes from both industrial and small-scale octopus fisheries are increasing, with the greatest increase occurring between 1980 and 2000 when catch rose eight-fold (Extended Data Fig. 1). Notably there was a dip in catch between 2004 and 2010, which may have been driven by multiple factors, including a temporary shift towards exploitation of other fish and seafood species under changing economic conditions associated with the global financial crisis¹¹, and underreporting of catches, which has been up to four-fold in some regions⁸. TSSOF catch is now back near pre-dip levels and could grow rapidly over the coming years—due to increasing market demand, improving access to markets, a shift of fishing effort from other small-scale tropical finfish fisheries to octopus and an increase in the octopus species being harvested⁹. The TSSOF sector is set to benefit from sustainable fisheries management methods including periodic fishery closures, minimum catch size limits, licensing and knowledge transfer, supporting innumerable coastal communities¹².

In this Analysis, we aim to perform a comprehensive assessment of TSSOFs and the major current and future role they can play in global food security. The socioeconomic benefit of TSSOFs in both providing food on a local level and in generating national income is assessed. The micronutrient profile of octopus is quantified and compared against other major food items in nations with TSSOFs, allowing identification of the key nutritional gaps that octopus fill. The sustainability of TSSOFs is reviewed with a detailed breakdown of the gear types used and specific species targeted. To achieve this, data were collated from global seafood databases, and we also performed a literature review (<https://blueventures.org>)⁹. This Analysis underlines the major role that global TSSOFs play in food security and identifies opportunities for sustainable development and management of TSSOFs that can lead to a step change in food production and generate new financial income.

Results

Socioeconomic value and nutrition

TSSOFs provide important economic and nutritional value to people in the tropics, where there is a high prevalence of food insecurity. In total, octopus from TSSOFs contributed over 88,000 t of food (catch and processed octopus) to the human food supply in 2017. Mexico was the biggest octopus catcher at 42,400 t, followed by Indonesia (Box 1), Mauritania and Morocco, all producing around 10,000 t or more of octopus in 2017 (Fig. 1a). However, the relative quantities of octopus consumed nationally in the human food supply versus the quantity exported differs greatly between these catchers (Fig. 1b,c). For example, while Mauritania and Morocco both catch around 10,000 t of octopus, less than 600 t enters the local food supply between them, with the vast majority instead being exported. This contrasts with nations such as Mexico where a similar quantity is consumed locally compared to that caught (42,400 t caught and 49,900 t in food supply), although exports are still high at 6,700 t. In comparison, in Brazil and Colombia there is a net import of octopus and consumption in the food supply is greater than the quantity caught (Fig. 1a–c). Exports can also be greater than catch in some nations where they are importing and processing octopus from other countries before re-exporting. The landed value of octopus follows the same trend as the catch quantity, being greatest in the largest catchers Mexico, Mauritania, Morocco and Indonesia, with Mauritania having the highest landed value in 2017 at US\$ 620 million of the global US\$ 2.3 billion total (Fig. 1d).

Octopus provide a valuable source of key micronutrients not abundant in the other staple food items consumed in nations with TSSOFs. Figure 2 shows the nutritional profile of octopus compared with the six main plant foods, four main animal foods and four main seafoods by total production volume in the nations with TSSOFs. The percentage of

BOX 1

TSSOFs in Indonesia

Indonesia is the world's second largest fishing nation after China by catch volume, with 80% of this coming from marine fisheries and the remaining 20% inland¹⁰. SSFs play a key role in Indonesian society, making up 92% of the nation's fishing production across all fish and seafood species, directly employing 4.4 million people and indirectly employing a further 25 million people, and 54% of Indonesia's animal protein supply comes from seafood⁴⁰.

TSSOFs play a particularly important role in Indonesia. In 2017, small-scale octopus catch was 17,900 t, food supply 4970 t, and food exports 13,200 t, making Indonesia the second largest producer and largest exporter worldwide (Fig. 1)^{2,10}. Crucially, octopus sales and exports generate important income to local fishers. The mean income in December 2017 was 150,000 Indonesian rupiah (IDR) per fisher per day⁴¹, comparing favourably to the average net wage in 2017 of 96,000 IDR per day⁴².

Indonesian fishers are linked to processors and exporters through a network of highly integrated supply chains involving neighbourhood and village collectors, and intermediary traders at district and provincial levels. As an example of this supply chain, octopus caught by fishers in south, southeast, central and north Sulawesi, as well as regions such as north Maluku and east Kalimantan, finds its way to processors and exporters in Makassar. Across the nation, exporters capture up to 55% of total export value; traders capture around 15%, fishers around 30%⁴⁰.

The octopus mainly are caught on reefs by individual artisanal fishers – by both men and in particular women – using lures and spears at low tide, by fishermen diving, and by individual fishermen fishing from small wooden boats using lures on hand lines in deeper coral reef and coral rubble habitats. Traps and pots are also used in some regions, but not widely because they catch less and can involve complex hauling operations. Most fishing methods, especially lures on hand lines, are targeted, have no bycatch and cause little to no damage to habitat⁴⁰. The primary species caught is *Octopus cyanea*, which has a low vulnerability to fishing pressure because of its high fecundity, low age at maturity, relatively short lifespan and rapid growth rate⁴⁰.

Temporary fishing closures (see Box 2) have been employed as a measure to further improve the sustainability of octopus fishing and to enhance income to fishers. A 281-day-old (2000 g) octopus will achieve a sale price 25 times that of a 120-day-old (350 g) octopus, so there is a direct economic incentive to employ more sustainable practices that allow octopus to reach a larger size⁴⁰. By 2021 seven temporary closures of octopus fisheries had been implemented, covering a total area of 500 ha across five different communities⁴¹. Expansion of this practice in the future can help to support the long-term sustainability of octopus fishing in the region.

required dietary intake (RDI) of micronutrients provided by a serving of octopus is shown in Extended Data Table 2. On a micronutrient level (Fig. 2a–c), octopus provide a valuable source of vitamin B12 (20 µg per 100 g, 1,330% RDI), copper (0.4 mg per 100 g, 33% RDI), iron (5.3 mg per 100 g, 61% RDI) and selenium (44.8 µg per 100 g, 60% RDI), more so than any of the other plant or meat items (Fig. 2a,b). Shrimps (0.39 mg per 100 g) and sprats (36.5 µg per 100 g) are the only other foods able to deliver a comparable level of copper, and tuna (36.5 µg per 100 g) is the only other food able to deliver a comparable level of selenium (Fig. 2c). On a macronutrient level, octopus is relatively rich in protein but not

