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Optimising the use of nearshore fish aggregating devices for food security in the Pacific Islands

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ABSTRACT

It is widely recognised that anchored, nearshore fish aggregating devices (FADs) are one of the few practical 'vehicles' for increasing access to tuna to help feed the rapidly growing rural and urban populations in many Pacific Island countries and territories (PICTs). However, considerable planning, monitoring and research is still needed to understand and fulfil the potential of nearshore FADs. Investments are required to (1) identify the locations where FADs are likely to make the greatest contributions to the food security of rural (coastal) communities, and yield good catches near urban centres; (2) integrate the use of FADs with other livelihood options available to rural communities and remove any blockages preventing such communities from harnessing the full range of benefits from FADs; (3) assess whether exclusion zones for industrial fishing provide adequate access to tuna for small-scale-fishers; (4) determine if small-scale fishers are able to catch sufficient tuna to meet the protein needs of rural communities; (5) evaluate whether FADs add value to coral reef management initiatives; and (6) improve the design and placement of nearshore FADs. This paper describes these investments and outlines other steps that governments and their development partners need to take to establish and maintain nearshore FADs as part of national infrastructure for food security of PICTs.

1. Introduction

Pacific Island people have an extraordinary dependence on fish[1] for food. Fish consumption in Pacific Island countries and territories (PICTs), which is based mainly on small-scale subsistence and commercial fishing for fish associated with coral reefs, and large pelagic fish (including tuna), is several times higher than the global average [1,2]. Fish typically supplies 50–90% of dietary animal protein for coastal communities [1,2] and in 10 PICTs per capita fish consumption in these communities exceeds 70 kg yr^{-1}.

As the human populations of PICTs grow, governments have been encouraged to provide access to at least 35 kg of fish per person per year [3], or maintain higher traditional levels of fish consumption where they occur [1], for two reasons. First, fish is rich in protein, essential fatty acids, vitamins and minerals [4], and is a logical cornerstone for food security given the high levels of subsistence and scarcity of arable land on many of the islands. Second, increased access to fish provides a healthy alternative to the nutritionally-poor imported foods now pervading Pacific diets [5,6]. Greater consumption of fish and other traditional foods is needed to combat the high prevalence of non-communicable diseases in the region [7].

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[1] Fish is used here in the broad sense to include fish and invertebrates.

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Table 1
Indicative quantities of fish needed for food in 2020 and 2035, and surpluses (+) or deficits (−) in coastal fish supply, relative to the recommended 35 kg per person per year or traditionally higher levels of fish consumption, for two groups of Pacific Island countries and territories (PICTs) (after Ref. [7]).

PICT	Coastal fish production ($t\ yr^{-1}$)[a]	2020		2035	
		Fish needed for food (t)[b]	Surplus (+)/deficit (−) (t)	Fish needed for food (t)[b]	Surplus (+)/deficit (−) (t)[c]
Group 1: countries and territories expected to have a fish deficit					
Papua New Guinea[d]	81,260	81,860	−600	108,500	−30,090
Solomon Islands[e]	27,610[f]	25,400	2,210	35,600	−7,990
Samoa[g]	14,000	15,600	−1,600	15,700	−2,190
Kiribati[g]	12,960	10,900	2,060	13,400	−890
Vanuatu[e]	3,730	10,800	−7,070	14,000	−10,400
American Samoa[g]	1,100	2,100	−1,000	2,400	−1,340
CNMI[e]	750	2,100	−1,350	2,300	−1,580
Guam[e]	710	6,900	−6,190	7,400	−6,710
Nauru[g]	130	700	−570	800	−670
Group 2: countries and territories with difficulties distributing fish to urban centres					
Fiji[e]	77,000	31,100	+45,900	33,700	+40,610
FSM[g]	45,220	7,600	+37,620	7,100	+36,540
French Polynesia[g]	45,380	18,800	+26,580	20,000	+23,790
Tonga[e]	17,430	3,600	+13,830	3,900	+12,920
Tuvalu[g]	9,530	1,300	+8,230	1,500	+7,700
Wallis and Futuna[g]	2,800	900	+1,900	900	+1,800
Niue[g]	170	100	+70	100	+60

[a] Based on median estimates of sustainable fish harvests of $3\ t\ km^{-2}$ of coral reef [46,47], and other sources of information [7].
[b] Based on population projections by the Statistics for Development Division, Secretariat of the Pacific Community.
[c] Calculations for 2035 include a 2–5% reduction in the production of coastal fisheries due to the effects of climate change [18].
[d] Fish needed for food based on providing 35 kg per person to people living within 5 km of the coast, and 28 kg per person for people living in coastal urban areas (see Supplementary material for details). Note that estimates differ from those in Ref. [7] because they do not include the fish needed by the nation's inland population. There will also be difficulties transporting fish from remote coral reefs to population centres.
[e] Fish needed for food based on recommended fish consumption of 35 kg per person per year.
[f] Includes 2000 t of freshwater fish.
[g] Fish needed for food based on recent traditional levels of fish consumption for rural and/or urban populations which are greater than 35 kg per person per year [1,2].

