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Operationalising access to oceanic fisheries resources by small-scale fishers to improve food security in the Pacific Islands

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ABSTRACT

Maintaining the level of fish consumption in Pacific Island countries recommended for good nutrition as the populations of coastal communities grow, and as coral reefs are degraded by global warming and ocean acidification, will depend on small-scale fishers catching more tuna and other large pelagic fish. Concerted research and development by regional agencies shows that nearshore fish aggregating devices (FADs) provide one way for small-scale fishers to make this transition. Although the full potential of FADs remains to be assessed, several investments to optimise their use have been identified. These investments include pinpointing the locations where FADs are likely to make the greatest contributions to nutrition of coastal communities, integrating use of FADs with other livelihood activities, and improving the designs of FADs. Where Pacific Island countries have committed to developing nearshore FAD programmes, additional investments are needed to operationalise the use of FADs, particularly in cyclone-prone countries. These investments include: 1) training in safe and effective FAD-fishing methods; 2) developing reliable ways for forecasting when tuna, and other large pelagic fish (e.g., mahi mahi and wahoo), are likely to associate with FADs and delivering this information to fishers effectively; and 3) storing spare FAD materials, boats and fishing gear in cyclone-proof containers so that FADs lost during cyclones can be replaced quickly. When combined with measures to sustain catches of coastal demersal fish, operationalising the use of nearshore FADs is expected to help several Pacific Island countries attain the food security goals of regional policy frameworks.

1. Introduction

In 2015, Pacific Island leaders signed the *Regional Roadmap for Sustainable Pacific Fisheries* to maintain or improve the contributions of the region's rich tuna resources to their economies and societies [24]. An important goal of the *Roadmap* is to increase the availability of tuna

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for local consumption by 40,000 t per year by 2024 to help maintain the food security of rapidly growing populations. This important regional policy framework is supported by the *New Song for Coastal Fisheries: Pathways to Change* [58], which was approved by the 11th Ministerial Forum Fisheries Committee Meeting in 2015. The *New Song* also recognises the need to use the region's tuna resources to fill the gap between the fish needed for food security and sustainable harvests from coastal fisheries.

The main ways of increasing access to tuna for local consumption have been identified [10]. Making better use of the small tuna and bycatch offloaded in Pacific Island ports during transhipping operations by industrial purse-seine fishing fleets should provide more fish for rapidly-growing urban populations. Improving the distribution of tuna canned in the region should increase access to fish for communities in inland areas. And assisting small-scale fishers to catch more tuna and other large pelagic fish species should make fish more readily available for coastal communities.

Research and development by the Pacific Community (SPC)[1] over the past two decades indicates that an effective way to assist small-scale fishers to catch more tuna is to expand the use of nearshore fish aggregating devices (FADs) [3,16,57,59].

Building national networks of nearshore FADs should not only increase the availability of fish in the near term, it is also considered to be a key adaptation to climate change. In particular, increased use of FADs should enable communities to obtain the fish they need for good nutrition as the productivity of coastal demersal fisheries declines due to degradation of coral reefs caused by higher water temperatures and ocean acidification [7,8,12,46].

Several studies have demonstrated that catch rates of small-scale fishers can be improved when they fish around nearshore FADs [13,53–55]. Based on these encouraging results, considerable thought has already gone into identifying the actions needed to optimise the use of nearshore FADs for local food security [11]. These actions are necessary because not all FADs anchored in nearshore waters have had the full endorsement of local communities, or increased access to fish for food security when they were requested by communities [1,15] (Supplementary materials). The necessary actions include, for example, pinpointing locations where FADs are likely to make the greatest contributions to nutrition of coastal and island communities, integrating the use of FADs with other livelihood activities, and improving the designs and effectiveness of nearshore FADs [1,4,11]. As important as they are, however, these actions do not directly assist people to catch fish around FADs, or provide them with an effective way of replacing FADs lost during cyclones of for other reasons, such as wear and tear [4].

Three additional investments are needed to assist small-scale fishers to operationalise the use of FADs. The first involves training small-scale fishers in safe and effective FAD-fishing methods, especially where they have limited experience fishing offshore [4]. In particular, there is a need to raise awareness that more precautions are required when fishing around FADs, which are typically located 2–5 km beyond the fringing or lagoonal barrier reefs where most small-scale fishing operations have traditionally taken place. The lives lost at sea during the rapid development of the Alia longline fishery for South Pacific albacore in Samoa in the 1990s [27] is a sobering reminder of what can happen when small-scale fishers are not accustomed to operating further offshore.