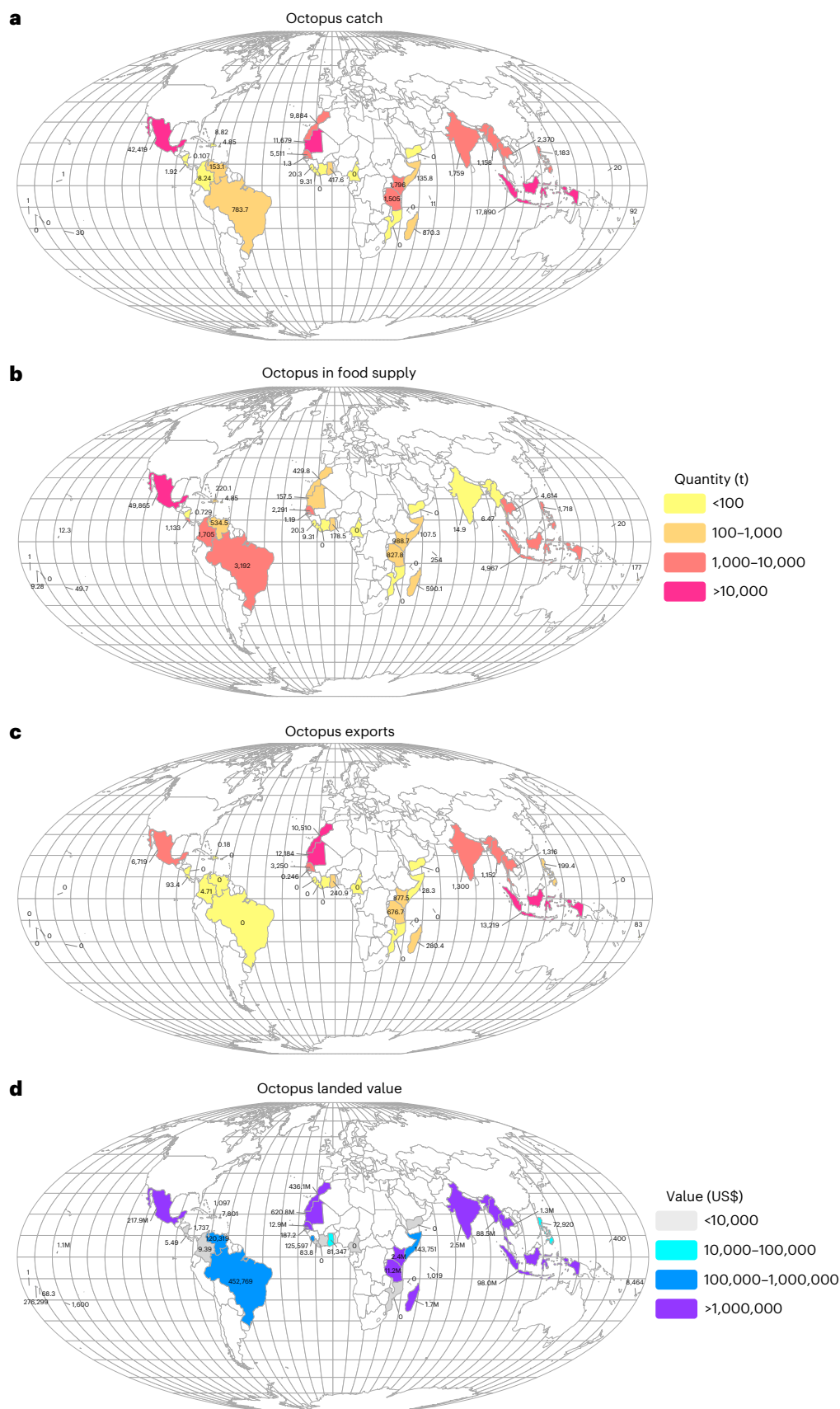


Fig. 1 | Catch, food supply, export quantity and landed value of octopus from small-scale tropical octopus fisheries in 2017. a–d. The numbers on the map and colour scale indicate the quantity in tonnes of octopus caught by SSFs (a), used directly in the human food supply (b) and exported (c), alongside the

landed value in US dollars (d), for each nation with small-scale tropical octopus fisheries. Note that for each nation the sum of exports and food supply does not equal the total catch quantity, as some octopus caught is used for other purposes such as animal feed or is lost due to spoilage. Data sources^{2,10}.

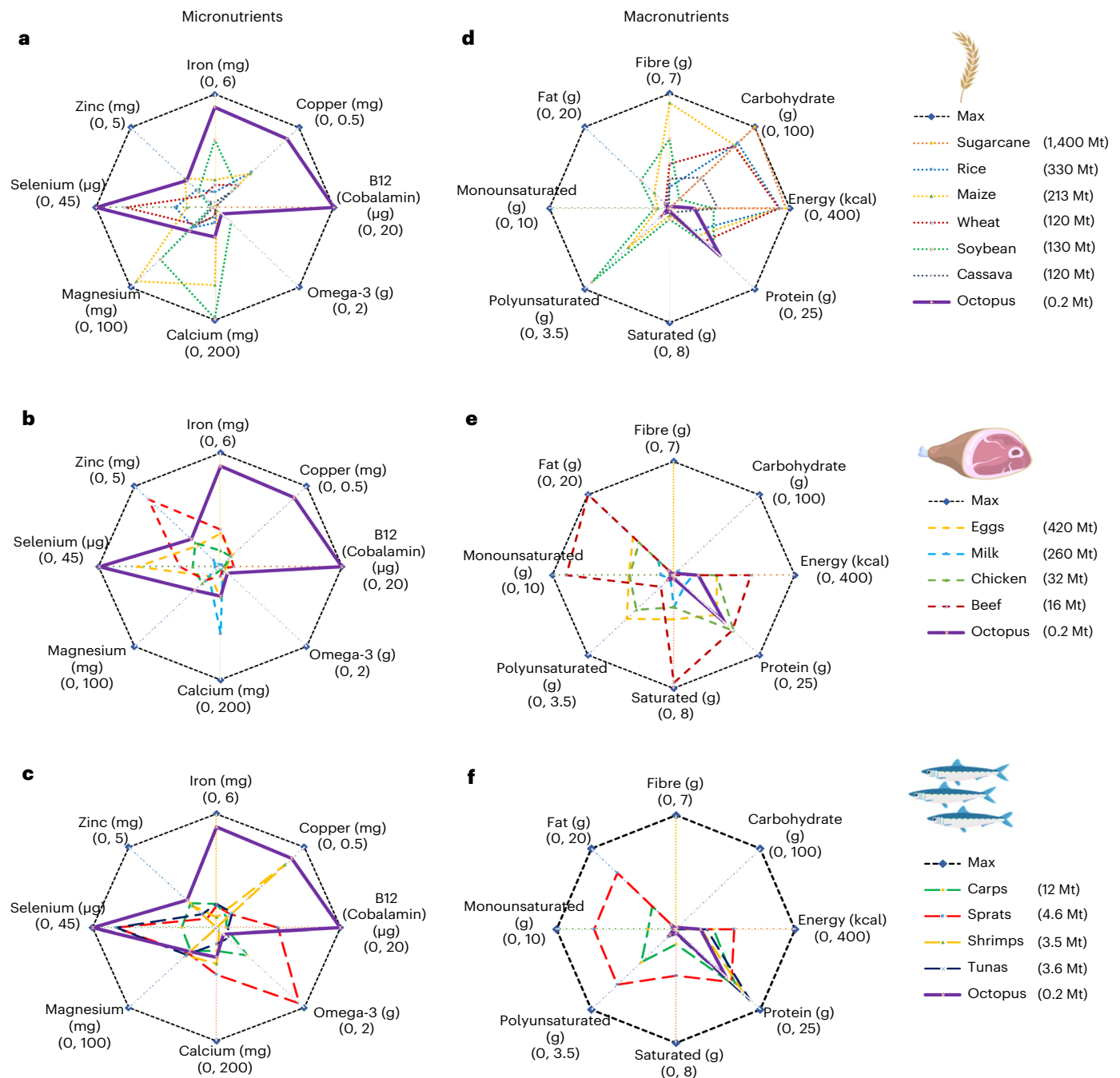


Fig. 2 | Nutritional profile of octopus compared with other major food sources in regions with small-scale octopus fisheries. a–f. The radar plots compare octopus (solid purple line) with the six main plant foods (dotted lines), four main animal foods (short dashed lines) and four main seafoods (long dashed lines), quantified by total production volume, for global regions with small-scale octopus fisheries. Micronutrient (a–c) and macronutrient (d–f) levels per 100 g

