Adapting tuna-dependent Pacific Island communities and economies to climate change

Annex 28: Value added by the Advanced Warning System to existing tuna modeling

1. Background

The Pacific Island countries are in a unique position among Small Island Developing States because considerable effort has already been made to model the response of their tuna resources to ocean warming. This support has been provided by the Oceanic Fisheries Programme at the Pacific Community (SPC), the regional technical agency serving Pacific Island countries and territories, and the Executing Entity for the GCF regional tuna programme (hereafter 'Programme').

In 2008, SPC and partners launched the 'Spatial Ecosystem and Population Dynamics Model' (SEAPODYM) (Lehodey et al. 2008). Since then, this model has been progressively developed to inform Pacific Island countries and territories about the vulnerability to the effects of climate change of the four tropical tuna species (skipjack, yellowfin and bigeye tuna, and South Pacific albacore) targeted by the industrial tuna fisheries operating in their exclusive economic zones (EEZs).

The SEAPODYM modelling has been of significant interest to the region, primarily because industrial tuna fishing underpins the economies of so many Pacific Island countries and territories, including nine of the countries participating in the Programme. For these nine countries, fishing access fees paid by industrial fleets to fish in their EEZs contribute an average of 32% of their (non-grant) government revenue (Figure 1). Industrial tuna fishing also provides an important source of employment in the region through onshore fish processing in several countries, and in others by providing jobs as crew and observers on vessels, and in national and regional tuna management agencies (Ruaia et al. 2022).

Iterative improvements in the development and application of SEAPODYM (Lehodey et al. 2010a,b, 2011, 2013, 2015, 2020; Senina et al. 2008, 2018, 2020a,b,c) enabled the model to be used to demonstrate that there could be an average 20% reduction in catch (Appendix 1), and annual losses of government revenue of up to 13% (Appendix 2) for many Pacific Island economies, by 2050 due to climate-driven tuna redistribution (Bell et al. 2021). These projections provided the rationale for preparing Component B of the GCF Funding Proposal.

Although SEAPODYM is arguably the most robust of the models available to simulate the effects of ocean warming on the abundance and distribution of tuna, the remaining uncertainty in the modelling approach needs to be reduced before it can reliably guide adaptations to maintain the important contributions of tuna to national economies (i.e., SEAPODYM needs to be developed into the framework of operational oceanography to provide robust nowcasts, forecasts, hindcasts and projections).

There is currently no complementary model to assess the future dynamics of fishing fleets when projecting the impacts of climate change on Pacific tuna fisheries. Consequently, climate projections to date have been restricted to expected range shifts in the absence of any fisheries impact. Moreover, this has restricted any complimentary economic analyses to rudimentary assumptions that economic performance is directly proportional to current and future estimates of unfished tuna distribution. While this is likely to broadly hold true at the regional level it is unlikely to be valid at the spatial scale of national EEZs. The absence of appropriate fleet dynamics model(s) has resulted in no coupling of the fishery to the biophysical outputs of SEAPODYM and hence no detailed evaluation of current and alternate policies, practices and adaptations to the impacts of climate change.

The most recent projections of climate change on tuna fisheries in the Pacific (Bell et al. 2021) used an ensemble of CMIP5 models coupled to NEMO (ocean) and PISCES (biogeochemical) models to capture differences in the physics used to prepare CMIP Earth System Models. The coupled CMIP models selected were not corrected for regional biases. Operationalizing SEAPODYM will require developing a robust framework to correct bias in CMIP models to downscale them to provide usefully accurate nowcasts, forecast and projections at the scale of national EEZs. Uncertainties in ocean and biogeochemical models have not yet been included in the ensemble. These need to be added to appropriately capture future ocean-climate scenarios for the Pacific Island countries.

The purpose of this annex is to summarise the main features of SEAPODYM, and explain the way in which the proposed investments in the Advanced Warning System in Component B of the Programme will improve the modelling approach so that the participating countries can use SEAPODYM with confidence to identify and implement the adaptations needed to stabilize the revenues they receive from their tuna resources.