The second investment is the development of tools for forecasting favourable conditions for catching yellowfin and skipjack tuna, and other large pelagic fish (e.g., wahoo and mahi mahi), around nearshore FADs and delivering this information effectively to small-scale fishers [21]. This is important because coastal and island communities have many competing demands on their time, e.g., production of subsistence food crops [9,62]. Forecasting when safe conditions for fishing around FADs coincide with times when target fish species are expected to occur in coastal waters will also assist communities to optimise their various livelihood activities.

The third investment centres around development of systems for storing spare FAD materials, boats and fishing gear in cyclone-proof containers so that FADs lost during natural disasters can be replaced quickly. In the aftermath of cyclones, the many demands for (often limited) national shipping can cause long delays in the replacement of FADs. Unless the materials needed to deploy FADs are stored locally by provincial fisheries officers or communities, it is unlikely that lost or damaged FADs will be replaced in time to yield fish catches when they are needed most – during the months required for newly planted crops to be harvested following natural disasters.

Here, we describe the specific activities that will be needed for each of these investments. We use Vanuatu as a case study because it has a rapidly growing population, a need to increase access to tuna for food security [6,56] (Supplementary materials), and is one of the Pacific Island countries affected most frequently by cyclones [43]. Vanuatu has also been an early adopter of FADs [2] and as an archipelagic nation with many remote island communities (Fig. 1) is well placed to benefit from the three proposed investments.

The ideas presented here should also apply to other Pacific Island countries where FADs are needed to help provide an important source of protein for coastal communities, especially those countries prone to cyclones.

2. Training in safe and effective FAD-fishing methods

In Vanuatu, small-scale fishers who use FADs fall into two categories: 1) subsistence fishers operating from paddling canoes catching fish relatively close to shore (1–3 km from the coast and in depths of 200–500 m), principally for their own households; and 2) commercial (artisanal) fishers using motor boats who typically catch fish around FADs further offshore (5–7 km from the coast, and in depths of 500–1000 m) for sale at local markets or in Port Vila and Luganville. It is estimated that there are ~16,000 small-scale fishers in Vanuatu (Supplementary Table 1) and that by the end of 2017 more than 50 nearshore FADs will be deployed at ~30 locations (Fig. 1, Supplementary Table 1).

To improve the safety and effectiveness of their fishing operations, both canoe and motor boat fishers need: 1) meteorological forecasts of wind speed, wind direction, atmospheric pressure, wave height and ocean current velocity to evaluate the risks associated with fishing offshore in small craft; 2) advice about safety procedures, which safety equipment to carry, and how and when to use it; and 3) training in the best ways to catch target fish species around FADs at different times of year.

2.1. Meteorological forecasts

The Vanuatu Meteorological Service (VMS) provides regular, short-term, forecasts of atmospheric conditions (e.g., wind speed, pressure) and related oceanic conditions (e.g., wave height)[2] essential for the marine weather bulletins needed to inform small-scale fishers about the safety of boating in coastal waters. VMS also issues bulletins and warnings for high winds, cyclones, and high seas. However, VMS needs support to 1) customise this information to the needs of canoe and motor boat fishers, 2) routinely transmit customised bulletins to each province on all types of mobile devices, and 3) ensure that communities know how to interpret the information correctly.

For customising the information to meet the needs of small-scale

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[1] www.spc.int.

[2] These forecasts are delivered by VMS via its web site (http://www.meteo.gov.vu/) and by radio several times each day.