are compared. The numbers in brackets below each micronutrient refer to the maximum and minimum value for the given axis, and the black dotted line refers to the maximum values. The numbers to the right of the legend refer to the total production volume of each food in global regions with small-scale octopus fisheries, in 2020 for plants and animals, in 2019 for seafood and in 2017 for octopus. Data sources^{2,10,18,37}.

other macronutrients (Fig. 2d–f). A small quantity of octopus thus acts as a valuable source of key micronutrients in nations with TSSOFs, but the octopus is far less important as a staple source of energy or key macronutrients in these nations.

Sustainability of fishing methods

TSSOFs use a wide range of fishing gear types, which are generally species-specific with minimal bycatch and give TSSOFs a strong stand

from a sustainability perspective. Across all TSSOFs, the most-used gear type between 1961 and 2016 was small-scale lines (512 Gt) followed by subsistence fishing gear and small-scale pots or traps (Fig. 3a–f). However, on a regional level there are key differences in the dominant gear types used. For example, in the Americas, which has been the second largest area by volume of TSSOFs over the period 1961–2016, 80% of octopus are caught using small-scale pots or traps (Fig. 3f). West Africa has seen a similar total harvest volume to the Americas over the period,

BOX 2

Blue Ventures octopus model—periodic fishery closures

Periodic fishery closures can and have played a key role in maintaining local fisheries production. In this form of fishery closure, fishers temporarily refrain from harvesting in specific areas to allow target populations to regenerate. The approach is a popular community-based tool that has been part of many traditional fishing cultures for centuries⁴³. However, this traditional management can easily be rendered ineffective in the face of commercialization.

Octopus fisheries provide a unique opportunity for communities to re-engage with local management and quickly demonstrate the benefits of periodic fishery closures in a time frame that makes sense to small-scale fishers. Octopus grow quickly, almost doubling in weight each month⁴⁴. Thus, closing a small area of octopus fishing grounds for a few months can lead to substantial growth of resident octopus and result in visible increases in catches when the closure site is reopened⁴⁵.

Engagement of communities with the practice of periodically closing small areas of their fishing grounds has several knock-on benefits. The active participation of communities in the design of the closures results in the development of the social structures and governance processes that are needed for broader fisheries management. The simplicity of periodic octopus closures means that adoption in adjacent communities can be rapid. Implementing rules that prevent neighbouring communities from harvesting inside the closures in the first days of reopening, the most productive days, further motivate neighbouring communities to implement their own closures to achieve the same productivity benefits. So, while small periodic octopus fishing closures in a single community may be insufficient to effectively manage the stock, the easy replication of closures along a coastline and their ability to encourage communities to engage in wider management actions can lead to large-scale improvements in the octopus stock⁴⁵.

but just 1% of this came from small-scale pots or traps, with small-scale lines instead being dominant (Fig. 3d). There are also some gear types found almost exclusively in specific global regions, such as cast nets in Southeast Asia (Fig. 3b). All the gear types used by these TSSOFs are in general less environmentally harmful than large industrial fishing techniques (such as deliberate bottom trawling for octopus or bycatch from trammel nets⁸), but it is important to also emphasize that the small-scale techniques that have the potential to do the most harm (small-scale encircling nets, gillnets and seine nets) are techniques that comprised just 107 Gt of the 1,570 Gt total between 1961 and 2016. The relatively low-impact gears (comparative to industrial bottom trawls), combined with management measures (including national size restrictions, temporal fishery closures and site-based periodic closures such as those supported by Blue Ventures; Box 2), suggest that TSSOFs offer a relatively more sustainable way of providing nutrient-rich seafood.

Data from the literature review also emphasize the sustainability of the gear types used in TSSOFs, the species caught and the importance of the catch in sustaining the local community (Table 1). A wide variety of species are caught, with the dominant catches *Octopus insularis* and *O. vulgaris* in the Americas, *O. cyanea* and *O. ornatus* in the South Pacific, *O. cyanea* in Southeast Asia, *O. vulgaris* in West Africa and *O. cyanea* in the Western Indian Ocean. Gear types used across all

regions are targeted with minimal bycatch, and among others include spears, harpoons, pots, hand lines, diving and buckets. The majority of the catch is reported as being used for subsistence, local consumption and local sale, helping to sustain the local community, although in some locations such as Madagascar there are strong export markets.

Discussion

TSSOFs provide valuable socioeconomic and nutritional value to people in the tropics. In all producer regions, octopus provides a source of income alongside a direct supply of nutritious food. In some areas, such as West Africa, most octopus is exported; in other areas, including Central and South America, a large proportion of octopus is consumed in the human food supply; and in the largest producers, such as Indonesia, contribution to both exports and food supply is high. Landed values of octopus follow the same trend as catch volumes, and are greatest in major producers including Mexico, Mauritania, Morocco and Indonesia, where they provide a strong income to fishers from catching octopus. It is critical, however, to note that the dynamics of octopus international markets are complex and vary annually in synchrony with octopus populations. This can be seen in Supplementary Videos 1–3, where catch, food supply and export values fluctuate within each region over the course of time. One example of this is Mexico: when catch of octopus drops in other major octopus producers including Mauritania and Morocco, prices rise and exports from Mexico increase¹³.

The role of TSSOFs in providing local employment and welfare, particularly for women, is important. In the Pacific region in 2012, women accounted for 56% of annual small-scale catch across all fish and seafood species, with an economic impact of US\$363 million, and worldwide 130 million women contributed in some way towards marine capture fisheries¹⁴. In Indonesia, the mean income to octopus fishers is well above the average national wage, small-scale octopus fishing provides employment across the supply chain from local to district to the provincial level, and women play a key role in octopus capture (Box 1). As another example, in Madagascar, over half of the small-scale octopus catch is obtained by women¹⁵. Indeed overall, in Pacific island region diets, women's contribution of fish is often more important than men's, as fishing trips by women are typically more frequent and their catch tends to go towards feeding the family rather than to the market¹⁴. In contrast, in major TSSOF producers such as Mexico, a large proportion of the octopus catch is sold and distributed nationally (usually frozen), providing a source of income to individuals along the value chain, and also enabling a greater proportion of the population to access the nutritional benefits octopus provide¹³.