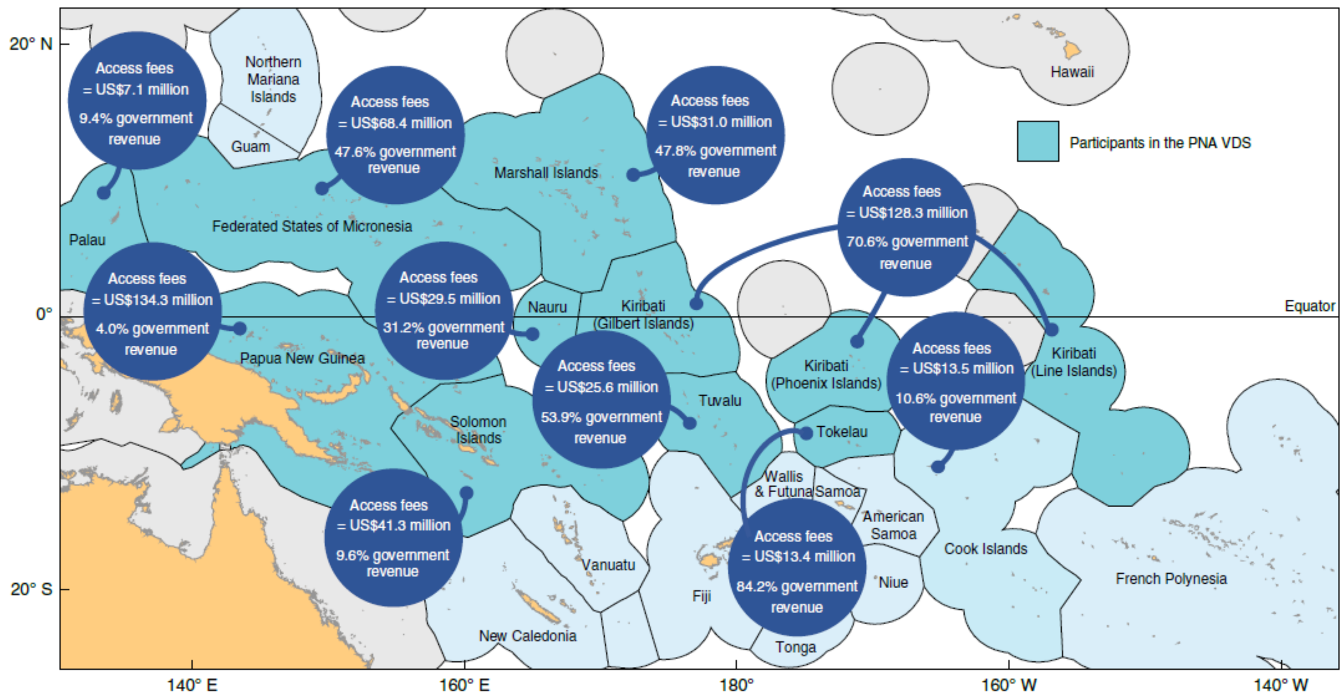


Figure 1. Average annual tuna-fishing access fees (USD) for the period 2015–2018 earned by the nine Pacific Island countries participating in the Programme, together with the average percentage contributions of these access fees to their total government revenue (excluding grants). Note that all these countries, except Cook Islands, also participate in the Parties to the Nauru Agreement (PNA) Vessel Day scheme (VDS) (see Box 1 in Bell et al. 2021 for details, also attached as Appendix 3). The territory of Tokelau also participates in the PNA VDS and has been included here, even though it is not eligible for direct support from the GCF.

2. Existing features of SEAPODYM

The latest version of the SEAPODYM modelling approach is based on a continuous advection-diffusion-reaction (ADR) equation with an ageing term (see SEAPODYM Reference Manual, 2022, https://purl.org/spc/digilib/doc/vxsz3). The SEAPODYM framework includes several models and supports both simulation and parameter estimation runs. The simulation runs are done with dedicated applications and enable:

i) simulation of the full population dynamics model for each tropical tuna species with or without exploitation;

ii) computation of the movement dynamics of tagged cohorts of modelled tuna species;

iii) simulation of the spawning and feeding habitats of tuna species; and

iv) evaluation of stock connectivity between regions of the tropical Pacific Ocean and between the EEZs of Pacific Island countries.

Parameter estimation is based on the maximum likelihood estimation approach and can be executed with applications i), ii) and iii) above. Four types of data are currently integrated to inform model parameters across age, time, and space dimensions: catch, length frequency of catch, conventional tagging data, and data on early life stages (e.g., eggs, larvae, spawning status of adult female gonads). Note that there are currently no data available to validate absolute biomass estimation.

Parameter estimation is conducted using a local optimization method, the iterative quasi-Newton method, with an exact, analytical gradient of the likelihood function provided by the model's adjoint code. Additional tools to facilitate unbiased parameter estimation include:

i) local and global sensitivity analyses,

ii) parameter correlations and error analysis,

iii) identical twin experiments,

iv) likelihood profiling, and

v) model validation.

The SEAPODYM computer code implements a numerical solver for partial differential equations (PDEs) with initial and boundary conditions discretized on a regular grid and approximated using the finite-difference method (fully described in Chapter 2 of the SEAPODYM Reference Manual, 2022). The time derivatives are approximated using an implicit Euler scheme in two half-steps, resulting in the spatial operator splitting in the x and y dimensions. Then the integration is done by applying the alternate-direction implicit (ADI) method. The age dimension is discretized into age classes, and the age derivative is approximated with the first-order finite difference outside of the iterative ADI solver. Currently, the model applications are single-threaded, meaning that only one central processing unit is used to execute an instance of the model (note: code modification to facilitate parallel processing has been designed but not yet implemented).