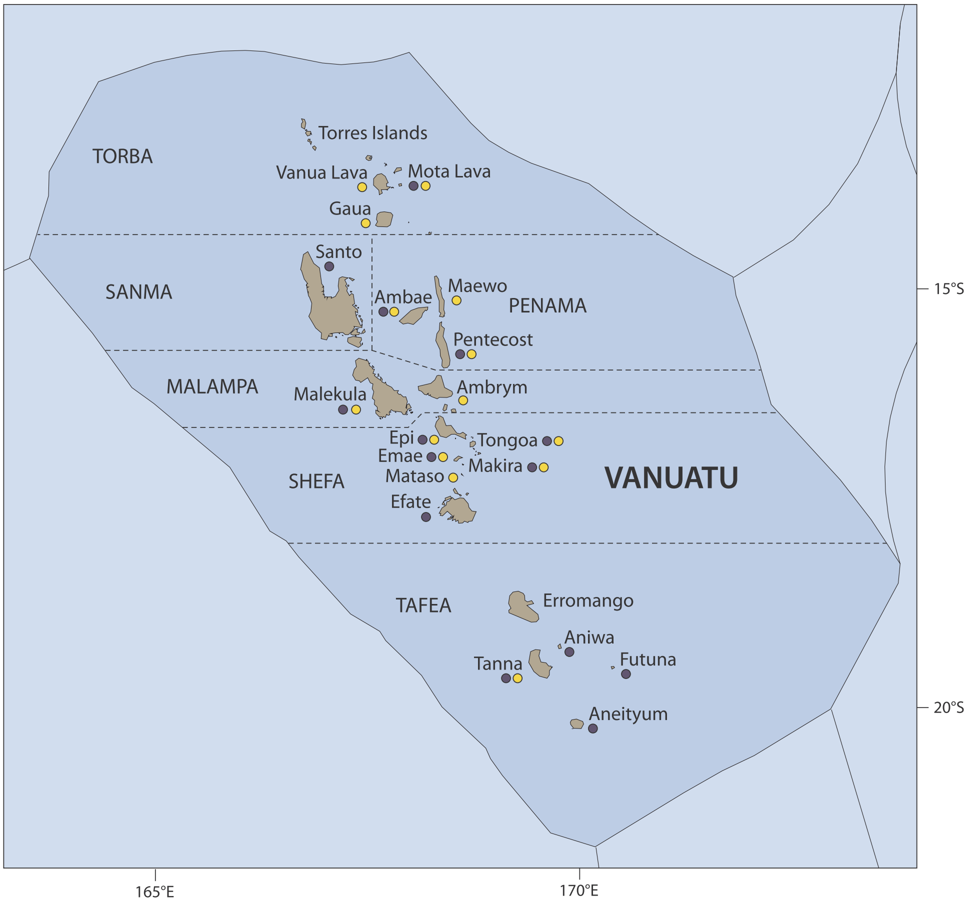

Fig. 1. Map of Vanuatu showing the exclusive economic zone, the six provinces, the locations where fish aggregating devices (FADs) were installed close to the coast for small-scale fishers (blue circles) prior to 2017, and the locations where FADs were installed during 2017 (yellow circles) (see also Supplementary Table 1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fishers and assisting them to interpret it correctly, VMS will need support to organise workshops for fishers to interact with VMS staff to explain what kind of information they need and the temporal and spatial scales on which they need it; and to check that fishers are interpreting the information they receive correctly. For regular transmission of customised bulletins, VMS will need technical support to convert bulletins to digital form, and then send them out via a subscription service.

2.2. *Safety*

Safety at sea for small-scale fishers centres on training in the relevant procedures, such as informing people where they are going, when they plan to return, who is on board, etc., and ensuring that fishers have appropriate safety equipment and the knowledge to use it. However, the relatively high cost of safety equipment means that it is likely to be beyond the reach of many small-scale fishers, especially subsistence fishers. Communities can usually overcome this problem by requesting funds from development agencies to purchase multiple sets of safety equipment and establishing custodian systems for issuing it to, and retrieving it from, small-scale fishers each day. Appropriate custodians of safety equipment include the community women's groups or local fishers' associations. Although the type of safety equipment needed by subsistence canoe fishers differs from that required by commercial fishers in motor boats operating further offshore (Supplementary Table 2), use of safety equipment is always made easier when it is assembled into a 'safety grab bag'.

Initiatives to improve boating safety for small-scale fishers should take into account that having safety equipment available and the knowledge about how and when to use it is no guarantee that safer boating practices will be adopted (reluctance to wear a life jacket by some fishers is a case in point). Investments in improving safety at sea for small-scale fishers should extend to identifying and dismantling any blockages to the uptake of safer boating practices.

2.3. *Training in efficient FAD-fishing methods*

The most successful techniques for catching tuna and other large pelagic fish around FADs from canoes involve handline fishing in mid water, e.g., drop-stone fishing, rod-spreader jigging and 'palu-ahi' fishing. Other efficient methods also include trolling at low speed, drift-line fishing for mahi-mahi, and 'sabiki' rig jigging for baitfish. Small-scale commercial fishers operating from motor boats have a greater range of fishing methods to choose from. In addition to those described above, they can use vertical longlining, small-scale horizontal longlining, 'ika-shibi' fishing, sub-surface or deep trolling, and Hawaiian-style hoop-net fishing [47,48].

Based on the experiences of Fisheries Development Officers at the SPC, training in boating safety and effective FAD-fishing methods is most effective with a group of 10–15 fishers at a time. For both categories of small-scale fishers, the training usually takes 5–10 days and should be done once the FAD has accumulated enough fish (i.e., once it has been in the water for at least one month).

'Train the trainers' approaches, where regional or local technical experts train an initial group of trainers (national/provincial fisheries officers and key members of fishers' associations), are needed to increase the uptake of safe and effective FAD-fishing methods by coastal and island communities [4]. This places the onus on countries to allocate the financial resources needed to 1) arrange for a core set of fisheries officers and representatives of fishers' associations to be trained in safe and effective FAD-fishing operations; and 2) support this group of trainers to conduct similar training for fishing communities throughout their country.

