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Diversifying the use of tuna to improve food security and public health in Pacific Island countries and territories

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ABSTRACT

The large tuna resources of the Western and Central Pacific Ocean are delivering great economic benefits to Pacific Island countries and territories (PICTs) through sale of licences to distant water fishing nations and employment in fish processing. However, tuna needs to contribute to Pacific Island societies in another important way—by increasing local access to the fish required for good nutrition to help combat the world's highest levels of diabetes and obesity. Analyses reported here demonstrate that coastal fisheries in 16 of the 22 PICTs will not provide the fish recommended for good nutrition of growing Pacific Island populations, and that by 2020 tuna will need to supply 12% of the fish required by PICTs for food security, increasing to 25% by 2035. In relative terms, the percentages of the region's tuna catch that will be needed in 2020 and 2035 to fill the gap in domestic fish supply are small, i.e., 2.1% and 5.9% of the average present-day industrial catch, respectively. Interventions based on expanding the use of nearshore fish aggregating devices (FADs) to assist small-scale fishers catch tuna, distributing small tuna and bycatch offloaded by industrial fleets at regional ports, and improving access to canned tuna for inland populations, promise to increase access to fish for sustaining the health of the region's growing populations. The actions, research and policies required to implement these interventions effectively, and the investments needed to maintain the stocks underpinning the considerable socio-economic benefits that flow from tuna, are described.

1. Introduction

Many Pacific Island countries and territories (PICTs) are receiving unprecedented economic benefits from the tuna fisheries operating within their exclusive economic zones (EEZs). These benefits stem from the fact that the large catches made within the EEZs of PICTs (Supplementary Table 1) supply >30% of the world's tuna, and from the control exerted over purse-seine fishing by the eight countries where most of the tuna are caught through the 'vessel day scheme' [1,2]. The constraint on fishing effort, combined with the importance of tuna to world fish supply[1], has seen licence fees from foreign fishing fleets increase by 400% in recent years. These access fees

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[1] The annual global catch of oceanic tuna species exceeds 4.4 million tonnes and represents ~7.5% of the ~60 million tonnes of fish captured from the world's marine waters each year used directly for food; see http://www.fao.org/docrep/016/i2727e/i2727e.pdf.

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contributed 11–63% of government revenue for six Pacific Island countries in 2012 and will make even greater contributions in 2014 (Table 1). Tuna processing and fishing also provide up to 25% of GDP, and employ thousands of people, in several PICTs [3].

As impressive as the economic gains have been, the rich tuna resources of the region are needed to assist Pacific Island people in another important way—combating the high and rising prevalence of non-communicable diseases (NCDs), such as heart disease and diabetes, and the incidence of obesity [4]. The severity of the problem is illustrated by the fact that nine of the 10 countries with the highest rates of overweight and obesity, and seven of the 10 countries with the highest rates of diabetes, are Pacific Island nations (Supplementary material). The increase in NCDs is due largely to a change in diet and lifestyles, driven by rapid rates of population growth and urbanization, scarcity of arable land and growth of the global food trade [5]. Seafood, which is rich in protein, essential fatty acids, vitamins and minerals, and traditional root crops, are being replaced in Pacific diets by relatively cheap, energy-dense and nutritionally-poor imported foods [4,5].

Given this context, Pacific Island governments have been encouraged to maintain high traditional levels of fish consumption by providing access to a minimum of 35 kg of fish per person per year [6].

The problem is that rapid population growth in several PICTs has already outstripped the capacity of even well-managed coastal fisheries (based mainly on coral reefs) to supply the required quantities of fish [6]. As populations continue to grow (Supplementary Table 2), and as coral reefs are degraded by climate change [7], the gap between the fish required for food and the amount of fish that can be harvested sustainably from reefs will increase considerably. In several PICTs, ciguatera poisoning [8,9] also reduces the quantities of reef fish available for consumption.

Aquaculture has some potential to contribute to fish supplies, but the region's tuna[2] fishery has the greatest capacity to fill most of the gap [6,7]. An option is to use the greater revenue from industrial fishing licences to strengthen local economies and improve the ability of Pacific Island citizens to buy more nutritious foods. However, in the absence of government controls on the quality of food imports [10] greater purchasing power could well exacerbate the problem because increases in disposable income and the rise in global food trade are among the causes of NCDs [5].