3. Component B of the Programme

Component B of the GCF Funding Proposal builds on the existing SEAPODYM infrastructure to operationalise SEAPODYM within an Advanced Warning System that tuna-dependent countries can use to develop policies and adaptations that build climate resilience into their tuna fisheries. The work program includes four focal areas: (1) operational oceanography for regional-scale application in the Pacific; (2) refining the SEAPODYM code for EEZ-scale nowcast and forecasts; (3) fleet dynamics and economic models to provide short-, medium- and long-term policy evaluation and adaptation formulation; and (4) provision of observational data to validate EEZ-scale outputs of SEAPODYM and the fleet dynamics and economic models.

3.1 Proposed improvements to operational oceanography

Three workstreams are planned to enable the operationalisation of the Advanced Warning System. Workstream 1 will focus on developing and applying an operational framework to mitigate the influence of present-day biases in Earth System Models (ESMs) on future regional ocean physical and biogeochemical projections. Present-day biases in ESMs can significantly compromise the reliability of regional projections. For instance, the strong cold-tongue bias in the IPSL-CM6A-LR model leads to greater warming and chlorophyll decrease in the western equatorial Pacific Ocean compared to the eastern region, whereas bias-corrected simulations show opposite patterns. Current research has focused on applying corrections in the bulk formulae and to flux perturbations (i.e., developing an oceanic counterpart of dynamical atmospheric approaches to mitigate the influence of background atmospheric biases on future atmospheric projections). Operationalising these methods will be a central activity of this workstream. Regionalizing ESMs is an active research area in oceanography and the framework will remain flexible to new and novel approaches to bias correction.

Workstream 2 will focus on improvements to the historical environmental forcings used to optimise parameters in the SEAPODYM model. Extending the historical time-series (i.e., to periods before satellite observation) in the atmospheric reanalysis models (e.g., ERA-Interim, ERA5, JRA55) facilitates splitting the historical period into training and validation periods allowing for improved optimisation of the SEAPODYM models. Atmospheric reanalysis models used for optimisation are subject to bias which requires correction before application in SEAPODYM. Operationalizing this bias correction will be an important component of this workstream. Development of historical forcings using ERA6 is scheduled for the early years during implementation of the GCF Programme. ERA6 will be a coupled reanalysis, using both atmospheric and ocean observations and is expected to be available in 2026. ERA6 has the potential to generate an even more balanced and consistent Earth System climate reconstruction. Historical forcing generated from higher-resolution reanalyses (e.g,. GLORYS) will be prepared for downscaled EEZ-scale hindcasts. Environmental forcing for forecasting will need to be developed under this workstream to provide the AWS with this capacity

Workstream 3 will focus on inclusion of additional biogeochemical (BGC) models to the environmental forcing ensemble. BGC models provide a framework to integrate chlorophyll-a, nutrients, carbon, and oxygen cycles to estimate lower trophic level structure and function in marine ecosystems. They are the foundation for estimating the distribution and abundance of tuna prey in the SEAPODYM model. PISCES has been the only BGC used in SEAPODYM to date. Workstream 3 will add the WOMBAT BGC to the ensemble. It also includes validation of BGC outputs and assimilation of observation data with lower- and mid-trophic biomass estimates from SEAPODYM. This later task is necessary for identifying and quantifying uncertainty in prey field estimation.

3.2 Proposed improvements to SEAPODYM

Two workstreams are planned to improve the SEAPODYM model:

1. Developing a more realistic model structure to account for variable growth of tuna depending on their feeding conditions. This is essential for accurately representing differences in tuna weight-at-age measurements observed in various oceanic areas with distinct ecosystem traits and productivity.
2. Refining the model resolutions to improve spatial variability and to better estimate tuna abundance at smaller scales, such as EEZs, as well as regionally.

However, these improvements cannot be achieved without first parallelizing the model's computer code. Parallelization strategies have already been proposed, and this work is expected to begin upon implementation of the GCF Programme in 2025. Parallelization experiments indicate that a speedup of 70-90 times from the current sequential processing can be achieved using 76-151 processors, respectively. The implementation of SEAPODYM parallelization and improvements to the numerical solver will need to be done in several stages and will take 1-2 years to complete. After this, it will be possible to proceed to high-resolution simulations. Further development of variable growth (Item 1) will be the next priority, focusing on improving reference models and quantitative model applications to tuna populations by integrating available observations from industrial fishing, port sampling, and scientific campaigns. This work is expected to take another 3 years.

3.3 Proposed development of fleet dynamics and economic models

This workstream will establish a fleet dynamics model suitable for evaluating the impacts of climate change on Pacific tuna fisheries. Two complementary approaches will be undertaken. The first will focus on econometric (or similar) models that integrate environmental, fleet behavior and cost structures to identify the underlying drivers of fishing decisions. This set of models will also facilitate the provision of short-term outlooks to guide application of short-duration adaptive responses to changing fishing activity. The second approach will focus on coupling fleet dynamics to the SEAPODYM model to facilitate projection of the dual impact of fishing and climate change on fishery economic performance (at both regional and EEZ scales). The coupled model will facilitate detailed evaluation of current and alternate policies, practices, and adaptations to the impacts of climate change across short-, medium-, and long-term time horizons.