3. Forecasting favourable conditions for catching large pelagic fish around FADs

Much of the information needed to develop reliable forecasts of the occurrence and abundance (hereafter 'distribution') of tuna and other large pelagic fish in the coastal waters of Pacific Island countries is now available in open-access, global databases (Supplementary material). Below, we describe: the main types of information needed for building such fish distribution forecasting tools; the suitability and availability of forecasting tools; the need to validate the reliability of forecasts; and feasible systems for disseminating forecasts to small-scale fishers. This discussion focuses on tuna because the information on habitat requirements and preferences for yellowfin and skipjack tuna [37,50] is more advanced than for other large pelagic fish expected to associate with nearshore FADs, e.g., mahi mahi and wahoo. Nevertheless, the forecasting approaches outlined here should also be applicable to other fish species targeted by small-scale fishers around nearshore FADs once the environmental conditions preferred by these species are understood more fully.

3.1. Information needed for forecasts

Identification of the environmental conditions preferred by tuna (and other large pelagic fish) is a key pre-requisite for development of tools for small-scale fishers that can forecast, and 'nowcast', conditions likely to attract tuna close to the coast. Both forecasting and nowcasting are important – forecasting allows fishing trips to be planned, whereas nowcasting confirms that forecasted conditions have eventuated.

Much information on the environmental preferences of skipjack and yellowfin tuna is already available from observations by industrial fisheries and research using electronic tags [37,50] (Supplementary Material) at a range of spatial scales. At the largest (ocean-basin) scale (1000s of km), climate drivers such as the El Niño Southern Oscillation (ENSO) influence the distribution of tuna by modifying, for example, sea surface temperature (SST) [26,34,36]. Distributions of tuna are also affected by variation in ocean features at regional scales (100s of km), such as shifts in currents [29,66], and at local scales (10s of km), such as formation and movement of eddies and fronts [31,45,66]. In addition, tuna aggregate at small scales (100s of metres) in response to bathymetric features like seamounts [15,18,30,44]. To forecast and nowcast conditions when tuna are likely to occur in nearshore waters where FADs are installed, information relating ocean features and the distributions of tuna species is needed at all these scales.

The most common variables used to identify environmental conditions preferred by tuna and predict the availability of suitable habitat are SST, chlorophyll-a concentration (a proxy measure for productivity/food supply for tuna), atmospheric pressure, and current speed and direction. Other useful variables, at least at regional and local scales, include mixed layer depth, eddy kinetic energy, presence of frontal systems, and prey distribution [31].

Sea surface temperature and chlorophyll-a have been used to describe historical distributions of tuna at regional and local scales [19,23,50]. More importantly, short-term changes in SST, atmospheric pressure, current speed and direction, eddy characteristics, and wind speed and direction have been applied to forecast local occurrence and abundance of tuna. For example, real-time (next day), short- (< 7 days) and medium-term (up to 3 months) forecasts of distribution based on SST have been developed to: assist commercial fishers to catch southern bluefin tuna in South Australia [23]; manage bycatch in eastern Australia [32]; identify the best locations for recreational fishing for mahi mahi on the east coast of Australia [14]; provide commercial fishers targeting albacore in Spain's Basque country with daily maps of habitat, re-parameterised each evening with the previous day's catch [5]; and forecast the distribution of bigeye tuna in Indonesia [38]. Such forecasts are expected to improve further once predictions of changes in chlorophyll-a concentrations become routinely available at regional and local scales – at present, only experimental chlorophyll-a products based on biogeochemical and statistical models are available for limited areas, e.g., coastal bays [35,49] and coasts [19]. Forecasts are also expected to be improved by integrating knowledge (including traditional knowledge) about the distribution of tuna related to seasonal patterns of migration, and to moon and tidal phases.

3.2. Suitability and availability of forecasts

The short-term forecasts of atmospheric conditions (e.g., wind, pressure) and related oceanic conditions (e.g., wave height) described in Section 2.1 are typically issued at ocean-basin to local scales out to seven or 10 days. However, most physical features of the ocean, including SST, generally vary on longer time scales than atmospheric variables [20,40], permitting forecasts with longer lead times. For ocean features where forecasts are not presently available, like chlorophyll-a concentration, long-term average seasonal patterns (climatologies) and the anomaly from, and variability about, the average state of the ocean feature can be used to indicate how conditions are likely to vary in the near future. Nevertheless, care should be taken to consider how consistent such patterns are because they can vary substantially in space and time [64]. Typically, the reliability of forecasts of environmental variables decreases with increasing lead-time – nowcasts and short-term forecasts have greater accuracy than predictions for several weeks or months into the future.