Octopus from TSSOFs provide a concentrated course of key micronutrients to communities in the tropics. The most notable micronutrients provided to people by octopus from TSSOFs are vitamin B12, copper, iron and selenium, with 100 g of octopus providing 13 days' worth of vitamin B12, alongside around half the daily requirement of copper, iron and selenium. In Mexico, Brazil and Colombia, all areas with an opportunity for TSSOF-derived octopus consumption, the prevalence of marginal or low vitamin B12 levels in the population is typically over 50%, demonstrating the potential value octopus could further add if it is distributed well across the population¹⁶. In these nations, sources of micronutrients for families are becoming increasingly restricted by the criminalization of and greater enforcement against bushmeat hunting, making the contribution of octopus more valuable¹⁷. Micronutrients such as vitamin B12, zinc, calcium and selenium are not readily bioavailable in the plant-based foods these people have access to^{18,19}. It is important to note that given the very rich micronutrient content of octopus, consumption in excessively high volumes or frequencies is not advisable. For example, excessive intake of copper in humans can lead to haemolysis, hepatic necrosis and renal damage²⁰. However, rather than being a problem with octopus from TSSOFs, this should be regarded as a strength. The high micronutrient density of octopus means that human populations only need to eat a small

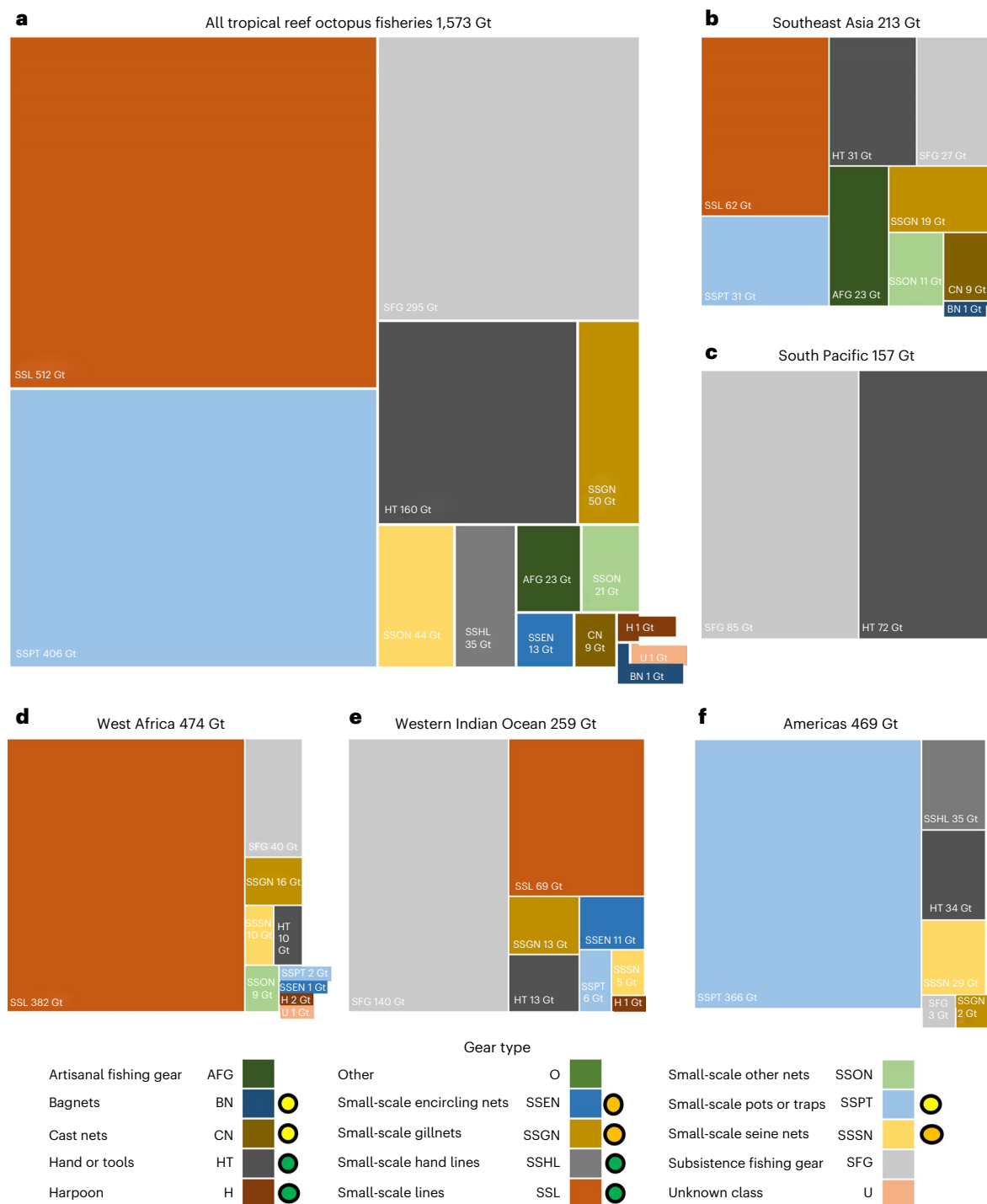


Fig. 3 | Fishing gear types in small-scale tropical octopus fisheries. Data are total catch volumes between 1961 and 2016. **a**, The volume in gigatonnes of octopus fished across all tropical octopus fisheries, separated by gear type. **b–f**, The volume in each global region. Data source². The traffic lights by the gear types indicate sustainability from green (most sustainable) to yellow to orange

(least sustainable). Note that all the gear types used in small-scale fisheries are more sustainable than most industrial fishing practices. Sustainability scores are not given for the gear types where catch approach is unclear, for example, subsistence fishing gear. Data sources for sustainability^{38,39}.

quantity to supplement a diet comprising primarily staple plant crops, meaning a small amount of TSSOF production delivers the micronutrient needs to a relatively larger number of people. As an example, a 100 g serving of octopus every two weeks would meet almost the entire vitamin B12 requirements of one adult, and at the current level of TSSOF catch of 74,000 t, the B12 needs of 28 million people could be met via octopus. The further expansion of TSSOFs could increase

this value, but it will be paramount that impacts on the environment are minimized during this process.