3.4 Provision of observational data to validate EEZ scale outputs

This last component of work will provide the necessary observational data to validate AWS outputs. Three workstream will be implemented. The first will apply modern methods to estimate the absolute abundances of tuna and the population structure of tuna in the Pacific Ocean. Validating abundance estimates is necessary for estimating the realistic impacts of tuna redistribution on the expected economic returns for each participating country and to evaluate the performance of alternate policy and adaptive measures. Quantifying tuna population structure similarly is necessary for establishing the potential impacts of shifting tuna distributions. Methods to quantify each of these needs have been established. The GCF Programme will roll out the implementation of these methods. Population structure is expected to be resolved in the first 3 years of the project. Absolute abundance monitoring is expected to be an ongoing activity. The second workstream will focus on the collection of market and vessel data necessary to parameterize and validate the fleet dynamics models. Methods for this form of data collection have been established with their roll-out will be ongoing throughout implementation of the Programme.

The third workstream will focus on supporting ocean monitoring data collection by fishing vessels and fisheries observers. Two priority data needs will be the focus: acoustic measurements of tuna prey; and water temperature profiles. Methods for these forms of data collection have been established along with the necessary processes for post-collection data processing and dissemination for use in model validation and assimilation. The roll-out of these methods will also be ongoing throughout the Programme.

4. Summary of benefits of the investments to be made in the AWS

The benefits expected to stem from the proposed improvements to the SEAPODYM modeling approach upon the completion of the 7-year implementation of the proposed activities to develop the AWS are summarized below.

1. The spatial resolution of the model will be improved dramatically – the current resolution of SEAPODYM (2° x 2°) is expected to be increased to at least 1° x 1° for projection and finer resolutions for nowcasts, forecasts and hindcasts. This will enable changes in the biomass of each of the four tropical tuna species in the EEZs of every Pacific Island country to be estimated with greater precision and confidence under multiple SSP climate scenarios. Furthermore, using the high-resolution simulations, it should be possible to identify 'hotspots' in the distribution of tuna biomass within the EEZs with sufficient certainty to plan fishing operations and associated investments, even for countries with relatively small EEZs, e.g. Samoa.

2. In addition to finer-scale projections of spatial changes in biomass for each tuna species on time scales of 2-3 decades, forecasts of changes in tuna biomass within EEZs in timeframes of 0.5 to 10 years will be possible for the first time due to the investments described above.

The improvements described above will enable the economists at the Forum Fisheries Agency (FFA) to develop sophisticated fleet dynamics models that forecast the economic implications of near-term changes in fishing effort and catch based on the finer-scale spatial and temporal simulations of the biomass distribution for each of the four tropical tuna species. This will improve the efficiency of fishing operations and enable countries to understand the attractiveness of their EEZs to industry with much greater certainty and adjust access fees accordingly. It will also provide much greater certainty about the extent to which tuna biomass, and fishing effort, are likely to be redistributed from the combined EEZs of the tuna-dependent economies (where 95% of the tuna from the entire Pacific Island region is currently caught) to high seas areas, where the countries do not yet have much control of fishing operations. This information will be vital to developing the adaptations that the tuna-dependent countries will need to retain the present-day benefits they receive from their tuna resources, regardless of the effects of climate change on the distribution of the fish. These adaptations will centre around the international negotiations required to raise awareness of the vital importance of tuna to the economies of Pacific Island countries and the need to find equitable solutions to the problems that climate-driven tuna redistribution will cause.

The work to be done on stock structure during development of the Advanced Warning System promises to play an important role in reducing uncertainty in the future distribution of tuna biomass even further. At present, much of the tuna science used to inform SEAPODYM assumes that each tropical tuna species forms one large panmictic (mixed) population across the tropical Pacific Ocean. It is now evident through the work of Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), one of the Implementing Partners for the Programme, that for yellowfin tuna at least there could be multiple self-replenishing populations within the geographical distribution of the species across the Pacific Ocean (Moore et al. 2020a,b).

The comprehensive collection of tissue samples from tuna species will determine the extent and nature of their spatial population structure across the tropical Pacific Ocean. Where strong spatial structuring exists, SEAPODYM can then be applied to each stock and, if multiple stocks occur in countries with large EEZs, the accuracy of projected changes in biomass will be improved by integrating the results from simulations of each stock. This work will also cast new light on the extent to which discrete tuna stocks may be shared by the two Regional Fisheries Management Organisations (RFMOs) with responsibility for tuna in the Pacific Ocean: the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC). Where the distribution of a stock spans the jurisdictions of WCPFC and IATTC the results of the AWS will empower the two RFMOs to manage the resource more effectively, both in the shorter term and throughout redistribution of stocks due to climate change (Goodman et al. 2022).