For many PICTs[2], the problem is that the production of fish from coral reefs will not yield the recommended 35 kg of fish per person per year, or continue to supply the traditionally higher quantities of fish, as human populations grow (Table 1). Several other PICTs[3] will have problems distributing fish from remote reefs to urban centres.

To provide access to the recommended quantities of fish, these PICTs will need to allocate more of the tuna caught within their waters to local food security. Across the region, tuna will need to provide 12% of all fish required for food security by 2020, and 25% by 2035 [7]. Although the amount of tuna needed in 2020 and 2035 represents only 2.1% and 5.9%, respectively, of the present-day industrial catch from the combined exclusive economic zones (EEZs) of PICTs [7], there are considerable challenges involved in distributing this tuna to the growing coastal and urban communities.

One of the most practical 'vehicles' for improving local access to tuna is installation of nearshore fish aggregating devices (FADs) (Fig. 1). Nearshore FADs are based on observations that tuna and other large pelagic fish are attracted to floating objects and often stay in their vicinity for several days. Nearshore FADs differ from the drifting FADs and large anchored FADs used by industrial tuna fleets [8–10] because they are usually placed closer to shore in depths of 300–700 m.

Nearshore FADs increase the supply and consumption of fish in rural communities [11] and have been progressively improved over the past 20 years to increase their working life and reduce their cost. Analyses of the cost:benefit of nearshore FADs in Cook Islands and Niue show that the value of tuna and other pelagic fish caught around them exceed their costs by 3–7 times [12]. Other studies, comparing catch-per-unit-effort (CPUE) and fuel consumption ($L\ h^{-1}$) of small-scale fishers operating with and without nearshore FADs demonstrate that: (1) CPUE near FADs is 7 to 23 $kg\ h^{-1}$ greater, and (2) average fuel consumption by fishers operating around FADs is 0.5 $L\ h^{-1}$ lower, than when fishing is not associated with FADs [13,14]. Recent research also shows that nearshore FADs provide returns on investment (internal rate of return) ranging from 80% to 180% [15,16].

There is also recognition that regular use of nearshore FADs could have two other possible benefits. First, it provides communities with the opportunity to transfer some of their fishing effort from coral reefs to oceanic fisheries resources—an intervention expected to help prevent over-exploitation of coral reef fish and maintain the normal representation of important functional groups of fish (e.g. herbivores) associated with coral reefs [17] required to assist these ecosystems to adapt to climate change [18–21]. Preliminary analyses in the Federated States of Micronesia and Vanuatu indicate that 50% to 75% of fishing effort can be transferred from reefs to FADs [16,22]. Second, nearshore FADs could enhance the success of coral reef management initiatives, e.g. those by the local marine managed area (LMMA) networks [23,24] and Micronesia Challenge[4], by providing practical ways for people to continue to catch pelagic fish when regulations are introduced to help coral reefs recover from overfishing and other local stressors, e.g. through designation of temporal or spatial fishing closures.

Despite the promise that nearshore FADs hold for improving access to tuna and other pelagic fish for coastal and urban communities, and for improving the management of coral reefs, extensive planning, monitoring and research are needed to reap all the potential benefits of FADs. Indeed, considerable caution is required to implement FAD programmes so that they do not fall into the same category as the many technically viable and seemingly sensible 'solutions' littering the region that have failed

[2] American Samoa, Guam, Kiribati, Nauru, Commonwealth of the Northern Mariana Islands, Papua New Guinea, Samoa, Solomon Islands and Vanuatu.
[3] Fiji, Federated States of Micronesia, French Polynesia, Niue, Tonga, Tuvalu and Wallis and Futuna.
[4] www.micronesiachallenge.org.