TSSOFs have played and can continue to play a key role as a form of sustainable fishing in the tropics. A wide variety of sustainable gear types have been used worldwide, with small-scale pots and traps being dominant approaches in the Americas, and small-scale lines and subsistence fishing gear in West Africa some of the most prevalent

Table 1 | Target octopus species, gears used and socioeconomic importance of octopus in countries with TSSOFs

Region	Country	Target octopus species	Gears used	Importance to local community	References
Americas	Brazil	<i>Octopus insularis</i> , <i>O. vulgaris</i> ; other species mentioned: (not major target) <i>Callistoctopus macropus</i>	Gaffs, longline pots, snorkel, hookah diving, wading with hook, hand lines, bated barbless hooks	Self consumption	OR053, OR014, OR032, OR031, OR030, OR023
Americas	Colombia	<i>O. tayrona</i>	Not listed	Not listed	OR026
Americas	Costa Rica	Not listed	Hooks, snorkel	Local consumption, sale	OR053
Americas	Dominican Republic	<i>O. briareus</i> , <i>O. vulgaris</i>	Traps, gillnet, diving, fishing lines	Bait, also sold domestically	OR065
Americas	Mexico	<i>O. bimaculatus</i> , <i>O. bimaculoides</i> , <i>O. hubbsorum</i> , <i>O. insularis</i> , <i>C. macropus</i> , <i>O. maya</i> , <i>O. rubescens</i> , <i>O. vulgaris</i>	Alijos/jimbas (wooden sticks with several lines and baits hung off small boats, which prevents the capture of breeding female octopus), hooks, diving, snorkel, traps, pots, spear	Local use/subsistence, sale	OR003, OR005, OR006, OR010, OR013, OR014, OR016, OR018, OR020, OR021, OR023, OR024, OR027, OR031, OR035, OR036, OR038, OR043, OR044, OR046, OR049, OR053
Americas	Venezuela	<i>O. vulgaris</i> , <i>O. insularis</i>	Lines/jigs, longline pots, traps	Local consumption, sale	OR015, OR022, OR035, OR053
South Pacific	Cook Islands	<i>O. cyanea</i> , <i>O. ornatus</i>	Not listed	Subsistence, recreational	OR053
South Pacific	Fiji	<i>O. cyanea</i> , <i>O. ornatus</i>	Not listed	Subsistence, recreational	OR053
South Pacific	Kiribati	<i>O. cyanea</i> , <i>O. ornatus</i>	Not listed	Subsistence, recreational	OR053
South Pacific	Micronesia	<i>O. cyanea</i> , <i>O. ornatus</i>	Lure, hand lines	Subsistence, recreational	OR053
South Pacific	Samoa	<i>O. cyanea</i> , <i>O. ornatus</i>	Snorkel, diving, spear, rod and reel	Subsistence, recreational	OR053
Southeast Asia	India	<i>O. cyanea</i>	Spears, lights, rods, traps, harpoons, poison, gillnet, hook and line	Subsistence, cultural significance, bait, local sale, local consumption	OR053
Southeast Asia	Thailand	<i>Amphioctopus aegina</i> (major), <i>A. rex</i> (minor)	Traps, gillnets, small push net, hook and line, cast net	Not listed	OR001, OR038, OR053
West Africa	Morocco	<i>O. vulgaris</i>	Pots (most common), hand, jigs, traps	Not listed	OR053, OR060, OR061
West Africa	Senegal	<i>O. vulgaris</i>	Jigs (most common), hand lines, longlines, gillnets (bycatch)	Export, no local market	OR011, OR012, OR014, OR062, OR063
West Africa	Gambia/Mauritania	<i>O. vulgaris</i>	Not listed	Not listed	OR053
Western Indian Ocean	Kenya	<i>O. cyanea</i>	Spears, harpoons, steel rods	Economic and subsistence value	OR053
Western Indian Ocean	Madagascar	<i>O. cyanea</i> (majority), <i>C.</i> <i>macropus</i> , <i>A. aegina</i> , <i>C.</i> <i>ornatus</i>	Spears, wood stick, harpoons, steel rods, bucket	Local livelihood (half of household income for >62% of households)	OR008, OR014, OR039, OR042, OR051, OR053
Western Indian Ocean	Mozambique	<i>O. cyanea</i> (majority), <i>A.</i> <i>aegina</i> , <i>Cistopus indicus</i> , <i>O. macropus</i>	Spears, bucket, harpoon, rods	Subsistence, economic	OR040, OR052, OR053
Western Indian Ocean	Seychelles	Not listed	Spears, harpoons, steel rods	Subsistence, economic	OR053
Western Indian Ocean	Tanzania	<i>O. cyanea</i>	Gaffs, hand, snorkel, spear, harpoon, rods	Subsistence, economic	OR014, OR024, OR025, OR053, OR045

The data shown are a summary of those extracted from the literature review performed alongside Blue Ventures (see Methods). A table of the references is provided in Supplementary Data 9.

techniques since 1961. Some of these differences in fishing practices may be historical, with fishing practices emerging independently in different global regions and spreading on a geographically vertical rather than horizontal axis due to the layout of the Earth's landmass, a trend also seen in domestic livestock and crop production systems²¹. As was the case with agriculture, there could be benefits to human nutrition via knowledge transfer of certain TSSOF fishing techniques to regions where they have not traditionally been used, for example, by allowing a greater variety of species to be caught or via making fishing trips less time-consuming²¹. However, of at least equal and if not more importance, knowledge transfer could help ensure that the most

sustainable octopus fishing techniques are being used in each specific location worldwide. For example, increasing the use of techniques such hand tools, harpoons or small-scale lines in areas where they are underutilized at the expense of less-sustainable techniques such as gillnets and seine nets could offer important benefits. We already know that there have been instances where relatively 'intensive' artisanal fishing has caused degradation of coral reef systems, and that there are many areas where data on the impact of octopus fisheries on the environment are sparse²². Knowledge transfer has already been indicated as a promising approach in other areas of marine conservation, for example, in the management of sea lamprey populations²³, and in

the case of octopus it can help us improve our understanding of the environmental impact of octopus fishing at a site-specific level while also ensuring the most sustainable techniques are used. To fully assess and ensure sustainability, it is also important to understand the value chain, and this can be difficult in SSFs. However, difficult does not mean impossible; for example, the octopus fishery in Mexico is considered to have a sustainable value chain due to a combination of management and knowledge of biology¹³.

Small-scale octopus fishing has the capacity to be a highly sustainable form of fishing because octopus tend to have relatively high fecundities and growth rates compared with vertebrate marine species^{8,24}. These traits also mean that octopus may cope better than finfish species under climatic change; indeed, there is evidence that the adult growth phase may extend, and fecundity and recruitment strength increase, under ocean warming^{7,8,24}. However, caution is required in this conclusion—octopus can still undergo range shifts, and the lack of a generational overlap means octopus are vulnerable to boom–bust population dynamics^{24–26}. Octopus are also not immune to overfishing and stock assessments are not undertaken for most octopus fisheries²⁷. Hence improving assessment, as now encouraged by the Marine Stewardship Council, is critical to help ensure the sustainability of small-scale octopus fishing^{27,28}. It is also important to consider how climatic change might affect coral reefs; the habitat octopus live in. Rising ocean acidity and associated coral bleaching could lead to a loss of habitat for key species living on tropical coral reefs such as *O. cyanea*⁸. There are, however, now approaches that can be used to help increase the resilience of coral reefs to climatic change and help restore reefs that have already been damaged. The US National Academies of Science, Engineering, and Medicine recently performed an extensive review of 23 techniques, many of which are now in active use—such as coral gardening, algae removal and substrate—and some of which are to enter the field soon, including assisted gene flow and microbiome manipulations²⁹. Combined with improved management approaches, this can help octopus fisheries based on tropical coral reefs to remain sustainable into the future.