Economic Benefits:

As a result of the combined grant and co-finance USD 92,104,963 investment in the AWS, the fourteen participating countries will benefit from science-based forecasts and projections that provide climate intelligence to facilitate strategic and tactical decisions that maximise sustainable economic returns to government and the industries they support. The combined government revenues derived by the nine-tuna dependent economies from the sale of tuna access fees are currently projected to decrease between 8-17% per year by 2050 due to climate change. This estimate is based on course resolution models that examine ocean basin-scale trends. These models ignore the meso-scale features that correlate with fishing activity and exclude economic measures that determine fishery performance. In this context, the estimates have been very effective at raising the alarm on some of the likely impacts of climate change on tuna distribution and derived revenues but contribute little to assisting with developing suitable adaptations. The AWS provides that capability.

Economic Benefits derived from Forecasting Capability

The Vessel Day Scheme has increased revenue from tuna fisheries in the eight PNA countries to which it applies from US$60 million to over $500 million since its inception. This benefit has largely been due to the capping of available fishing effort. The day trading component of the

VDS is relatively immature because tools for Pacific Island governments to have reliable three-to-six-month forecasts of tuna distribution are not available. Maturing the trading aspect of the VDS, through the forecasting capability of the AWS, is expected to increase current revenue returns by 5-15 % per year.[1]

Forecasting capability for the remaining six participating countries is also expected to improve revenue derived for the tuna fisheries operating in their EEZ and the high seas. Greater certainty on the likely demand for longline transshipment and containerisation sites will provide opportunities for negotiation of more secure joint ventures and port access. Increases of 8-12% per year[2] on current returns are expected.

Economic Benefits derived from Projection Capability

Capacity for medium (3-10 year) and more robust longer term (30-50 year) projection of tuna distribution and fleet dynamics by the AWS is expected. Pacific Island Countries have identified a need to adopt a 'hubs & spokes' approach to maximise economic returns from tuna through participation across the entire value chain. The AWS will enable national fisheries agencies, and the regional fisheries agencies that support them, to understand the effects of ocean warming on the distribution, abundance and economic drivers of their tuna fisheries with greater certainty. This in-turn is expected to contribute to enhanced investment and infrastructure planning, reducing risk of policy and market failure. By way of example, the implementation of the East New Britain Initiative (coinciding with the project implementation) is expected to substantially increase the economic value of the fishery over the coming decades[3].

The reduction in uncertainties provided by the AWS will enable appropriate adaptations to be made with greater confidence at appropriate times, minimising avoidable costs and maximising opportunities. Strengthened capacity to negotiate to retain present-day access, regardless of the redistribution of the fish, will facilitate the minimisation of avoidable costs. Success with

---

[1] Two different approaches applied (very back of envelope) using a mix of public and confidential private data (notably estimates of fleet profitability and VDS prices). Method 1: assumes forecasting could raise the average price of a vessel day in the VDS to $11,500 to $12,500 per day, increasing the combined revenue of PNA members by between $25 and $70 million, respectively. Method 2: Assumes a higher proportion of days sold at the top end, lifting the weighted average price from about $11,000 to $12,560. Some justifications for price increase:

- Indications of prices in excess of $14,000 per day being charged (current average price around $11,000 with indication prices can be as low as $9000)
- Fleets are highly profitable, with scope to absorb higher prices (internal financial modelling)
- Improved forecasting will reduce uncertainty (including for vessel operators)
- By better aligning vessel day availability with optimal fishing conditions, demand increases, allowing for prices to move closer to the higher end of the current range.

[2] The key benefit of improved forecasts lies in enhancing the overall efficiency of fishing operations, particularly for operators. This leads to higher CPUE, increased profitability, and ultimately allows governments to extract more rents. A 5-15% increase in CPUE with a 0.8 multiplier for government revenues has been assumed. This estimate is based on non-PNA members' average catch value and the corresponding government revenues, which typically represent 5% of the catch value. It is worth noting the 8-12% increase in revenues is only about $600,000 - 850,000 USD per year given the low overall value of government revenues to non-PNA members from longline fishing. Applying this approach, the average catch value (10 year) = ~ $141 million and the average Government Revenue (10 year) = ~$7.05 million. Without accounting for downstream benefits (and other factors unrelated to potential changes in CPUE), these numbers are likely an underestimate.

[3] Note the ENBI is currently undergoing economic evaluation, so we are under instruction that an estimate is not yet available

such negotiations will enable the countries to obtain an equitable return from fishing access fees available from the fishing industry.