Small-scale fishers in Vanuatu would benefit most from forecasts of ocean variables at relatively small spatial scales, and short temporal scales, that pinpoint suitable conditions for aggregation of tuna in coastal waters several days or a few weeks in advance.

Short-term SST forecasts (lead times up to seven days), such as those from OceanMaps[3] available on a 10-km grid for the Australian region, have much potential for identifying thermal conditions likely to attract tuna into coastal waters. Until these OceanMaps forecasts are available for Vanuatu, longer-term, global SST forecasts (several weeks to months), such as the coarse resolution modelling (~2° × 0.5–1.5°) from POAMA,[4] could be used. However, a more promising option for SST forecasts for immediate application in Vanuatu is NOAA's Climate Forecast System Version 2 (CFSv2) (resolution: 0.5° × 0.5°) [51]. Since 2012, NOAA's Coral Reef Watch has been using CFSv2 forecasts for SST (Fig. 2a) to predict the risk of mass coral bleaching on a weekly basis up to four months in advance[5] [22,41], based on the magnitude and timing of stressful warm temperatures (Fig. 2b). Importantly, the spatial resolution and data grid layout of the SST forecasts from CFSv2 can distinguish SST patterns across the six provinces of Vanuatu (Fig. 2). Given that the deployed FADs define the location of fishing operations in each region, the primary guidance from the forecasts is to provide small-scale fishers with information on the timing of favourable conditions. The CFSv2 output can provide effective and timely information on the likelihood of tuna occurring around FADs in the coastal waters of Vanuatu, based on known temperature preferences of yellowfin and skipjack tuna.

The skill of the CFSv2 SST prediction varies seasonally and with the length of lead-time,[6] however. For example, at a lead-time of up to one month, SST predictions around Vanuatu are more reliable for spring (September-November; correlation, r > 0.8) than for summer (January-March; r < 0.7) (Fig. 3). As lead-time increases, reliability of the predictions decreases, and is lowest from February to May. Overall, weekly forecasts of SST for Vanuatu are most reliable when made for periods no greater than two months in advance.

The addition of other important variables, like chlorophyll-a

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[3] http://www.bom.gov.au/oceanography/forecasts/.

[4] http://poama.bom.gov.au/.

[5] http://coralreefwatch.noaa.gov/satellite/bleachingoutlook_cfs/outlook_cfs.php.

[6] http://www.cpc.ncep.noaa.gov/products/people/mchen/CFSv2HCST/metrics/rmseCorl.html.

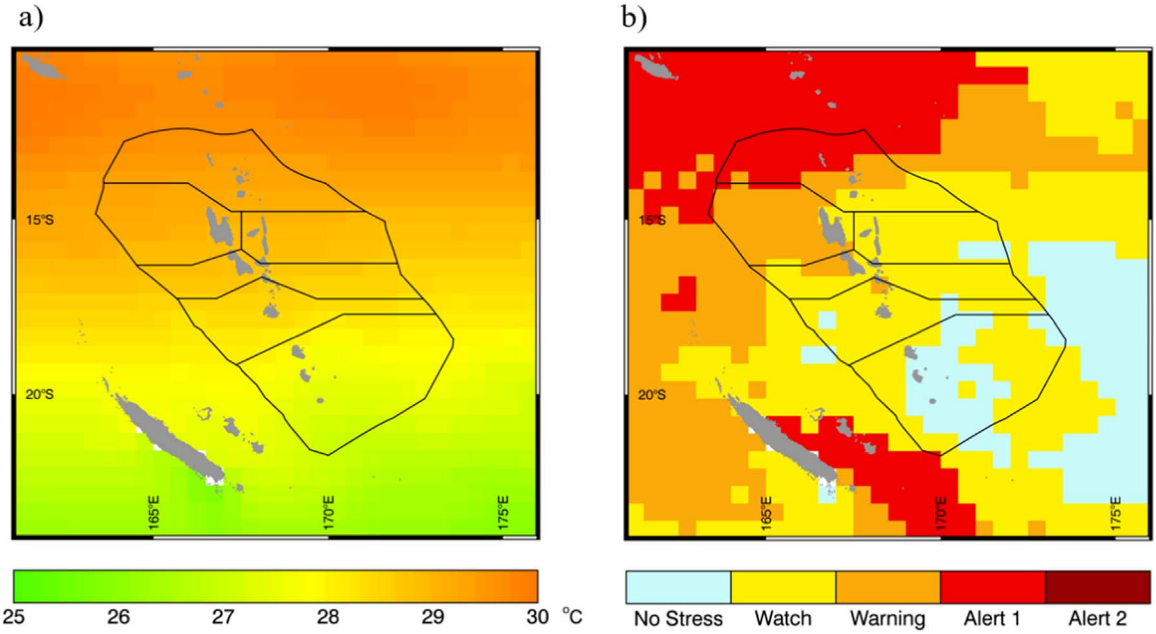

Fig. 2. a) NOAA Climate Forecast System v2 predicted sea surface temperature in the Vanuatu region for 13 March 2016 from the forecast issued on 24 January 2016; b) management product describing the highest predicted level of coral bleaching likelihood during the four-month period leading up to 13 March 2016, issued on 24 January 2016. The six provinces of Vanuatu are distinguished in both panels out to the boundary of the exclusive economic zone (black lines).