There are different management approaches in place for octopus, including size and/or gear restrictions, and a combination of local and regional and/or national closures. Specific examples include closed seasons, size restrictions, licences and gear restrictions in Mexico¹³, seasonal closures in Senegal to match local reproductive cycles³⁰, and size and gear restrictions (number of pots) in Brazil³¹. As we investigated, periodic fishery closures are one particularly promising approach that can enhance the sustainability of octopus fisheries. Periodic fishery closures (Boxes 1 and 2) can enable the catch weight of octopus to be nearly 6 times greater and sale price 25 times greater, by allowing octopus just over twice the amount of time to grow than they would have had without fishery closures. The approach is currently being carried out in a relatively small number of areas—for example, just 500 ha in the second largest producer, Indonesia—but expansion to new areas, and developing regional quantitative models, could optimize the sustainability and nutritional and economic output of octopus fisheries. It will, however, remain important to ensure that fishing pressure is carefully monitored during periods of reopening to avoid issues seen in periodic closures for other species, where an apparent abundance of catch species has led to destructive overexploitation and damage to the stock³². In addition, the benefits of periodic fishery closures can be relatively short-term, so they need to be combined with other measures as part of an integrated management plan.

To remain sustainable in the future, improvements in the management of octopus fisheries will be required. A large proportion of total catch still goes unreported, and there is an urgent need for incentives to promote fishers' participation in surveillance and stock monitoring, enforced access rights through individual and region-specific quotas, and robust spatial management plans³³. Issues with sustainability also extend beyond the tropics and into areas such as the Mediterranean

in Europe. Here, excessive fishing effort, illegal fishing, exploitation of undersized octopus, and a lack of routine surveillance and monitoring of fishing effort as well as stock status are all areas of issue³⁴. There is a need for more temporal fishery closures and protection of key habitats and life cycle stages to protect new recruits to the octopus population. One example of a control method that could be used is to impose a minimum landing size requirement for octopus fishers, helping reap the benefits that can be seen in periodic fishery closures³⁴. For regions with TSSOFs that are primarily exporters rather than consumers of octopus, the introduction of ecolabels to increase the market visibility and value of octopus could serve a dual benefit in ensuring stocks are also managed sustainably³⁴. As an opportunity for further development, TSSOFs could play a role in boosting the income of developing tropical nations through tourism while promoting conservation of fishery resources. An example already being carried out in Japan, is 'nagisa-haku', in which tourists stay overnight and participate in a fishing community, connecting people with the conservation of the coast and renewing interest in traditional marine products and culture³⁵.

There is a great and emerging need for nutrient-rich food in the tropics³⁶. SSFs already do and can play an increasing role in meeting this need. They currently provide over two-thirds of the fish and seafood destined for human consumption worldwide, and employ over 90% of fishers involved in capture fisheries³³. Octopus fisheries offer a sustainable option to expand small-scale fishing activities into the future with sustainable catch methods, adaptability to climate change and fast growth rates all providing benefits. Careful monitoring and implementation of effective management strategies such as periodic fishery closures can help small-scale tropical octopus fisheries provide a growing source of nutrient-rich food to the next generation.

Methods

Defining TSSOFs

The following method was used to define TSSOFs and to select the countries analysed during this study. The academic literature was searched for tropical octopus fisheries between latitudes 23.5° N and 23.5° S. All global tropical fishery countries were covered, and each paper was read to determine if it met the criteria (reef or shallow soft-bottom associated, small-scale, octopus—this differs from small-scale offshore tropical octopus fisheries). All countries covered were grouped into five focus regions (Southeast Asia, South Pacific, West Africa, Western Indian Ocean, Americas) to allow comparisons between regions. The five focus regions selected cover the major areas where small-scale tropical octopus fishery communities reside. This literature review allowed us to look for individual studies that reported any information on topics including gear use, catch rates and the number of fishers for TSSOFs, providing further context and individual, local scale site information to the widely used databases.

Catch volumes from tropical octopus fisheries

To create Fig. 1, the quantity of catch that was small-scale or industrial for tropical octopus fisheries was calculated as described in the 'Socio-economic value and nutrition' section below. These data are available in Supplementary Data 1. All spreadsheets were created using Microsoft Excel software.

Socioeconomic value and nutrition

Figure 1 was created using the Food and Agriculture Organization of the United Nations (FAO) FishStatJ data for octopus catch, supply, and export data, and the Sea Around Us database to allow calculation of the proportion of this that was small-scale^{2,10}. We first filtered to select all countries defined as having tropical octopus fisheries by Blue Ventures (<https://blueventures.org>)⁹. Data from the Sea Around Us project were then used to calculate what percentage of octopus (and other cephalopods) caught was small-scale or industrial for each country for each year, with the small-scale category created by grouping the 'artisanal'

and 'subsistence' categories from the Sea Around Us (Supplementary Data 2). Artisanal fisheries are defined as those using small-scale or fixed gears whose catch is predominantly sold commercially, and they are limited to a coastal area to a maximum of 50 km from the coast or to 200 m depth, whichever comes first. Subsistence fisheries are fisheries that are run by non-commercial fishers or women where the catch is consumed by the fishers' families². For these data we used the following species categories to select for octopus (and other cephalopods): 'Octopuses (Octopodidae)', 'Octopuses, pikas (Octopus)', 'Octopuses, argonauts (Octopoda)', 'squids, cuttlefishes, octopuses (Cephalopoda)' and 'clams, seasnails, squids, octopuses (Mollusca)'². Note that in any given year for any given country where it was not defined whether the catch was small-scale or industrial, we have assumed that the percentage of catch that was small-scale was the same as the next successive year where small-scale percentage data were available. The number of instances where this correction needed to be made was small and instances are marked with an asterisk in Supplementary Data 4. We did not use the Sea Around Us dataset to quantify catch volume, supply or export, because the dataset classifications did not enable us to filter out octopus from other cephalopods due to the categories 'squids, cuttlefishes, octopuses (Cephalopoda)' and 'clams, seasnails, squids, octopuses (Mollusca)'. The Sea Around Us dataset also lacked supply and export data. The Sea Around Us database was just used to provide information on the percentage of the catch that was small-scale, and information on the gear methods.

Data on total catch, total human food supply and food exports of 'cephalopods' were then obtained for the years 1961–2017 using the FAO FishStatJ food supply and balance dataset¹⁰. We used the FAO definition for food supply as the total fish available for human consumption = catch less non-food uses, plus imports, less exports, plus or less variation in stocks (all expressed in terms of fresh equivalent). The FAO FishStatJ global production by catch source dataset was then used to calculate what percentage of cephalopods caught by each country with TSSOFs in each year was octopus (Supplementary Data 3)¹⁰. Note that Cameroon, Comoros, Madagascar, Myanmar, Samoa and Somalia did not distinguish octopus catch from cephalopods, so a global average for each year of the percentage of cephalopods that was octopus was used. These FishStatJ data, combined with the Sea Around Us data, were then used to calculate what percentage of octopus catch, total human food supply and food exports came from SSFs for each nation in each year (Supplementary Data 4).