Advance information on tuna redistribution will also enable the subtropical countries to prepare to capture increased benefit from tuna if the AWS confirms that there will be more tuna in their waters in the future. While the level of return is not expected to be as large as occurred with the introduction of the VDS, a 1.5-fold increase in the revenue derived can be expected for these countries.[4]

A significant benefit will arise as a result of increased confidence in forecasting national budget revenue. In the past, revenue projections have relied on performance in previous years. Over the duration of the implementation of the GCF Regional Tuna Programme, it is anticipated Programme-supported improvements in both the quality of data and the veracity of oceanographic and climate models will lead to significant improvements in revenue forecasts for each EEZ for the participating countries. As a consequence, participating countries will have increased confidence in preparing forward estimates for key Government services and infrastructure.

Overall, a fully operational AWS is expected to return a minimum of approximately $40 million per year in additional revenue to the combined economies of the participating countries.

[4] The purse-seine VDS led to an almost tenfold increase in revenue, rising from $60 million to $500 million. The total catch value for longline fisheries among FFA members averages around $460 million annually, with government revenue at approximately $23 million (assuming a 5% capture of catch value). Estimating potential revenue scaling for longline fisheries relative to purse seine is challenging, given that a greater proportion of longline fishing grounds occur in the high seas (and thus are unable to extract substantially higher rents relative to the purse-seine fishery due to high seas spill over). Nonetheless, some additional rents are expected regionally (as well as smoothing of distributions impacts). Assuming a 1.5 multiplier (as opposed to about 8.5 for the purse-seine fishery), government revenue from longline fishing would increase by approximately $11.5 million per year.

5. References

Bell, J.D., Senina, I., Adams, T., Aumont, O. et al. (2021). Pathways to sustaining tuna-dependent Pacific Island economies during climate change. *Nature Sustainability*, 4, 900–910. https://doi.org/10.1038/s41893-021-00745-z

Goodman, C., Davis, R., Azmi, K., Bell, J. et al. (2022). Enhancing cooperative responses by regional fisheries management organisations to climate-driven redistribution of tropical Pacific tuna stocks. *Frontiers in Marine Science*, https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2022.1046018/full

Lehodey P., Senina I., Murtugudde R. (2008). A Spatial Ecosystem And Populations Dynamics Model (SEAPODYM) - Modelling of tuna and tuna-like populations. *Progress in Oceanography*, 78, 304-318, https://doi.org/10.1016/j.pocean.2008.06.004

Lehodey P., Murtugudde R., Senina I. (2010a). Bridging the gap from ocean models to population dynamics of large marine predators: a model of mid-trophic functional groups. *Progress in Oceanography*, 84,69–84, https://doi.org/10.1016/j.pocean.2009.09.008

Lehodey, P. et al. (2010b). Preliminary forecasts of population trends for Pacific bigeye tuna under the A2 IPCC scenario. *Progress in Oceanography*, 86, 302–315.

Lehodey P., Hampton J., Brill R.W., Nicol S., Senina I. et al. (2011). Vulnerability of oceanic fisheries in the tropical Pacific to climate change. In Bell J., Johnson JE, Hobday AJ (Ed.), Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community. Noumea New Caledonia. pp. 433-492. https://coastfish.spc.int/component/content/article/412-vulnerability-of-tropical-pacifc-fisheries-and-aquaculture-to-climate-change.html

Lehodey P., Senina I., Calmettes B., Hampton J., Nicol S. (2013). Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. *Climatic Change*, 119,95-109. https://doi.org/10.1007/s10584-012-0595-1

Lehodey P., Senina I., Nicol S., Hampton J. (2015). Modelling the impact of climate change on South Pacific albacore tuna. *Deep Sea Research*, 113, 246–259, https://doi.org/10.1016/j.dsr2.2014.10.028

Lehodey P., Bertrand A., Hobday A., Kiyofuji H., Mc Clatchie S., Menkes C. E., Pilling G., Polovina J., Tommasi D. (2020). ENSO Impact on Marine Fisheries and Ecosystems. In El Niño Southern Oscillation in a Changing Climate. McPhaden M.J., Santoso A. & Cai W. (Ed.). Book Series: *Geophysical Monograph Series*, https://doi.org/10.1002/9781119548164.ch19

Moore, B.R., Bell, J.D., Evans, K., Farley, J. et al. (2020a). Defining the stock structures of key commercial tunas in the Pacific Ocean I: Current knowledge and main uncertainties. *Fisheries Research,* 230, 105525 https://www.sciencedirect.com/science/article/pii/S0165783620300424

Moore, B.R., Adams, T., Allain, V., Bell, J.D. et al. (2020b). Defining the stock structures of key commercial tunas in the Pacific Ocean II: Sampling considerations and future directions. *Fisheries Research*, 230, 105524 10.1016/j.fishres.2020.105524

Ruaia, T., Gu'urau, S. and Wheatley, L. (2022). Economic and Development Indicators and Statistics: Tuna Fisheries of the Western and Central Pacific Ocean 2022. Pacific Islands Forum Fisheries Agency.