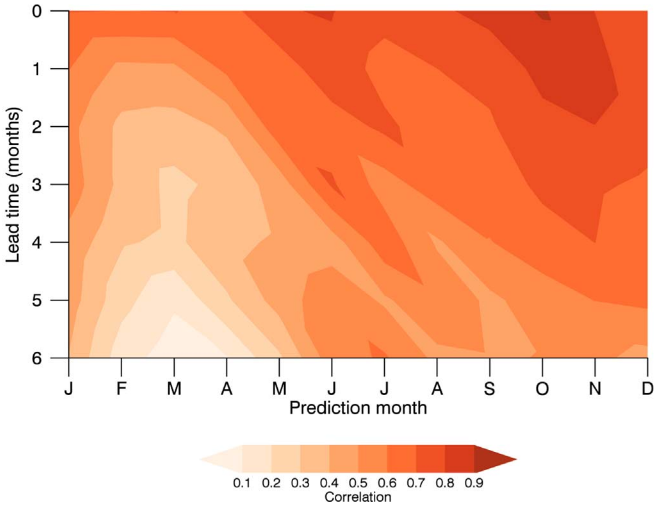

Fig. 3. Variation in the correlation coefficient of SST predictions by the NOAA Climate Forecast System v2 for the Vanuatu region with season and model lead-time.

concentration, to produce an integrated tool has the potential to further enhance the skill of forecasts [63]. Any such improvement would depend on the accuracy of predicted variables, as well as how strongly they are correlated with tuna aggregation. For the example of chlorophyll-a concentration, development of forecasts based on coupled biogeochemical models for the Pacific Island region is likely in the next few years (R. Matear, pers. comm.). The development of stochastic prediction tools [64] can be undertaken immediately. Integrating predictions of ocean conditions preferred by tuna, outlined above, requires additional investment to develop, calibrate and operationally produce multi-factor forecasts and nowcasts of tuna distribution in the coastal waters of Vanuatu (and other Pacific Island countries).

Investments are now needed to integrate the information outlined above to provide forecasts and nowcasts of tuna distribution in the coastal waters of Vanuatu (and other Pacific Island countries) based on predictions of ocean features expected to match the environmental conditions preferred by tuna.

The skill of forecasts of tuna distribution in coastal waters can be assessed through hindcast performance. This involves correlating historical *forecasted* model values of environmental variables with historical *observed* values in both space and time, and assessing accuracy with several statistical techniques [60,61]. In the case of SST, satellite data or re-analysis products can be used [65]. In general, skill is higher for forecasts of fish presence based on physical conditions, such as SST, than for forecasts that integrate physical and biological data [32]. This is because the response of fish to physical conditions is mediated by physiological and behavioural factors, such as the size of the fish (e.g., larger tuna can tolerate cooler waters) or the reproductive life stage (e.g., spawning tuna may seek particular environmental conditions that are more limited than their usual range, or be willing to tolerate conditions that are unsuitable for feeding).

3.3. Validating forecasts

Ultimately, catch or other scientific data are needed to validate any tool designed to forecast the distribution of these large pelagic fish. In the absence of data needed for validation, full release of forecasts should be delayed until there is a high level of confidence that the information is useful and reliable. Limited release of forecasts may be appropriate, however, to help evaluate experimental products or to guide the collection of validation data. In such circumstances, communication among project partners and small-scale fishers regarding the experimental nature of forecasts is essential.

There are good prospects for obtaining catch data to validate forecasts of tuna distribution in the coastal waters of Vanuatu. During 2017 and 2018, catch-per-unit-effort (CPUE) data are being collected from FADs distributed throughout much of Vanuatu using the 'Tails' database developed by SPC[7] (Supplementary material). Also, since August 2016, some CPUE data have been collected from artisanal fishers in several provinces (Tafea, Sanma, Penama, Tafea and Malampa) by the Vanuatu Fisheries Department using Tails. A positive correlation between these catch data and forecasts of good fishing conditions would provide a first

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[7] Available online: https://play.google.com/store/apps/details?id=spc.ofp.tails&hl=en.

validation of a forecasting tool, which can be improved with formal skill assessment when a longer time series is available [32].