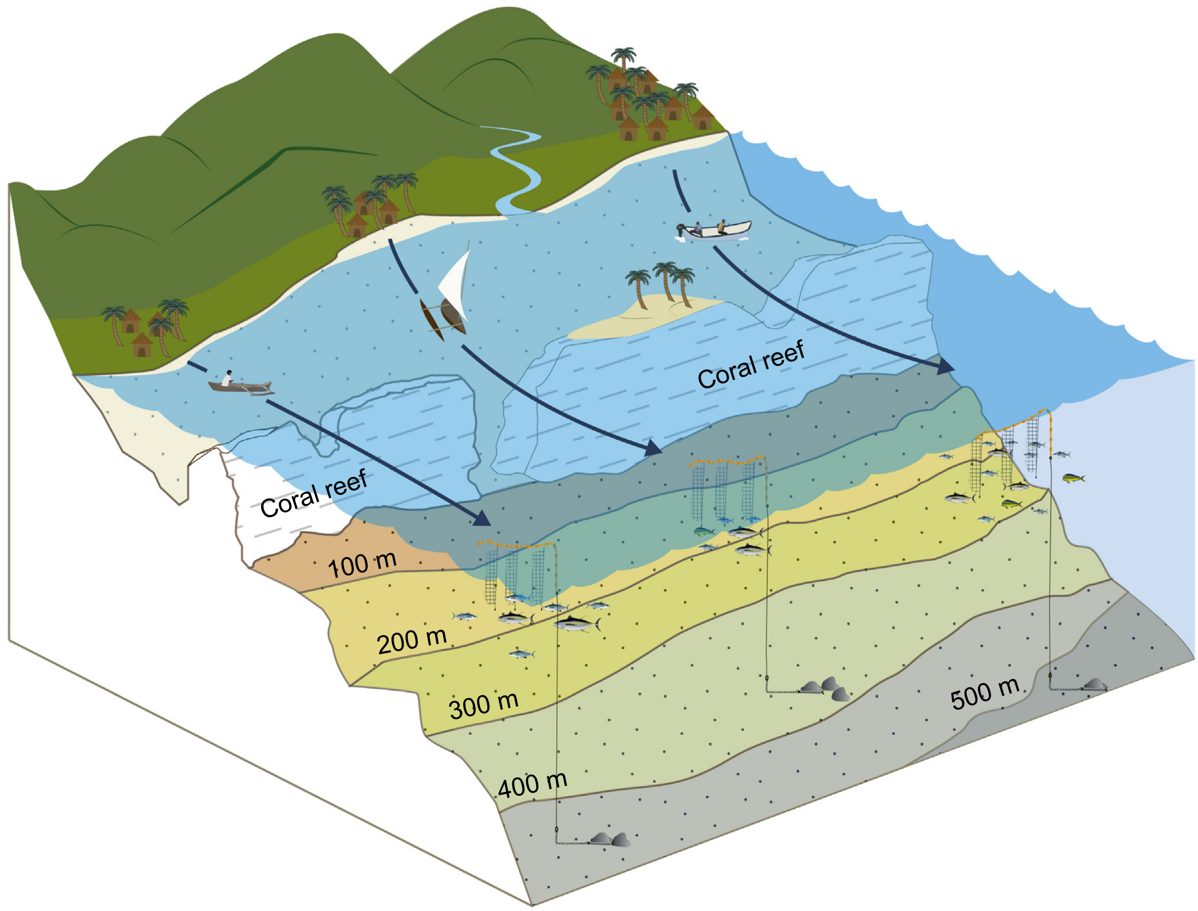

Fig. 1. General structure and typical placement of nearshore FADs in depths of 300 to 700 m.

to live up to expectations (e.g. Ref. [25]). In particular, the lessons from introducing other interventions to communities need to be learned [23,26,27]. Without participatory approaches and significant 'ownership' by communities it will be difficult to operationalise nearshore FADs effectively. The vandalism and sabotage of nearshore FADs in several areas reflects the complex politics and institutional landscape that can exist, and the issues that need to be resolved to harness the full potential of these promising tools.

Experience with planning the limited number of nearshore FADs that have already been installed across the region (Supplementary Table 1) also shows that: (1) there is often no national framework for identifying priority sites and community criteria for installation of FADs; (2) some nearshore FADs do not yield good catches of large pelagic fish [11]; (3) fishing by industrial fleets operating close to fishing exclusion zones could affect the catch of tuna and other large pelagic fish by small-scale fishers; (4) more extensive monitoring programmes are needed to produce robust estimates of average catches of tuna and other target species around nearshore FADs, and to determine whether coastal communities are catching enough tuna and other pelagic fish to meet their needs; (5) rigorous sampling designs will be required to determine whether nearshore FADs add value to coral reef management initiatives; and (6) there is still scope for improving the designs and placement of nearshore FADs.

This paper describes the investments, over and above the costs of construction and deployment, needed to optimise the use of nearshore FADs for improving access to tuna and other pelagic fish for the food security of rural[5] and urban communities in Pacific Island countries and territories.

[5] Defined here as coastal rural communities.