Senina, I., Sibert, J. and Lehodey, P. (2008). Parameter investigation for basin-scale ecosystem-linked population models of large pelagic predators: application to skipjack tuna. *Progress in Oceanography,* 78, 319–335. https://www.sciencedirect.com/science/article/abs/pii/S0079661108001171

Senina I., Lehodey P., Calmettes B., Dessert M. et al. (2018). Impact of climate change on tropical tuna species and tuna fisheries in Pacific Island waters and high seas areas. 14th Scientific Committee of the western Central Pacific Fisheries Commission, Busan, Republic of South Korea, 8-16 August 2018. *Working Paper* WCPFC-SC14-2018/ EB-WP-01, 44 pp, https://www.wcpfc.int/node/30981

Senina I., Lehodey P., Sibert J., Hampton J., (2020a). Improving predictions of a spatially explicit fish population dynamics model using tagging data. *Canadian Journal of Aquatic and Fisheries Sciences*, 77, 576-593, https://doi.org/10.1139/cjfas-2018-0470

Senina, I., Lehodey, P., Hampton, J. & Sibert, J. (2020b). Quantitative modelling of the spatial dynamics of South Pacific and Atlantic albacore tuna populations. *Deep Sea Research Part II: Topical Studies in Oceanography*, 175, 104667 https://www.sciencedirect.com/science/article/pii/S0967064519301511

Senina, I., Lehodey, P., Sibert, J. & Hampton, J. (2020c). Integrating tagging and fisheries data into a spatial population dynamics model to improve its predictive skills. *Canadian Journal of Fisheries and Aquatic Sciences*, 77, https://doi.org/10.1139/cjfas-2018-04

Appendix 1: 10-year (2009–2018) average purse-seine tuna catches in tonnes (t) from the exclusive economic zones (EEZs) of tuna-dependent Pacific Island countries (and Tokelau), together with average projected changes to these catches by 2050 in tonnes and percentage terms under RCP8.5 and RCP4.5 (equivalent to SSP5-8.5 and SSP2-4.5) emissions scenarios. Shaded rows are the three EEZ areas of Kiribati, which have been integrated to produce the total for Kiribati; FSM = Federated States of Micronesia (source: Bell et al. 2021).

EEZ	Average catch (t)	RCP8.5 – 2050			RCP4.5 – 2050		
		Catch (t)	Change (t)	Change (%)	Catch (t)	Change (t)	Change (%)
Cook Islands	11,080	10,640	-440	-4.0	12,065	+985	+ 8.9
FSM	178,587	155,407	-23,180	-13.0	173,773	-4,815	-2.7
Kiribati	396,048	363,520	-32,528	-8.2	423,251	+ 27,202	+6.9
Gilbert Islands	(260,073)	(225,177)	(-34,896)	(-13.4)	(278,023)	(+17,950)	(+6.9)
Phoenix Islands	(94,696)	(92,140)	(-2,557)	(-2.7)	(101,132)	(+6,435)	(+6.8)
Line Islands	(41,279)	(46,203)	(+4,924)	(+11.9)	(44,096)	(+2,817)	(+6.8)
Marshall Islands	37,003	36,728	-275	-0.7	37,778	+ 775	+2.1
Nauru	110,794	86,886	-23,908	-21.6	117,059	+6,266	+5.7
Palau	2,655	2,646	-9	-0.3	2,738	+ 82	+3.1
Papua New Guinea	461,032	308,404	-152,628	-33.1	389,654	-71,378	-15.5
Solomon Islands	116,877	86,399	-30,477	-26.1	106,740	-10,137	-8.7
Tokelau	21,392	17,954	-3,438	-16.1	22,610	+1,218	+ 5.7
Tuvalu	73,080	55,992	-17,088	-23.4	75,589	+2,509	+ 3.4
TOTAL EEZs	1,408,548	1,124,577	-283,971	-20.2	1,361,257	-47,291	-3.4

Appendix 2: Average government revenue (excluding grants), tuna-fishing access fees, and the percentage of government revenue derived from access fees, for 10 tuna-dependent Pacific Island economies (including Tokelau) between 2015–2018, together with estimated changes in purse-seine tuna catch, access fees, and the percentage contribution of access fees to government revenue, by 2050 under the RCP8.5 and RCP4.5 (equivalent to SSP5-8.5 and SSP2-4.5) emissions scenarios (source: Bell et al. 2021).

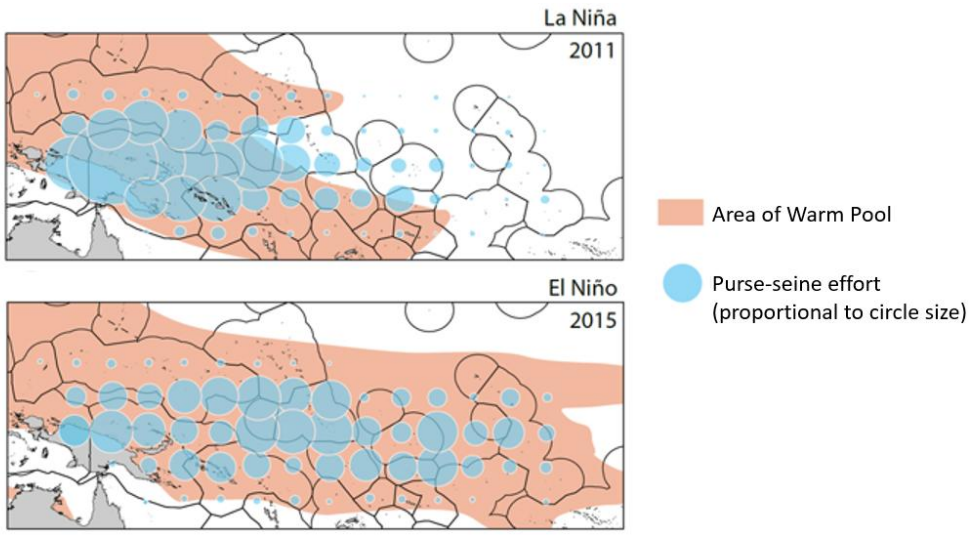
Economy	Average 2015–2018			Change by 2050 (RCP8.5)			Change by 2050 (RCP4.5)		
	Gov't revenue (USD million)	Access fees (USD million)	Gov't revenue (%)	Purse-seine tuna catch (%)[1]	Access fees (USD million)	Gov't revenue (%)	Purse-seine tuna catch (%)[1]	Access fees (USD million)	Gov't revenue (%)
Cook Is.	126.1	13.5	10.6	-4.0	-0.5	-0.4	+8.9	+1.2	+1.0
FSM*	150.6	68.4	47.6	-13.0	-8.9	-5.9	-2.7	-1.8	-1.2
Kiribati	181.7	128.3	70.6	-8.2	-10.5	-5.8	+6.9	+8.9	+4.9
Marshall Is.	66.1	31.0	47.8	-0.7	-0.2	-0.3	+2.1	+0.7	+1.0
Nauru	98.6	29.5	31.1	-21.6	-6.4	-6.5	+5.7	+1.7	+1.7
Palau	75.2	7.1	9.4	-0.3	-0.02	-0.03	+3.1	+0.2	+0.3
PNG**	3360.8	134.3	4.0	-33.1	-44.4	-1.3	-15.5	-20.8	-0.6
Solomon Is.	429.0	41.3	9.6	-26.1	-10.8	-2.5	-8.7	-3.6	-0.8
Tokelau***	16.0	13.4	84.2	-16.1	-2.1	-13.4	+5.7	+0.8	+4.8
Tuvalu	47.4	25.6	53.9	-23.4	-6.0	-12.6	+3.4	+0.9	+1.9
TOTAL		492.4			-89.9			-12.0	

1 = projected change in average total purse-seine catch due to climate-drive redistribution of total tuna biomass (range is given in Supplementary Tables 17 and 18 in Bell et al. 2021); *Federated States of Micronesia; **Papua New Guinea; Tokelau is included here but is a Pacific Island territory and not eligible to receive direct support from GCF

Appendix 3: The Parties to the Nauru Agreement Vessel Day Scheme (source: Box 1 in Bell et al. 2021)

The Pacific Island countries that are the Parties to the Nauru Agreement (PNA) (Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu) have developed a system for jointly managing the purse-seine fishery targeting skipjack tuna within their combined exclusive economic zones (EEZs) called the Vessel Day Scheme (VDS).

The 'cap and trade' VDS sets the total annual purse-seine fishing effort within the combined EEZs of PNA members at ~45,000 fishing days and allocates these days to members based on individual EEZ areas and their past 8–10 years of fishing effort history. The VDS provides a trading mechanism among PNA members, allowing them to respond to the profound effects of the El Niño Southern Oscillation (ENSO) on the Western Pacific Warm Pool and the prime fishing grounds for skipjack tuna. During La Niña events, the best catches of skipjack tuna are made in the west of the region (see left panel in the diagram below), whereas during El Niño events fishing is most efficient up to 4,000 km to the east (see right panel). During La Niña events, the VDS enables countries in the west to buy fishing days from members in the east, enabling fleets to keep fishing in the west. The reverse occurs during El Niño events. Therefore, regardless of where the tuna are caught, all PNA members receive access fees every year. In this way, the VDS evens out the previously high inter-annual variability in access fees received by PNA members and helps stabilize government revenue for tuna-dependent economies.



The various provisions of the VDS, i.e., transferability of fishing days among PNA members, 'pooling' of days by groups of members, and 'roaming' of vessels from PNA member countries among their collective EEZs, also provide non-confrontational adaptations to the progressive redistribution of skipjack tuna within the combined EEZs of PNA members due to ocean warming. However, the VDS does not encompass adaptations for the redistribution of tuna from the EEZs of PNA members to high-seas areas.