The rapid development and relatively low cost of acoustic buoys fitted to the drifting FADs used by industrial purse-seine vessels [17,25] provides another avenue for obtaining the data needed to validate a tool for forecasting tuna distribution for the benefit of small-scale fishers in Vanuatu. These acoustic buoys are equipped with echo sounders or sonar and transmit estimates of fish biomass associated with FADs to a depth of 80 m [42]. Although these systems are not yet able to identify the fish species associated with FADs, purse-seine crew are now experienced at predicting the presence and relative abundance of tuna through interpreting signal strength and diurnal vertical behaviour. Therefore, attaching echo sounder buoys to representative nearshore FADs and transmitting the information to the Vanuatu Fisheries Department has considerable potential to validate a forecasting tool by correlating estimates of fish biomass associated with the FAD with conditions predicted to be favourable for tuna and other pelagic fish species.

3.4. Disseminating forecasts to small-scale fishers

Once the forecasting tool has been validated and placed on the web, either as part of the VMS suite of products or via the Vanuatu Meteorological and Geohazards Division, it can be accessed by users via mobile phone networks. Indeed, the stage is set for uptake of forecasts of tuna distribution in Vanuatu because the national 3G network provides reasonable coverage in five of the six provinces and more than 50% of the mobile phones in use are now smart phones.

4. Rapid replacement of lost FADs

A key lesson from Tropical Cyclone Pam (Category 5) that struck Vanuatu in March 2015 has been that it is very difficult for national governments to replace FADs quickly in the aftermath of devastating natural disasters – it took 18 months before FADs began to be replaced. New policies and practices are needed to ensure that FADs can be replaced within weeks of being lost during cyclones so that communities have access to nutritious fish before emergency food aid comes to an end and new crops mature.

A practical way to do this is to assist communities in Vanuatu to prepare for rapid recovery after future cyclones by securing 40′ shipping containers on all major islands to provide cyclone-proof storage for spare FADs materials, and as a place where small-scale fishers can keep boats and fishing gear safe when a cyclone is approaching. Once the cyclone has passed, the boats can be used to deploy the FADs and to fish around them. The Vatuika FADs designed by the Vanuatu Fisheries Department [2] are ideal for this purpose because they can be deployed from a small boat.

However, the logistics involved in installing and securing 40′ containers on remote islands can be difficult and costly in archipelagic nations like Vanuatu. To install such cyclone-proof storage in remote locations, Vanuatu and other Pacific Island countries prone to cyclones could request assistance from Australia or New Zealand. Both nations have naval vessels, such as HMAS Canberra (Australia) and HMNZS Canterbury (New Zealand), purpose-built for humanitarian assistance. These vessels could be used to deliver and install the containers during the course of naval exercises in the region.

5. Discussion

The three investments described here are expected to create opportunities for small-scale fishers to increase their access to tuna and other large oceanic fish species in safe and effective ways. They are also expected to make small-scale fishers more resilient to the devastating effects of cyclones and help them adapt to the impacts of climate change on coastal fisheries. Together, these investments should assist countries that are already in the process of expanding the use of nearshore FADs to meet the food security goals of regional policy frameworks – the *Regional Roadmap for Sustainable Pacific Fisheries* and the *New Song for Coastal Fisheries*.

There are, however, a few factors that could temper the benefits of the recommended investments in forecasting and nowcasting tools. The first is the possible effects of industrial fishing on the catches of small-scale fishers and the need to incorporate the proximity of industrial fishing operations into the forecasts of tuna distribution in coastal waters. Although the time needed for tuna to re-aggregate following localised depletion by industrial fishing is poorly understood, reduced catch rates have been reported in artisanal fisheries following nearby industrial purse-seine fishing operations [28]. Analyses of tagging data from areas where purse-seine fishing does and does not occur in the Pacific Island region also indicate that industrial fisheries may reduce local densities of tuna [39]. In addition, recreational fishing competition data infer that catch rates for striped marlin can be affected by industrial longline fishing [33].

Integrating industrial fishing activity with variation in key environmental variables to produce better short-term forecasts of local tuna abundance will necessitate near-real-time access to information on industrial fishing operations. In the case of Vanuatu, however, this may not be of such importance – the potential for significant interaction between industrial and small-scale tuna fishing is presently very low because industrial fishing for tuna is limited largely to longline operations well outside the 12 nm industrial fishing exclusion zone. Analysis of the main locations of previous longline fishing within Vanuatu's exclusive economic zone (EEZ) shows that most activity occurred well east of the archipelago, between 50 and 100 km from the coast (Supplementary Material, Supplementary Figs. 2 and 3).

The second consideration is that recent modelling of the effects of climate change on the distribution and abundance of tuna shows that the biomass of yellowfin tuna is likely to decrease in the Vanuatu EEZ in 2035 and 2050, but that the biomass of skipjack tuna is likely to increase (Supplementary Fig. 5, Supplementary material). When the expected effects of increased fishing pressure over time are combined with those of climate change, the patterns are in the same direction, although the decreases in biomass for yellowfin tuna are projected to be greater, and the increases in biomass for skipjack tuna are projected to be lower (Supplementary Table 3).

Modelling the effects of climate change on the preferred habitats of two other large pelagic fish commonly caught by small-scale fishers around nearshore FADs in Vanuatu, mahi mahi and wahoo (Supplementary Fig. 6, Supplementary material), indicates that both of these species are likely to decrease in abundance over time, with the effects expected to be greater for mahi mahi than for wahoo (Supplementary Table 3).

The implications of these projections are that the relative abundances of the four species around nearshore FADs can be expected to change in the future, and that the focus for forecasting will eventually need to be on the species projected to increase in abundance, skipjack tuna.

Ultimately, effective forecasting will not only need to incorporate the projected effects of climate change but also local-scale effects of FADs on the behaviour of large pelagic fish species. Individual-based simulation models [52] (Supplementary material, Supplementary Fig. 7) provide an approach for exploring the possible interactions between FAD placement and fish behaviour.

The third factor is that expected decreases in the costs of acoustic equipment and using 3G networks should eventually enable an interface to be established for transmitting data from acoustic buoys attached to nearshore FADs directly to small-scale fishers, allowing them to assess the amount of fish associated with FADs on smart phones and tablets (Supplementary material). Eventually, this innovation would be expected to supersede the need for a tool to nowcast tuna distribution for those islands with good connectivity to the internet. However, nowcasts should continue to be useful for communities in more remote locations with limited connectivity. The benefits of short-term tuna distribution forecasts are expected to continue for communities at all locations.

Once nowcasting and forecasting tools have been developed and are ready to distribute for use by small-scale fishers, we recommend targeted monitoring of catches around FADs to assess the impact of the technology, preferably using the 'before vs after, impact vs control' sampling design recommended previously for assessing the benefits of nearshore FADs [11]. In Vanuatu and other Pacific Island countries where the 'Tails' application (Supplementary material) is used to monitor coastal fish catches, this type of sampling could possibly be done by using catch data from FADs at several (at least n = 8) communities before the technology is released and then comparing those data with catches made around FADs by at least four communities that do, and do not, use forecating and nowcasting tools, or acoustic devices.

The three investments recommended for operationalising the use of FADs will be facilitated if Pacific Island countries are able to implement supporting policies. Examples of suggested supporting policies are summarised below.

Link fisheries development and sea safety to ensure that national FAD programmes focus not only on building the infrastructure for food security, but also on providing thorough training in safe boating practices for all coastal fishing communities. Consideration should also be given to removing import duties on safety equipment needed by small-scale fishers.

Strengthen 3G and 4G connectivity for rural areas so that as many small-scale fishers as possible can have real-time access to boating weather forecasts and tools for 1) forecasting and nowcasting the conditions when good catches of tuna and other large pelagic fish are likely to be made, and 2) downloading information on abundance of fish associated with FADs fitted with acoustic devices.

Apply the 'Framework for Resilient Development in the Pacific'[8] in ways that assist communities to prepare for re-establishing food production, including fishing around FADs, as soon as possible after cyclones.

Revise (if needed) agreements for humanitarian assistance with Australia and New Zealand to enable assistance to be received to prepare for coping with the devastating effects of cyclones well in advance.

6. Conclusions

The investments that many Pacific Island countries are making in nearshore FADs as part of the national infrastructure for food security, based on decades of research and development by SPC, are expected to help them achieve the goals of regional policy frameworks. Nevertheless, national plans to expand the use of FADs to increase access to tuna and other large pelagic fish for small-scale fishers should benefit from the additional investments recommended here. Training in safe boating practices and effective fishing methods will reduce the risks for small-scale fishers operating further offshore and improve their catches. Forecasts of wind and sea conditions, combined with forecasts of the conditions preferred by the target fish species, will also improve safety at sea and enable communities to assess the likelihood of fishing success and dovetail fishing trips with other important livelihood activities. Relaying information on fish abundance from acoustic equipment fitted to nearshore FADs should also assist small-scale fishers to plan fishing trips. For Pacific Island countries prone to cyclones, installation of cyclone-proof storage for spare FAD materials and boats suitable for deploying FADs will assist communities to replace lost FADs rapidly following severe storms. Together, these investments should help operationalise the use of FADs and reduce the vulnerability of coastal communities that depend on tuna and other large pelagic fish for food security.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2017.11.008.

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