A more effective way to help fight the rise of NCDs will be to strengthen education campaigns on the health benefits of fish and to give people in urban and rural areas direct access to tuna, and the bycatch from tuna fisheries, to supply them with the recommended quantities of fish. Moreover, access to tuna for national food security is an obligation under the Convention for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean (Supplementary material), and in accordance with resolution 66/158 by the United Nations General Assembly on the right to food[3]. Importantly, no negative health effects linked to mercury concentrations are expected from increasing access to the most abundant tuna species in the region—skipjack and yellowfin tuna (Supplementary material).

This study quantifies the existing shortfalls in supply of reef fish for food security among PICTs, and those projected to occur by 2020 and 2035 based on the latest population forecasts and estimates of coral reef area; specifies the amount of tuna needed to fill the gap in 2020 and 2035; and identifies practical interventions to make tuna more available to the growing urban and rural populations of the region. It also describes the actions, research and policies needed to implement these interventions effectively; and the investments required to sustain the tuna stocks on which the economic and health benefits for PICTs depend.

[2] 'Tuna' as used here also includes other large associated pelagic fish species caught by the industrial fishery and targeted by small-scale fishers, e.g., mahi mahi, wahoo and rainbow runner.

[3] The full conclusions and recommendations of UN General Assembly Resolution 66/158 are contained in paragraphs 60–65 of the report available at http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N12/456/40/PDF/N1245640.pdf?OpenElement.

2. Material and methods

2.1. Population projections

The rural-urban population projections were based on the same methods used for previous projections of the fish needed for future food security in the Pacific [6,11]. These methods do not incorporate the complex interplay between rural–urban migration, rural–urban fertility and mortality differentials, international immigration and return migration trends. Migration data are the most problematic when undertaking sub-national population projections in highly mobile Pacific Island populations, because regular collections or compilations of population movement, e.g., community-based population registers, are virtually unknown in the region. The population projections for 2020 and 2035 can be expected to change as more comprehensive input data pertaining to births, deaths and migration become available.

2.2. Fish needed for good nutrition in Pacific Island countries and territories

The World Health Organization (WHO) recommends that daily protein intake for good nutrition should be ~0.7 g of protein per kg body weight per day, derived from a variety of sources to prevent micronutrient deficiencies. Based on the predicted age structure of populations in PICTs (SPC Statistics for Development Division) and age-weight relationships typical of the region, average protein content of fresh fish of ~20%, and the fact that most Pacific Island people cook fish whole and eat the flesh from the head as well as the body (thus using ~80% of the weight of fish for food), it is estimated that annual average fish consumption of 35–42 kg per capita is required to provide 40–50% of total protein intake for Pacific Island populations.

The amount of fish needed by PICTs for food over the coming decades was identified based on (1) the fish consumption required to provide at least 40% of dietary protein (i.e., 35 kg of fish per person per year) or the fish required to maintain the traditional levels of fish consumption [6] where these are greater; and (2) predicted population growth in 2020 and 2035 (Supplementary Table 2).

In the absence of detailed information on the sustainable production of coastal fisheries for the great majority of PICTs, four sets of information were used to estimate the quantities of fish likely to be available per person in each PICT for food under good local management of coral reefs and climate change in 2020 and 2035: (1) the area of coral reef (km^2) derived from the Millennium Coral Reef Mapping Project [12]; (2) a median estimate of sustainable fisheries production from coral reef habitats of 3 t per km^2 of reef per year [13]; (3) the predicted future population of each PICT (Supplementary Table 2); and (4) the projected effects of climate change on coastal fisheries production of PICTs for the 2035 estimate [9].

A different approach was used to estimate the fish required for food in Papua New Guinea (PNG), where the rapidly growing population presents particular problems for increasing fish consumption per capita. In particular, the large inland population

Table 1
Estimates of total government revenue derived from foreign fishing vessel access and licensing fees for the eight countries that are the Parties to the Nauru Agreement (PNA) in 2012.

PNA member	Purse-seine effort (days) sold or traded[a]	Access fees from purse-seine fisheries (USD)[b,c]	Other fisheries revenue[d] (USD million)	Total fisheries revenue (USD)	Government revenue (USD)	Fees as proportion of government revenue (%)
FSM	5307	$26,535,000	$3.5–5	$30,000,000	$158,091,416	19
Kiribati	9479	$47,395,000	$11	$58,000,000	$91,700,000	63
Marshall Islands	995	$4,975,000	$2–3	$7,500,000	$45,394,949	17
Nauru	1063	$5,315,000	$0.5–1	$6,000,000	$33,446,746	18
Palau	481	$2,405,000	$1–2	$4,000,000	$36,503,750	11
PNG	9229	$46,145,000	$15–20	$65,000,000	$2,544,928,117	3
Solomon Islands	1147	$5,735,000	$3–4	$9,000,000	$269,524,954	3
Tuvalu	718	$3,590,000	$4.5	$8,000,000	$27,007,455	30

FSM = Federated States of Micronesia; PNG = Papua New Guinea.

[a] *Source*: Report of the Purse-seine Vessel Day Scheme Administrator.
[b] Calculated at the PNA minimum benchmark rate of $5000 per day, prevailing in 2012.
[c] Note that the PNA benchmark rate will increase to $8000 per day in 2014.
[d] Estimate of revenue from fees paid to countries by the US Treaty, longline and pole-and-line fisheries, licensing and registration fees, and transhipping fees.

(defined as people living >5 km from the coast or the major river systems [6] and estimated to be ~60% of the total population), has poor access to fish and depends largely on crops for protein [14]. Planning to supply substantial additional fish to this inland population by 2020 and 2035 will be a major challenge [6]. Consequently, the forecast for inland PNG was based on providing no improved access to fish in 2013, access to 1 kg of marine fish per person in 2020, and access to 2 kg of marine fish and 1 kg of fish from freshwater pond aquaculture [11] in 2035. For urban populations, provision was made to maintain the average consumption of 28 kg of fish per year [6]. Although riverine and coastal communities have relatively high levels of fish consumption [6], the fish to be provided to these communities was limited to the recommended 35 kg of fish per person per year. Thus, the total amount of fish needed for food in PNG was calculated as the urban population [presently ~15% of total population (Supplementary Table 2)] $\times$ 28 kg, plus the 'coastal' population, representing both coastal communities and those within 5 km of a major river, (25%) $\times$ 35 kg, plus the inland population (60%) $\times$ 0 kg in 2013, $\times$ 1 kg in 2020 and $\times$ 3 kg in 2035.

2.3. Modelling

A qualitative modelling approach [15] was used to examine the relative effectiveness of various adaptations to provide fish for the food security for coastal communities. The analysis considered the effects of: (1) longstanding relationships among fishing effort, stocks of reef fish and inshore pelagic fish (including tuna), catch, markets and food security; (2) human population growth, habitat degradation and climate change (i.e., the effects of the IPCC A2 emissions scenario on reef fish and tuna stocks by 2035 [7]) as drivers of these relationships; and (3) practical adaptations to maintain access to adequate fish for food security in the face of these drivers.

The model incorporated: the effects of subsistence and artisanal fisheries on the stocks of reef fish and nearshore pelagic fish through the variables of fishing effort, catch and the market value of catch; dependence of food security on catch, which was determined by both fishing effort and stock abundance, and which suppressed the market value of the proportion of the catch sold via a supply/demand relationship; reductions in stock abundance due to increases in fishing effort, although the effect of coastal fishing on stocks of tuna is negligible compared with the large catches made by industrial fleets (Supplementary Table 1) and was omitted from the analysis; support for fishing effort and food security based on the benefits of catch; shaping of the system in positive and negative ways by the key drivers—human population growth and habitat degradation; creation of greater demand for food by an increasing human population, leading to increased fishing effort; degradation of the coral habitats that support reef fish stocks by population growth; and planned adaptations designed to maintain or increase access to fish for food security, including integrated coastal zone management, management to rebuild reef fish stocks, the use of nearshore fish aggregating devices (FADs) to increase the catch of pelagic fish (including tuna), pond aquaculture and post-harvest processing. Each variable in the model was given a negative self-effect.

3. Results and discussion

3.1. Tuna needed for food security

Integrating the analyses of present-day human population levels and those projected for 2020 and 2035 (Supplementary Table 2) with the area of coral reef (the best available proxy for reef fish production [13]) in each PICT indicates that 16 of the 22 Pacific Island countries and territories will either increasingly fail to produce enough reef fish to meet their basic or traditional needs for fish, or have trouble distributing the fish from remote reefs to urban centers (Table 2). The problem is particularly significant in Melanesia, where the great majority of the region's people live (Supplementary Table 2).

To supply the fish recommended for good nutrition, or to maintain traditionally higher levels of fish consumption, tuna will need to provide 12% of the fish required by all PICTs by 2020, increasing to 25% by 2035 (Fig. 1). In relative terms, the percentages of the region's tuna catch needed in 2020 and 2035 to fill the gap in domestic fish supply are small, i.e., 2.1% and 5.9% of the average recent industrial tuna catch, respectively. The greatest quantities of tuna will be required in PNG, Solomon Islands and Kiribati (Table 3).

3.2. Increasing access to tuna

Although only a modest proportion of the average regional tuna catch needs to be allocated to meet the future needs of PICTs for fish, making the fish readily accessible to coastal communities and urban populations will require careful planning. Three interventions promise to help increase direct access to tuna.

Table 2
Estimates of coastal fisheries production based on coral reef area for Pacific Island countries and territories (PICTs), the amount of fish needed for food in 2013, 2020 and 2035, and expected surplus (+) or deficit (−) in fish supply, relative to the recommended 35 kg per person per year or traditionally higher levels of fish consumption, for each PICT for each period. PICTs have been placed into the three groups described in the Supplementary material. The quantities of fish needed in rural and urban areas of PICTs in Melanesia, Micronesia and Polynesia are given in Supplementary Tables 6–8.

PICT	Area of coral reef habitat (km^2)[a]	Coastal fish production ($t\ y^{-1}$)[b]	Fish needed for food (t)[c]			Surplus (+)/deficit (−) of coastal fish (t)[d]		
			2013	2020	2035	2013	2020	2035
Group 1: Surplus supply of reef fish[e]								
New Caledonia[f]	35,925	107,780	9100	9900	11,300	98,680	97,880	92,710
Marshall Islands[g,m]	13,930	41,790	2100	2200	2,400	39,690	39,590	37,930
Palau[f]	2,496	7,490	600	600	600	6,890	6,890	6,630
Cook Islands[g,m]	667	2,000	600	600	600	1,400	1,400	1,330
Tokelau[g,m]	204	610	200	200	200	410	410	390
Group 2: Surplus supply of reef fish but with problems distributing this fish to urban centres								
Fiji[f]	25,666	77,000	30,100	31,100	33,700	46,900	45,900	40,610
FSM[g]	15,074	45,220	7,700	7,600	7,100	37,520	37,620	36,540
French Polynesia[g,m]	15,126	45,380	18,400	18,800	20,000	26,980	26,580	23,790
Tonga[f]	5811	17,430	3,600	3,600	3,900	13,830	13,830	12,920
Tuvalu[g,m]	3,175	9,530	1,200	1,300	1,500	8,330	8,230	7,700
Wallis and Futuna[g]	932	2,800	900	900	900	1,900	1,900	1,800
Niue[g,m]	56	170	100	100	100	70	70	60
Group 3: Deficit of reef fish								
Papua New Guinea[h]	27,086	98,760[i]	95,800	117,000	169,100	3000	−18,200	−73,800
Vanuatu[f]	1,244	3,730	9,300	10,800	14,000	−5,570	−7,070	−10,400
Solomon Islands[f]	8,535	27,610[j]	21,400	25,400	35,600	6,210	2,210	−7,990
Guam[f]	238	710	6,100	6,900	7,400	−5,390	−6,190	−6,710
Samoa[g]	465	14,000[k]	16,000	15,600	15,700	−2,000	−1,600	−2,190
CNMI[f]	250	750	1,900	2,100	2,300	−1,150	−1,350	−1,580
American Samoa[g]	368	1,100	2,100	2,100	2,400	−1,000	−1,000	−1,340
Kiribati[g,m]	4,320	12,960	9,700	10,900	13,400	3,260	2,060	−890
Nauru[g]	7	130[l]	600	700	800	−470	−570	−670

[a] Includes lagoons and drowned atolls and banks.
[b] Based on median estimates of sustainable fish harvests of 3 t per km^2 [13].
[c] Based on estimates in Supplementary Tables 6–8.
[d] Calculations for 2035 include a 2–5% reduction in the production of coastal fisheries due to the effects of climate change [9].
[e] Pitcairn Islands not included but the total reef area of 48 km^2 has more than enough fish for the 66 people who live there.
[f] Fish needed for food based on recommended fish consumption of 35 kg per person per year (see Section 2).
[g] Fish needed based on traditional levels of fish consumption for rural and/or urban populations which are greater than 35 kg per person per year [3,6].
[h] Fish needed for food based on providing different quantities per capita for the urban, coastal/riverine and inland populations of PNG (see Section 2).
[i] Includes 17,500 t of freshwater fish.
[j] Includes 2000 t of freshwater fish.
[k] Coastal fisheries production is high due to areas of relatively shallow water around the islands, catch estimate is provided by Samoa's Ministry of Agriculture.
[l] Based on reconstructions of catches of coastal fish by the 'Sea around us' project, University of British Columbia.
[m] National average incidence of ciguatera fish poisoning [8], renders several species of coral reef fish unfit for human consumption at some locations.