2. Investments required

2.1. Identifying priority locations for nearshore FADs

This investment applies to those PICTs where (1) sustainable harvests from coral reefs will not support the recommended or traditional levels of per capita fish consumption for growing populations; and (2) it is prohibitively expensive to transport fish caught from remote coral reefs to urban centres (see above). In the first group of PICTs, nearshore FADs will be needed in both rural and urban areas. For the second group, FADs will be required mainly near urban centres. The planning needed to identify priority locations for installing FADs in these situations is described below.

2.1.1. Rural areas

Identifying where best to install nearshore FADs in rural areas needs to be set in the broader context of assessing the vulnerability of coastal communities to shortages of fish. This involves GIS analysis to integrate information on the size and location of coastal villages, the area of coral reef within easy access of villages, and the distance to the nearest general area suitable for installing FADs based on available bathymetric data. Although fine resolution bathymetric maps are only available for relatively few PICTs, modelled bathymetry from the General Bathymetric Chart of the Oceans (GEBCO) provides sufficient detail to identify suitable depth zones for nearshore FADs (Fig. 2). Integrating GIS layers on the availability of freshwater and local topography will also be useful because some villages may be well placed to engage in freshwater pond aquaculture. Overall, however, it will be many years until pond aquaculture can provide significant quantities of fish per person in most rural areas [28].

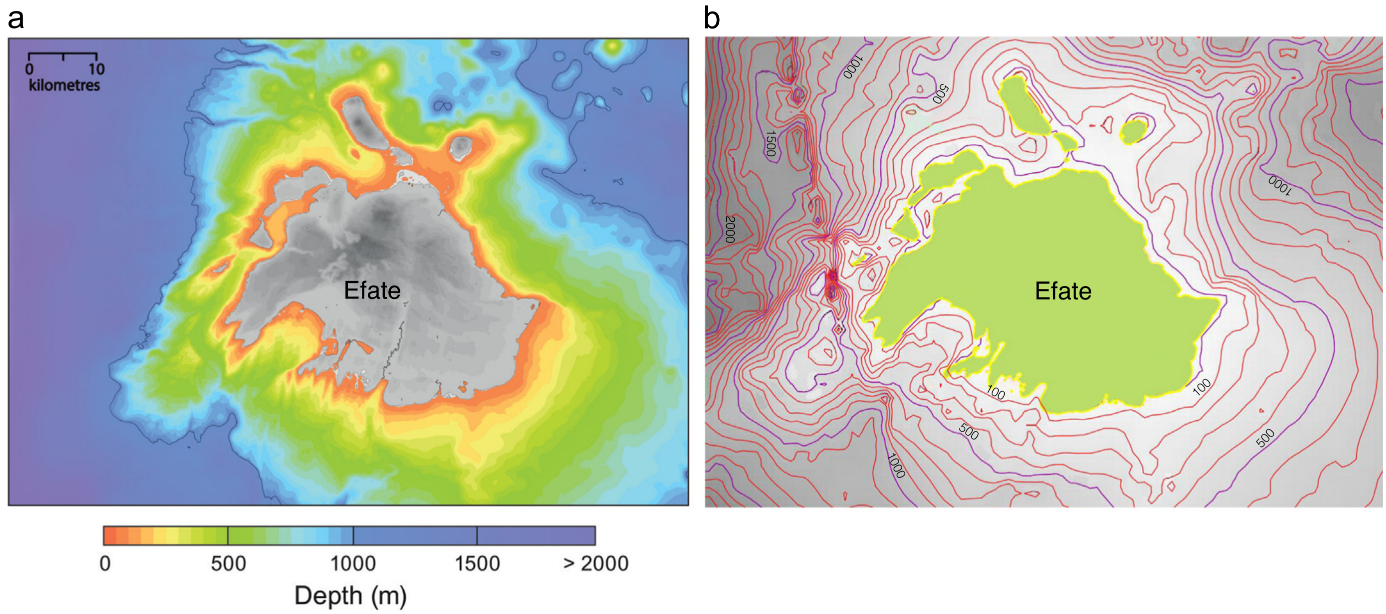

Fig. 2. (a) Fine-scale bathymetric map of Efate Island, Vanuatu (*source*: Secretariat of the Pacific Community); (b) modelled bathymetry of Efate Island based on the General Bathymetric Chart of the Oceans; lines represent 100 m depth contours and numbers are depths in m.

Table 2
Broad categories of vulnerability of rural (coastal) communities to future shortages of fish, based on access to coral reef areas, suitable bathymetry for installing nearshore fish aggregating devices (FADs), and local availability of freshwater and suitability of terrain for freshwater pond aquaculture (after Ref. [19]).