We also calculated the landed value of octopus from each nation. This was done by first obtaining landed values of all octopus and cephalopods from SSFs from the Sea Around Us database, using the same filter categories as above². We then used the FAO values for the percentage of cephalopods that were octopus to calculate the landed values of octopus from SSFs for each nation with TSSOFs¹⁰. Data for the most recent and complete dataset, the year 2017, were then plotted on maps and used to create Fig. 1 (Supplementary Data 5), using Magic Maps 2 software. Map videos are available in the Supplementary Information showing all the data between 1961 and 2017; see Supplementary Video 1 for catch, Supplementary Video 2 for supply and Supplementary Video 3 for exports. We did not produce a video for the landed value data, because there are large gaps in the Sea Around Us data on this in years prior to 2015 for major producers, including Mexico.

FAO and United States Department of Agriculture (USDA) data were used to build the nutritional radar plots in Fig. 2. The most recent production volumes of all crops, meats and seafoods were obtained from FAOSTAT (year 2020) and FAO FishStatJ (year 2019)^{10,18}. The countries with TSSOFs were selected from these data, with the exception of Tanzania, Zanzibar, and the Wallis and Futuna Islands, for which production data did not exist. A sum of the production volume of each food type from these nations combined was then calculated. The top six plant crops, four animal products (including eggs and milk) and top seafood species (fish and shellfish) by total production

volume were then selected. These were the plant crops sugar cane, rice, maize, wheat, soybean and cassava; the animal products eggs, milk (cow, buffalo, sheep, camel and goat), chicken and beef; and the seafoods carps (carps, barbels and other cyprinids), sprats (herrings, sardines, anchovies), shrimps (shrimp and prawns) and tunas (tunas, bonitos, billfishes). We excluded oil palm fruit from the top six plant crops as a large proportion of oil palm fruit is used for non-food uses such as biofuels and cosmetics (Supplementary Data 6). Octopus was selected too (the volume consumed in Fig. 2 includes the volume from both small-scale and large-scale fisheries). Nutritional data for each of these food items were then obtained from the USDA³⁷ and combined with this data (Supplementary Data 7). Data were then plotted on the radar charts in Fig. 2.

Sustainability of fishing methods

Data on the gear type used to catch octopus in TSSOFs between 1950 and 2016, the full range of dates available, were obtained from the Sea Around Us². For these data we used the following species categories to select for octopus (and other cephalopods): 'Octopuses (Octopodidae)', 'Octopuses, pikas (Octopus)', 'Octopuses, argonauts (Octopoda)', 'squids, cuttlefishes, octopuses (Cephalopoda)' and 'clams, seasnails, squids, octopuses (Mollusca)'². As was the case in the 'Socioeconomic value and nutrition' analyses, these data did not enable us to filter out octopus from other cephalopods due to the categories 'squids, cuttlefishes, octopuses (Cephalopoda)' and 'clams, seasnails, squids, octopuses (Mollusca)'. To account for the inclusion of other cephalopods in the data, the FAO FishStatJ global production by production source dataset was used to calculate what percentage of cephalopods caught by each country with TSSOFs in each year was octopus (Supplementary Data 3), with data available from 1961 to 2016¹⁰. This enabled us to calculate an estimate of the volume of octopus caught by each catch method in each country over the years 1961 to 2016. Plots were then created in Fig. 3 to show the volume of octopus caught in TSSOFs between 1961 to 2016, broken down by fishing gear type for each of five main global regions: Southeast Asia, South Pacific, West Africa, Western Indian Ocean and Americas (Supplementary Data 8).

We note there is still a great need for improved data on octopus catch and classification type. In this report we used the Sea Around Us database for assessing gear types. The Sea Around Us database, like any data source, has its own unique approach. The Sea Around Us conducts reconstructions of catch data by analysing additional data available from fisheries, socioeconomic and population data sources. Crucially this includes a calculation that allows unreported catch values to be included in the data. Unreported catch can make up a large component of small-scale fishery catch, and it does mean that Sea Around Us values differ slightly from FAO values. Our methodology allows fair comparisons between countries, being consistent for all countries within the catch type analysis and within the production, supply, export and landed value analyses. The same trends are seen within both the FAO and Sea Around Us data (for example, with Mexico being the largest producer of octopus), while the exact magnitudes differ slightly due to different methodological approaches.

Data on gear type were also obtained from a review performed alongside Blue Ventures on the status of the world's small-scale tropical octopus fisheries⁹. This involved a literature search to review country-level information within target regions. The literature review included searches within the Web of Science (6 January 2021), Mendeley (7 January 2021), Scopus (7 January 2021), EBSCOhost and WorldCat. The terms for inclusion were that a fishery must be small-scale (non-industrial, artisanal or local as described), directed at octopus, tropical (latitude: 23.5° N, 23.5° S) and reef or shallow soft-bottom associated. We excluded areas outside the tropical range and references that were not about fishing (for example, theory-based, modelling exercises, papers with no data). Papers had to be digitally accessible, available in English (although some Spanish references were included

and coded by native speakers), peer-reviewed or with standing (for example, grey literature, verified by in-country communications). The search strategy included the following: EBSCOhost—searched for ‘octopus AND fishery’ (found 14 entries, 12 of which did not meet criteria); WorldCat—searched for ‘octopus AND fishery AND artisanal’ (found 25 entries, 22 of which were duplicates); grey literature through searches on Google for ‘octopus fishery artisanal’, ‘octopus fishery small-scale’, and ‘octopus fishery management’; Web of Science and Mendeley—keyword search, TS = (‘octopus’ OR ‘cephalopod’ OR ‘o.vulgaris’ OR ‘o.cyanus’ OR ‘o.maya’ OR ‘common octopus’ OR ‘big blue octopus’ OR ‘polvo’ OR ‘horita’ OR ‘commercial octopus’ OR ‘orite’ OR ‘poulpe’ OR ‘maduko’ OR ‘o.sinesis’) refined by topic (‘small-scale’ OR ‘artisanal’ OR ‘livelihood’ OR ‘fishing community’ OR ‘fisher folk’ OR ‘subsistence’ OR ‘women’ OR ‘fisher’). After identifying possible sources of information, abstracts were reviewed for final inclusion in the review, then accepted papers were read at full text, then target information was extracted. Information was not extracted for Indonesia because Blue Ventures already had extensive in-country knowledge and had published a report on it. When data gaps were apparent, or to verify information, we conducted interviews through calls and emails to ask for additional site-specific information, particularly regarding COVID-19 impacts, trade, fishery status and management. A list of the references considered in the literature review are shown in Supplementary Data 9.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are available in the manuscript or supplementary materials. The following publicly available datasets provided source data for this manuscript: FAO FishStatJ, www.fao.org/fishery/statistics/software/fishstatj/en; Sea Around Us, <https://www.seaaroundus.org/>; and the USDA, <https://fdc.nal.usda.gov>.

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Author contributions

D.F.W., D.C.A. and K.K. all participated in study design and data analysis. D.F.W. wrote the final manuscript. All authors reviewed and approved the manuscript before submission.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to David F. Willer.