3.2.1. *Scaling up the use of nearshore fish aggregating devices (FADs)*

Nearshore FADs[4] assist small-scale fishers to catch tuna more easily and safely. When FADs are located correctly they do not attract vulnerable reef fish and the value of tuna caught around them well exceeds the costs of materials and installation (Supplementary material). Qualitative modelling (Fig. 2) shows that when nearshore FADs (combined with simple post-harvest methods to extend the shelf life of catches) are considered within the context of a broader range of drivers (e.g., human population growth, habitat degradation and climate change) and interventions by coastal communities to maintain or improve the supply of fish (e.g., integrated coastal zone management, management of reef fish, expansion of aquaculture), this simple technology is among the adaptations with the greatest positive effect on food security (Supplementary Table 3).

3.2.2. *Distributing small tuna and bycatch offloaded at regional ports*

Transhipping of the catch from purse-seine vessels to cargo vessels in port is mandated under regional tuna management arrangements (Supplementary material). The ban on discarding small tuna[5] and their lower value for canning means that some industrial fleets offload these fish at regional ports, providing a local supply of low-cost fish. Much of the retained bycatch[6] is also offloaded.

3.2.3. *Improving the distribution of canned tuna*

Locally-canned tuna is a potential source of high-quality, non-perishable food for inland populations, provided it can be made available at affordable prices. Improving access to canned tuna will be particularly important for PNG, where the inland population exceeds the combined population of all other PICTs and where people have little animal protein in their diet [14].

[4] For a definition of nearshore FADs, see http://www.spc.int/DigitalLibrary/Doc/FAME/Brochures/Anon_12_PolicyBrief19_FADs.pdf.

[5] 'Small tuna' includes skipjack, yellowfin and bigeye tuna caught by purse-seine vessels of sizes which attract lower prices at canneries; discarding small tuna has been prohibited under Western and Central Pacific Fisheries Commission Conservation and Management Measures (CMM) 2009-02 and 2012-01.

[6] 'Bycatch' includes non-target, edible pelagic fish caught by purse-seine and longline fishing vessels, e.g., rainbow runner, mahi–mahi, wahoo, certain sharks and triggerfish.

3.3. Priority actions, research and supporting policies

Providing better access to tuna for the people of the Pacific, and measuring the effects of the recommended interventions on fish consumption and NCDs, will depend on the following actions, research and policies.

Assisting small-scale fishers to catch tuna by expanding the use of nearshore FADs; including these FADs as part of the national infrastructure for food security; and minimizing any negative interactions between artisanal/subsistence tuna fisheries and industrial fishing fleets. Investments in nearshore FADs will be maximized by: mapping bathymetry to identify suitable sites; monitoring catches to fine-tune site selection and FAD design; providing training in FAD fishing techniques and catch handling; harmonizing use of FADs within and between coastal communities; promoting simple post-harvest methods (smoking and drying) to increase the shelf life of catches; and identifying and addressing any issues preventing greater use of tuna by coastal communities (Supplementary material).

The effectiveness of exclusion zones for industrial fishing, which all PICTs have established around islands to help allocate tuna to coastal communities, also needs to be examined. This involves identifying the extent of industrial fishing close to these zones; monitoring the tuna catches of artisanal and subsistence fishers to evaluate overlaps in catch composition and fishing times between industrial fleets and small-scale fisheries; assessing the mixing of tuna from nearshore and offshore areas and, ultimately, determining whether communities can catch enough tuna to meet their needs (Supplementary material).

Facilitating the supply of low-cost fish to urban centers by extending the existing ban on discarding small tuna at sea by industrial purse-seine fishing fleets to include bycatch. Harnessing the potential fish supply from transhipping operations will involve understanding the factors expected to progressively reduce the quantities of small tuna and bycatch landed by industrial fleets, e.g., the inconvenience to vessels of storing lower-value fish, and management measures to reduce the use of drifting FADs in the purse-seine fishery (Supplementary material). The transient nature of transhipping activities at many ports due to the effects of the El Niño-Southern Oscillation on tuna distribution, and the remote locations of some transhipping ports, also pose challenges for delivering fish regularly where it is needed most.

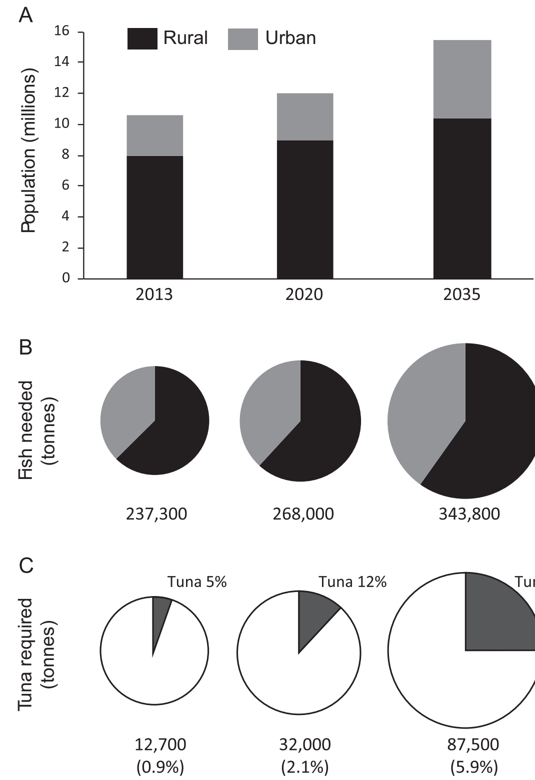

Fig. 1. Estimates of (A) the combined population of the 22 Pacific Island countries and territories, (B) quantities of fish needed for good nutrition in rural and urban areas, and (C) the quantities of tuna required for food in 2013, 2020 and 2035. The amount of tuna needed is also shown as a percentage of the total quantity of fish required for food, and as a percentage (in brackets) of average annual regional tuna catch between 2009 and 2013.

To help overcome these constraints, governments can monitor the availability of small tuna and bycatch (Supplementary material) and explore the use of national license conditions for foreign fishing fleets to (1) specify the locations and minimum frequency of transhipments; (2) arrange for all foreign fleets to offload small tuna and bycatch; and (3) mandate landing of export-quality tuna at population centers when the quantities of small tuna and bycatch from transhipping are

Table 3
Estimates of the tuna needed to fill the gap between the level of fish consumption recommended for good nutrition, or traditional levels of fish consumption, and the fish available from coral reefs in 2013, 2020 and 2035; and the percentage of total annual average tuna catch (2009–2013) from the exclusive economic zones (EEZs) of selected Pacific Island countries and territories (PICTs) (in bold). Estimates of tuna required for food in other groups of PICTs (see Supplementary material and footnotes) are also shown.

PICT	Tuna needed for food (t)[a]			Average tuna catch (t)[b]	Percentage of average tuna catch[c]		
	2013	2020	2035		2013	2020	2035
Papua New Guinea	0	18,200	63,200[f]	597,657	0	3.0	10.6
Solomon Islands	0	0	7,990	144,454	0	0	5.5
Kiribati[d]	4,250	4,900	6,370	330,177	1.3	1.5	1.9
Nauru	470	570	670	99,033	0.4	0.6	0.7
5 Other PICTs in Group 3[e]	1,530	1,680	2,035	15,267	10.0	11.0	13.3
7 PICTs in Group 2	5,590	5,740	6,210	248,940	2.2	2.3	2.5
6 PICTs in Group 1	870	930	1,050	60,576	1.4	1.5	1.7
Total	**12,710**	**32,020**	**87,525**	**1,496,103**	**0.9**	**2.1**	**5.9**

[a] Derived from Table 2 and incorporates effects of climate change on coastal fisheries production in 2035 [9].
[b] Based on the 5-year average total tuna catch (all gear types) for the period 2009–2013, rounded to the nearest tonne.
[c] Assumes that all tuna will come from industrial fishing within the EEZ and does not allow for catches from nearshore FADs, the contribution of bycatch, or the effects of climate change on tuna catch [7].
[d] Based on the fact that tuna is already widely used for food in Kiribati due to the remote location of many reefs from the densely populated urban center on Tarawa, estimate for 2013 is derived from Ref. [9] and extrapolated for population growth in 2020 and 2035.
[e] Acknowledges that even though these countries are in fish deficit, access to tuna from offshore longline fisheries will be minimal due to export of these fish and that purchasing power is relatively high in all other PICTs except Vanuatu and enables import (in principle) of alternative high-quality animal protein.
[f] Allows for freshwater pond aquaculture to supply 1 kg of fish per person per year by 2035 [11], reducing the overall deficit in fish of 73,800 t (Table 2) to 63,200 t.

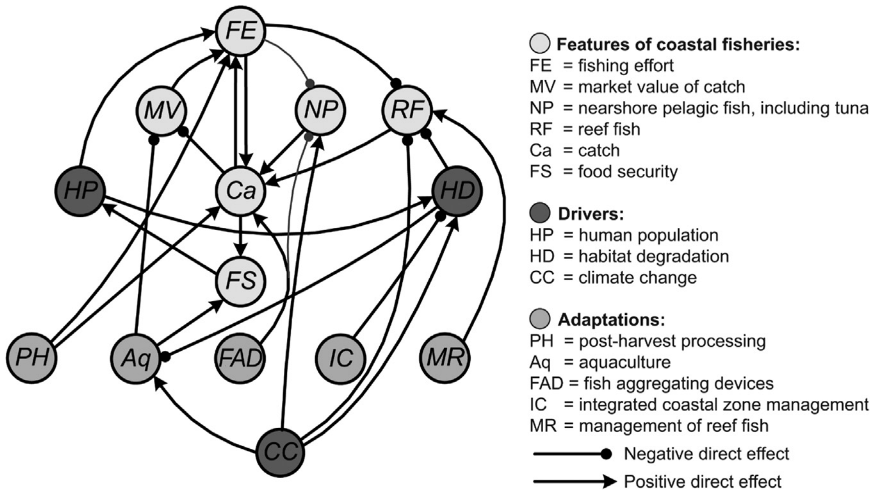

Fig. 2. Signed digraph model of factors affecting the use of fish for food security by coastal communities in Pacific Island countries and territories. Light circles represent major variables regulating delivery of protein from coastal fisheries; dark circles represent some important drivers in the system and medium circles represent possible key adaptations for food security. The two thin-lined links indicate that small-scale coastal fishing effort has a negligible effect on the tuna stocks that comprise much of the nearshore pelagic fishery.

low. Governments can also oversee transhipping operations to ensure fish quality is maintained, and provide incentives for small businesses to distribute the fish to peri-urban areas.

To the greatest extent possible, these actions should be implemented in ways that do not undermine the livelihoods of small-scale fishers. Highlighting the differences in product quality between the fresh tuna landed by artisanal fisheries, and the brined fish from purse-seine vessels, will be one way of helping small-scale fishers to maintain market share.

Reducing the cost of canned tuna by (1) investing some fishing licence revenue to help distribute canned tuna to inland areas; (2) exploring joint ventures with vertically integrated tuna companies to return the canned dark tuna meat preferred by many Pacific Islanders to the region rather than selling those products on other markets; and (3) using licence conditions for foreign fleets to ensure that local canneries receive the quantities of tuna needed to operate efficiently.

Measuring success by using household income and expenditure surveys (HIES) and censuses to evaluate the effectiveness of interventions to improve local access to tuna. HIES and censuses are already being modified to collect data on per capita fish consumption in some PICTs (Supplementary material) and these changes now need to be standardized and adopted across the region. Demographic and health surveys can also be modified to measure the effects of changes in tuna consumption on NCDs and obesity.

Effective implementation of these actions to increase access to tuna for both rural and urban populations will also require addressing the questions listed in Table 4.

3.4. Investments required to maintain tuna stocks

Optimising the socio-economic benefits of tuna for rapidly growing Pacific Island populations depends not only on diverting some tuna from export markets to meet local needs for nutritious food to sustain public health, it also depends on maintaining regional tuna stocks at robust levels and controlling the impacts of industrial fishing on the availability of tuna for coastal communities. The current framework used to assess the status of the region's tuna stocks, MULTIFAN-CL[7], integrates data on catch, effort, fish size and fish movement to model tuna abundance and age structure within broad areas of the tropical Pacific Ocean [16]. However, greater investments are needed to guide the management of industrial tuna fisheries by the Western and Central Pacific Fisheries Commission (WCPFC). In particular, collection of logbook catch and effort data at finer spatial scales, and strengthening of observer programs, port sampling and tuna tagging, are needed to provide better estimates of the status of tuna stocks and the impacts of fishing. New technology, such as satellite-based vessel monitoring systems and e-reporting, promise to provide better details of fishing operations and enable fishery monitoring in near real time. Such innovation is expected to reduce model uncertainties, allowing greater precision in the estimates of stock status against agreed reference points.

Improvements to the 'Spatial ecosystem and population dynamics' (SEAPODYM) model [17], designed to investigate changes in the structure of tuna populations at multiple scales, are also needed to help determine how industrial tuna fisheries affect small-scale fisheries for tuna in nearshore areas. SEAPODYM is an end-to-end model, incorporating parameters spanning the environment (temperature, currents, oxygen, and primary production) through to tuna population dynamics, to tuna catches. It includes a forage (prey) sub-model describing the transfer of energy from primary production to tuna species through mid-trophic levels [18]. The model is driven by a bio-physical environment predicted from a coupled ocean physical-biogeochemical model. Predicted environmental habitats generated by the model integrate observations on seasonal, annual and decadal variation in oceanographic processes acquired from satellites. Similarly, at the other end of the model, assimilation of catch data from industrial fisheries allows optimizing and validating the predictions for tuna abundance and distribution [19].

To improve confidence in forecasts by SEAPODYM, increased observations are required to validate the model. For example, the more closely the resolution of the industrial fisheries catch data matches the resolution of the environmental data, the better the predictive performance of SEAPODYM. Similarly, finer resolution environmental data will improve the model's capability to describe meso-scale variations in ocean habitats and skill at predicting tuna distributions and abundance. While most fisheries and environmental data will come from industrial fleets, improvements to the monitoring of tuna catches made by small-scale fishers in coastal waters will also benefit the model.

[7] www.multifan-cl.org.

Table 4
Important questions to be answered during development of policies and research for effective implementation of the main interventions to increase access to tuna in rural and urban areas.

Rural areas
What quantities of tuna and other large pelagic fish are being caught by small-scale coastal fishers with and without the use of nearshore, anchored fish aggregating devices?
Can sufficient tuna be caught by subsistence and artisanal fishers to meet existing and projected demands for fish, or is industrial fishing affecting, or likely to affect, tuna supply for coastal communities?
What is the demand by inland communities in Papua New Guinea for the range of canned tuna products from national canneries, and what is the optimum way of packaging (e.g., can size, plastic packs) these products and distributing tuna to these communities?
Urban areas
What sampling and monitoring is required to determine the quantities of small tuna and bycatch available for offloading at regional ports by industrial fishing fleets?
What are the spatial patterns of tuna catches driven by the El Niño-Southern Oscillation relative to urban populations with the greatest needs for fish, and what are the most practical policies for delivering tuna to these populations given year-to-year spatial fluctuations in the location of fishing?
How are the quantities of small tuna and bycatch available for offloading at regional ports likely to be affected by the WCPFC conservation and management measures to reduce the impacts of fishing on bigeye tuna, and future measures to implement ecosystem-based approaches to fisheries management?
Are incentives needed for small businesses to distribute small tuna and bycatch to peri-urban areas?
What are the operational implications, in terms of economic efficiency, for fishing vessels of sending fish ashore during transhipping, and what licence conditions and incentives can governments use to increase the frequency of transhipping in their ports?
Which regulations are needed to harmonise sale of small tuna and bycatch from transhipping operations with catches of fresh tuna by local fishers to reconcile demand for low-cost fish with maintenance of livelihoods?
Could other forms of healthy animal protein be imported at the same price as higher-grade tuna purchased locally from industrial fleets? Could plant sources of omega 3 oils and protein supplement those derived from tuna in larger island nations (e.g. Papua New Guinea and Solomon Islands)?
When it is necessary to request purse-seine vessels to offload high-quality tuna at regional ports for local consumption, how can fishing companies be compensated for the opportunity costs involved?

A weakness in the SEAPODYM approach is the scarcity of observations on mid-trophic level organisms ('micronekton') [20,21], which limits validation of the forage population sub-model. The paucity of micronekton observations is due to the diversity and depth range (1200 m) of the organisms, and the costs involved in sampling them with nets from ocean-going research vessels [20]. Collection of stomach contents from tuna and other top predators, which are 'biological samplers' of micronekton, by the extensive network of 'at sea' scientific observers on industrial fishing vessels, promises to increase 'observations' of mid-trophic level organisms [22,23]. Greater deployment of acoustic sounders on scientific, fishing and commercial shipping vessels also has potential to establish basin-scale monitoring programmes for micronekton [24,25].

Time series of micronekton observations are needed on larger spatial scales to improve forecasts of tuna distribution and abundance by the SEAPODYM model, and to gain a better understanding of the impact of climate variability on the abundance and distribution of mid-trophic level organisms and tuna [25–27]. Tagging data are also required to inform SEAPODYM about the degree of exchange and mixing of tuna between nearshore and offshore areas.

4. Conclusions

The revenue from fishing licences flowing into Pacific Island countries and territories may be a mixed blessing if any increase in purchasing power exacerbates the incidence of non-communicable diseases and obesity. On the other hand, diversifying the use of the region's rich tuna resources to provide better local access to fish for food promises to help improve the health of Pacific Island people. This goal needs to be included in regional and national tuna management plans and supported by research and policies to improve the availability of tuna for rapidly growing rural and urban populations. Greater use of licence conditions to increase local supplies of tuna, customised solutions for each country and territory, and continued assessment, modelling and precautionary management of the region's tuna stocks will be essential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2014.10.005.

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