Vulnerability	Context of coastal village		
	Area of coral reef expected to meet future demand for fish	Distance to the nearest FAD is practical/ acceptable	Potential for freshwater pond aquaculture
Very low	Yes	Yes/no	Yes/no
Very low–low	No	Yes[a]	Yes
Low	No	Yes[b]	Yes
Low–medium	No	Yes[a]	No
Medium	No	Yes[b]	No
High	No	No	Yes
Very high	No	No	No

[a] FAD can be reached by paddling canoe.
[b] Motorized boat needed to reach FAD.

Coastal communities are expected to fall into one of seven broad categories of vulnerability to shortages of fish based on GIS analysis (Table 2). Nearshore FADs will be particularly important for villages that do not have large areas of healthy coral reef per capita, little scope for pond aquaculture, and limited potential to produce other sources of protein.

There are three other important considerations in deploying nearshore FADs within the suitable depth range. First, consultations should be held with coastal communities to secure assurances that assistance will be provided to provincial or national agencies to install and maintain FADs (see Sections 2.2 and 4), and to identify sites where the best catches of tuna and other pelagic fish species have traditionally been made.

Second, FADs should be anchored far enough away from coral reefs to ensure that they do not increase pressure on these ecosystems by attracting reef-associated fish species, e.g. Spanish mackerel and trevally (Carangidae). Distances of ~1 km from the nearest reef should meet this requirement.

Third, FADs should be far enough apart to ensure that the potential for each FAD to aggregate tuna is not compromised. Tagging of a limited number of yellowfin and skipjack tuna indicates that these fish can detect FADs from a distance of ~10 km [29,30], suggesting that FADs could be spaced 20 km apart. On the other hand, observations by master fishermen in the Coastal Fisheries Programme at the Secretariat of the Pacific Community (SPC) responsible for assisting PICTs to install nearshore FADs indicate that FADs can be as close as 5 km apart when placed relatively close to the coast.

Ideally, nearshore FADs also need to be located close enough to coastal villages so that fishers can paddle to them in canoes. Deploying FADs at greater distances will be necessary in some situations, e.g. where the bathymetry close to shore is not suitable, where large lagoons have to be traversed, or where traditional knowledge shows that the best catches are made further offshore. However, locating FADs further from the coast may oblige communities to invest in motor boats—something that is often beyond the means of subsistence fishers. The greater depths further offshore also increase the costs involved in building FADs, and may prevent the use of submerged designs due to the effects of stronger and more variable currents on the position of the aggregators. Another advantage of keeping FADs close enough to the coast so that small-scale fishers can reach them by paddling canoe is that FAD programmes should not lead to substantial increases in fishing capacity (motorised boats), which could further increase overfishing of coral reefs.

Until the GIS analysis described above is complete, it is not possible to determine how many coastal villages in PICTs could potentially benefit from nearshore FADs. Where such villages are closer than 20 km to each other, resolution of the best average distance between FADs (see Section 2.6) will enable appropriate arrangements to be made to share FADs.

2.1.2. Urban areas

Investments in nearshore FADs to increase access to tuna for urban populations will be more modest than investments in FADs for rural communities. This is because there is a limit to how many FADs can be installed near urban areas due to the need to place FADs within an economically viable operating distance (~20 km) from towns for the small-scale fishers who will use them. As proposed for planning the placement of nearshore FADs in rural areas, modelled bathymetric data from GEBCO, combined with the knowledge of local fishers and commitments of local communities to 'host' FADs used to supply fish to urban populations, will be needed to identify the best locations for aggregating devices within 20 km of urban centres.

On the basis that it may be possible to place nearshore FADs as close as 5 km apart, a total of ~230 sites for submerged FADs will be needed around urban areas in those PICTs with fish deficits or with difficulties distributing fish from remote reefs (Supplementary Table 2). It will be particularly important to use submerged FADs near major urban centres to prevent fouling by shipping servicing national and provincial ports. Permission to install FADs at depths below the draft of the largest vessels will need to be obtained from port authorities.

The constraints on the number of nearshore FADs that can be placed close to urban centres means that they will not meet all the additional urban demand for fish in some countries. However, in several regional ports, e.g. Honiara in Solomon Islands, Tarawa in Kiribati, Rabaul in PNG and Funafuti in Tuvalu, there is considerable potential to obtain the balance of the fish required from offloading of small tuna and bycatch from purse-seine vessels during transhipping operations [7,31]. In some locations, it may also be possible to develop economically viable cold-chain infrastructure to facilitate trade in tuna and other pelagic fish caught around more distant nearshore FADs to supply urban centres and boost income in rural areas.

2.2. *Engaging with communities to realise the full potential of nearshore FADs*

To make the most of nearshore FADs deployed in rural areas, consultations with communities need to be held to identify: (1) any social or operational impediments between and within communities to fishing effectively around FADs; (2) opportunities to engage with government departments and NGO partners in co-management of FADs, e.g. taking responsibility for notifying these agencies about the loss of FADs and assisting with the labour involved in replacing damaged or lost FADs; (3) how to partition the work involved in catching, processing, distributing or selling fish caught from FADs in a gender-sensitive way; and (4) how best to integrate fishing around FADs with existing livelihood activities, household responsibilities and other community-based fisheries management initiatives.

Ultimately, nearshore FAD programs should be embedded in the wider development planning of communities and provincial and national governments [11]. When it comes to implementation, governments and NGO partners need to develop processes for engaging with communities in operationalising and sustaining FAD programmes that specify: (1) the level of participation, awareness and investment by community members, including broad representation of households and surrounding communities to minimise vandalism; (2) arrangements to harness traditional knowledge to contribute to the selection of FAD sites and FAD designs; (3) user rights, potential social impacts, and linkages with other coastal fisheries management activities; (4) community members in the greatest need of training in fishing techniques, boat safety, and fish preservation and handling; and (5) procedures for mobilising assets required for FAD fishing (e.g. canoes/boats, specialised fishing gear), post-harvest processing and safety at sea. The community FAD management guidelines developed recently in Vanuatu [22] provide a pertinent example.

2.3. *Assessing the effectiveness of exclusion zones for industrial fleets*

A key assumption of plans to make nearshore FADs part of the national infrastructure for food security is that sufficient tuna will be available in coastal waters to meet the needs of rural communities. However, concerns have been raised about the potential for industrial tuna catches within the EEZs of PICTs to have negative effects on small-scale tuna fisheries. To help address these concerns, many PICTs have declared 12 nm exclusion zones for foreign industrial fleets around all their islands [32]. Kiribati has increased the exclusion area to 60 nm around some islands, and Marshall Islands, Palau and Samoa also have 50 nm exclusions zones in some areas. However, exclusion zones within the archipelagic waters of PNG and Solomon Islands, where the greatest needs for increased access to tuna for rural communities occurs, are more limited. In PNG, national vessels and fleets from countries that have invested in onshore processing are permitted to fish within archipelagic waters. In these waters, such industrial longline vessels can come as close as 6 nm from the nearest land, island or declared reef and purse-seine vessels are allowed within 12 nm. In Solomon Islands, national purse-seine vessels are licensed to fish in archipelagic waters within 6 nm of land and national pole-and-line vessels can operate within 3 nm. Industrial fleets fishing in the archipelagic waters of PNG and Solomon Islands have deployed large numbers of anchored FADs in offshore area to increase the efficiency of their operations (Supplementary Fig. 1).

To evaluate the effectiveness of the exclusion zones for industrial fleets, a targeted tagging programme is needed to answer the question 'What proportions of tuna tagged within exclusion zones in archipelagic waters are recaptured by industrial fleets and by small-scale fisheries?' Although re-analysis of past tagging data to assess the recapture rates of tuna marked with conventional dart tags within or close to exclusion zones could help to reveal whether tuna remain close to the coast in some parts of the region, difficulties in recovering tags from small-scale fishers at those times means that the data cannot be used to answer the question with confidence. Mobile phone technology now provides the opportunity to remove the previous bias associated with tag returns from small-scale fishers by sending messages regularly to coastal households informing them about the tagging programme and the rewards available for returning tags.

The costs of this targeted tagging programme are expected to be lower than those for the other tuna tagging programmes operated by the Secretariat of the Pacific Community[6], which used large pole-and-line vessels to tag tuna both close to and long distances from the coast. For this task, tuna could be tagged with conventional and acoustic tags from small (15 m) pole-and-line boats operating from coastal towns on a daily basis. Monitors for detecting acoustic tags can be placed on nearshore FADs.

2.4. *Monitoring catches around nearshore FADs*

Estimates of average catches of tuna and other pelagic fish around nearshore FADs are currently based on relatively few observations (Supplementary Table 3). Long-term sampling around replicate FADs at multiple sites in several PICTs is needed to provide robust estimates of average catches. Well-designed, fishery-dependent surveys that take into account fishing method/gear type, canoe/boat size, time of day, season, water depth, distance from shore, etc, will improve knowledge of the factors that influence catches around nearshore FADs and enable the deployment of FADs to be progressively improved. Such sampling programmes should also be designed to assess the catches of small-scale fisheries targeting tuna that are not associated with nearshore FADs. Broadening the monitoring and survey design in this way will not only help quantity the benefits of FADs for small-scale fishers, it will also help answer the question 'Are artisanal and subsistence small-scale fisheries catching sufficient tuna to meet the food requirements of coastal communities?'

Considerable thought has already gone into the components of programmes to monitor small-scale tuna catch and data recording[7]. The recommendation is for the data to be managed through national or provincial databases, supported by (1) a web-based

[6] www.spc.int/tagging/.

[7] Regionally established standard monitoring forms are available at http://www.spc.int/oceanfish/en/data-collection/241-data-collection-forms.

reporting tool to provide immediate access to the results, and (2) development of applications for mobile devices to facilitate e-reporting.

Socioeconomic surveys, e.g. household income and expenditure surveys (HIES) [33], can also be used to measure increases in consumption of tuna by coastal communities. The participation of households in HIES, particularly the completion of diaries, can also be expected to raise awareness of communities about the role of FADs in increasing local supplies of tuna.

2.5. Evaluating whether FADs improve coral reef management initiatives

The scope for FADs to strengthen the management of coral reefs using spatial closures and other community-based approaches, such as those applied by the LMMA network [23] and through the Micronesia Challenge, is predicated on the assumption that compliance with management measures will be enhanced where communities have access to other sources of fish or livelihoods. This assumption is intuitive but has yet to be substantiated [11,34].

The potential for FADs to add value to coral reef management initiatives needs to be tested rigorously. This is difficult to do but the 'Before vs after, control vs impact' (BACI) sampling designs [35,36], which have already been applied in coral reef ecosystems [37–39], provide the best approach. In this context, effective BACI sampling designs will involve measuring a series of appropriate indicators of coral reef health (e.g. diversity, percentage cover and structural complexity of corals, and percentage algal cover) and reef fish stock status (e.g. abundance, diversity, size structure and mean trophic level), at multiple sites with and without FADs in at least three PICTs on several occasions before and after installation of FADs. Then, if the indicators at the sites with FADs are not significantly different from those at control sites prior to deployment of FADs but are significantly different after a period of deployment, it is reasonable to conclude that FADs account for the observed changes (see Supplementary material for details).

In addition to measuring appropriate indicators of coral reef health and fish stock status, it will also be necessary to monitor (1) compliance with community-based management regulations (e.g. fishing location and gear type); (2) the social sustainability of fishing around FADs (e.g. incidence of conflict over FAD use or vandalism of FADs); and (3) the amount of fishing for tuna and other pelagic fish at all sites before and after deployment of FADs to record the extent to which FADs change fishing behaviour. Such monitoring will also provide important data on the effectiveness of FADs as a source of additional fish for coastal communities.

A proposed sampling design is given in Supplementary Table 4 and the recommended analytical model, based on the use of Permutational Analysis of Variance [40], is provided in Supplementary Table 5. The model consists of a 5-factor design incorporating two temporal components (Before vs After installation of FADs, and multiple periods within Before and After), two spatial components (PICTs and LMMAs within PICTs) and the key factor of interest, presence v absence of FADs.

2.6. Improving the design and placement of FADs

Submerged designs for nearshore FADs have already been developed to reduce the risk of vandalism and the effects of wave action on FAD components (Supplementary Fig. 2). The advent of submerged FADs, and the fact that many coastal communities are keen to target small pelagic fish as well as tuna, means that there is still a need to experiment with the design of FADs. Key questions that need to be addressed include: does the depth of floats on a submerged FAD affect the types of fish caught and the catch rate? Are different aggregating materials needed to attract small pelagic fish? How should submerged FADs be designed to increase their longevity and minimise any risks to marine mammals, turtles and sea birds?

Research involving acoustic tagging of tuna is also needed to identify the optimum distance between FADs, and to test the hypothesis that it may be more effective to deploy FADs in small clusters, with each FAD separated by $\sim$500 m. This hypothesis is based on observations by master fishermen at SPC that deploying FADs in clusters increases the likelihood of installing at least one FAD in the best place at a given site.

3. Discussion

The investments summarised here offer a pathway for increasing the availability of tuna and other pelagic fish for rural and urban communities in Pacific Island countries and territories. Indeed, they represent some of the most practical ways of allowing these communities to obtain the relatively small share of the region's rich tuna resources they need for food security [7].

In addition to providing a platform for improved public health, such investments also promise to be win–win adaptations to climate change. In particular, national FAD infrastructure should help supply more fish for growing populations in the short term and provide a continued source of fish as coastal fisheries decline due to the degradation of coral reefs caused by increasing sea surface temperatures and ocean acidification [18,19]. Even in PICTs where the abundance of tuna is projected to decrease as climate change causes an eastward shift in their distribution [41,42], nearshore FADs are likely to contribute to the needs of growing rural populations for two reasons. First, relatively large numbers of tuna are expected to remain in the EEZs of countries in the western Pacific by 2035 [41,42]. Second, the percentage of average tuna catches from the EEZs of all PICTs required for local food security in 2035 is low (< 6%) [7].

A proviso is that industrial fishing operations near the boundaries of exclusion zones in archipelagic and territorial waters of PICTs do not have a significant effect on the tuna catches of small-scale fishers. In the event that tagging programmes indicate that the great majority of tuna marked within existing exclusion zones are eventually caught by industrial fleets, and monitoring the catch of small-scale tuna fishers reveals that their catches are not meeting the demand for tuna by rural communities, expansion of exclusion zones will need to be considered. However, where extension of exclusion zones is likely to reduce the catches of industrial fleets significantly, cost:benefit analyses will be needed. These analyses should weigh up (1) the effects of reduced industrial catches on government revenue and opportunities to work in local tuna canneries or as crew on tuna fishing vessels; (2) the costs of providing coastal communities with improved access to tuna in other ways; and (3) the cost in terms of public health of inadequate access to tuna.

The outcome of the proposed suite of investments described here provides a blueprint for planning the installation of FADs as part of the national infrastructure for food security in PICTs. Such investments need to be given priority in national development plans because the number of nearshore FADs presently deployed in PICTs (Supplementary Table 1) is estimated to be well below the numbers likely to be needed by coastal communities. Other benefits of the proposed investments will be more robust information about the quantities of tuna and other pelagic fish likely to be harvested from FADs, and the cohesive community arrangements needed to reap the full range of benefits.

Once the FADs have been deployed in rural and urban areas, it will be imperative to maintain this infrastructure. If FADs are not replaced as soon as practical following loss or damage due to storms, vandalism or fouling by coastal shipping, the momentum involved in creating opportunities to provide the additional fish needed for food security, and transferring fishing effort from coral reefs to oceanic fisheries resources, will be lost.

Even though co-management of FADs is essential, national and provincial governments, or their development partners, should bear the main responsibility for the replacement of FADs lost or damaged under circumstances beyond the control of communities because small-scale fishers are unlikely to have the resources to replace FADs quickly. In much the same way that farmers are not expected to repair roads and bridges damaged by floods, build wharfs, provide shipping or construct marketplaces to sell their food (except through payment of taxes), small-scale fishers should not be expected to shoulder the cost of providing infrastructure that is so important to national food security. This is the domain of governments. However, communities should be custodians of investments made on their behalf and maintain FADs to improve the working life of these assets. Also, where FADs are lost due to negligence, vandalism or sabotage by community members, the onus should be on communities to replace them.

The prime requirements for replacing lost FADs quickly are stockpiles of spare parts in provincial areas, together with access to the vessels, staff and operating budgets needed to install new FADs. The budgets of national and provincial fisheries agencies are not presently large enough in most PICTs to cater for the replacement of FADs in this way [43,44]. Therefore, national planning offices should alert development partners about the importance of nearshore FADs to local food security and request the resources needed to maintain the required stocks of FAD materials and specialised staff. Importantly, stockpiles of spare FADs should be replenished regularly and maintained above threshold levels.

It is also important that national governments are committed to, and have ownership of, FAD programmes. In particular, there is scope in several Pacific Island countries for using some of the substantial licence revenues received from distant water fishing nations [7] to help fund nearshore FAD infrastructure. In those nations where industrial fishing companies deploy large anchored FADs for use by purse-seine vessels, e.g. PNG and Solomon Islands (Supplementary Fig. 1), arrangements could also be made with such companies to assist with the installation of nearshore FADs needed for local food security.

Although the investments discussed here apply to a broad range of PICTs, it will be important to ensure that FAD programmes in each country or territory are developed within the national or provincial context. Differences in local governance among (and sometimes within) PICTs mean that attempts to apply ‘one-size-fits-all’ approaches [45] are likely to add further complexity to the implementation of FAD programmes.

4. Conclusions

Installation of nearshore FADs is one of the few interventions that could provide access to the additional fish needed for good nutrition of growing Pacific Island populations, particularly in rural coastal areas. To ensure that nearshore FADs fulfil their potential to become an important component of national infrastructure for food security, it is imperative that investments in FAD programmes are not limited to improving the logistics of installing FADs. Investments must also extend to the participatory processes needed to identify those communities that are (1) most in need of FADs, (2) committed to sharing the benefits equitably, and (3) prepared to engage with government agencies and their development partners in the maintenance of FADs. Smooth co-management of nearshore FADs by communities, provincial and national governments and NGOs will not only help optimise the potential contributions of tuna and other pelagic fish to local food security, it will set the stage for determining whether nearshore FADs add value to management initiatives for coral reefs by transferring some fishing effort to oceanic fisheries resources.

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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.2015.02.010.

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