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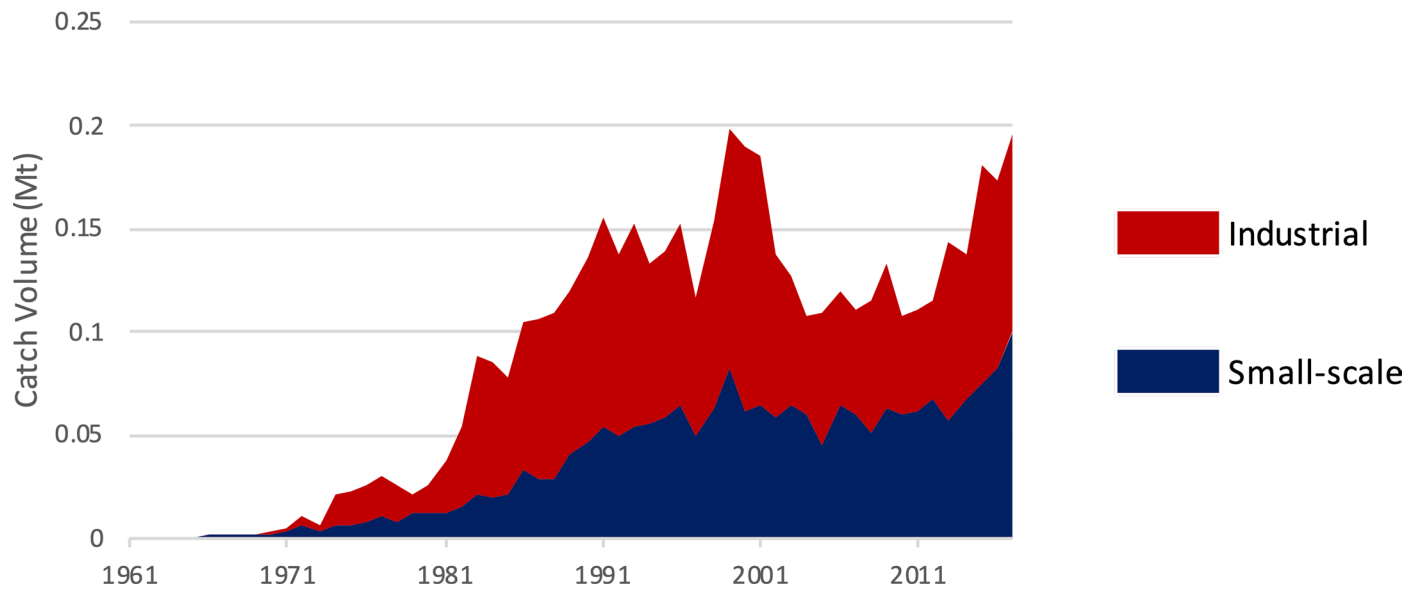
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Tropical Reef Octopus Fisheries



Extended Data Fig. 1 | Catch volumes from tropical octopus fisheries. Catch volumes for industrial (brown) and small-scale (dark blue) tropical fisheries between 1970 and 2017. Data sources ^{2,10}.

Extended Data Table 1 | Food insecurity in countries with tropical small-scale octopus fisheries (TSSOFs)

Country	Prevalence of undernourishment (%)	Prevalence of stunting in children under age 5 (%)
American Samoa	No data	No data
Brazil	4.1	6.1
Cameroon	6.7	27.2
Colombia	8.2	11.5
Comoros	20.4	22.6
Cook Islands	No data	No data
Costa Rica	3.4	8.6
Dominican Republic	6.7	5.9
Federated States of Micronesia	No data	No data
Fiji	5.7	7.9
Gambia	21.6	16.1
Ghana	4.1	14.2
India	16.3	30.9
Indonesia	6.5	31.8
Ivory Coast	4.4	17.8
Kenya	26.9	19.4
Kiribati	4.2	14.9
Liberia	38.3	28
Madagascar	48.5	40.2
Mauritania	10.1	24.2
Mexico	6.1	12.1
Morocco	5.6	12.9
Mozambique	No data	37.8
Myanmar	3.1	25.2
Nicaragua	18.6	14.1
Philippines	5.2	28.7
Puerto Rico	No data	No data
Samoa	4.4	6.8
Senegal	7.5	17.2
Seychelles	No data	7.4
Sierra Leone	27.4	26.8
Somalia	No data	27.4
Tanzania	22.6	32
Thailand	8.8	12.3
Venezuela	22.9	10.6
Wallis and Futuna	No data	No data
Yemen	41.4	37.2
United Kingdom	<2.5	<1

The table shows the prevalence of undernourishment and per capita food supply variability in all of the countries considered in this analysis, those with TSSOFs. The United Kingdom is shown at the bottom of the table for comparison. Data from the year 2020¹⁸, note for some countries there is no data available.

Extended Data Table 2 | Percentage of Required Dietary Intake (RDI) of micronutrients provided by a serving of octopus

Nutrient	Required Dietary Intake (RDI)	Content in 100g serving of octopus	Percentage of RDI met by 100g serving of octopus
Iron (mg)	8.7	5.3	61%
Copper (mg)	1.2	0.4	33%
B12 (cobalamin) (µg)	1.5	20	1333%
Omega 3 (g)	1.6	0.16	10%
Calcium (mg)	700	50	7%
Magnesium (mg)	300	30	10%
Selenium (µg)	75	44.8	60%
Zinc (mg)	9.5	1.68	18%

Data sources^{37,46}.

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Software and code

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Data collection No specific software was used for data collection.

Data analysis Microsoft Excel (v16.67) and Magic Maps 2 were used for data analysis.

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Data

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All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

All data is available in the manuscript or supplementary materials. The following publicly available datasets provided source data for this manuscript: FAO Fishstat J www.fao.org/fishery/statistics/software/fishstatj/en, Sea Around Us <https://www.seaaroundus.org/>, USDA <https://fdc.nal.usda.gov>.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Comprehensive analysis of tropical small-scale octopus fisheries and the current and future role they can play in global food security .
Research sample	Production volumes from industrial and small-scale fisheries data: FAO FishStat J and Sea Around Us databases used to build production datasets. Socioeconomic value and nutrition: FAO FishStat J, Sea Around Us, and Blue Ventures databases were used to build the socioeconomic value datasets. FAOSTAT, FAO FishStat J, and USDA databases were used to build the nutrition datasets. Sustainability: FAO FishStat J and Sea Around Us databases used to build sustainability datasets. Literature review: Included searches within Web of Science , Mendeley, SCOPUS, EBSCO Host and WorldCat.
Sampling strategy	No sample size calculation was performed as this was an analysis on existing global datasets.
Data collection	Data was collected from existing global datasets using a web browser by Dr David F Willer.
Timing and spatial scale	Production volumes: 1970-2017. Socioeconomic value: 1961-2017. Nutrition: 2019-2020. Sustainability: 1961-2016. Literature Review: Years up to and including 2021
Data exclusions	No data were excluded.
Reproducibility	NA
Randomization	NA
Blinding	NA
Did the study involve field work?	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Human research participants
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

Methods

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging