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Tongan socio-environmental spatial layers for marine ecosystem management

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Supplementary material

1. Dataset descriptors

a. **Dataset identity**: Tongan socio-environmental spatial layers for marine ecosystem management (TSEL)

Dataset description: Environmental conditions and anthropogenic impacts are key influences on ecological processes and associated ecosystem services. Effective management of Tonga's marine ecosystems therefore depends on accurate and up-to-date knowledge of environmental and anthropogenic variables. Although many types of environmental and anthropogenic data are now available in global layers, they are often inaccessible to end users, particularly in developing countries with limited accessibility and analytical training. Furthermore, the resolution of many global layers might not be sufficient to make informed local decisions. Although the near-shore marine ecosystem of Tonga is extensive, the resources available for its management are limited and little is known about its current ecological state. Here we provide a marine socio-environmental dataset covering Tonga's near-shore marine ecosystem as compiled from various global layers, remote sensing projects, local ministries, and the 2016 national census. The dataset consists of 11 environmental and 6 anthropogenic variables summarized in ecologically relevant ways, spatially overlaid across the near-shore marine ecosystem of Tonga. The environmental variables selected include: bathymetry, coral reef density, distance from deep water, distance from land, distance from major terrestrial inputs, habitat, land area, net primary productivity, salinity, sea surface temperature, and wave energy. The anthropogenic variables selected include: fishing pressure, management status, distance to fish markets, distance from villages, population pressure, and a socioeconomic development index based on population density, growth, mean age, mean education level, and unemployment. This extensive and accessible dataset will be a useful tool for future assessment and management of marine ecosystems in Tonga.

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b. **Dataset identification code**: TSEL v1.1

c. **Latest update:** 04/08/2019

d. **Site description:** This dataset describes the near-shore shallow marine environment of the Kingdom of Tonga as defined as defined by level 4 habitat classification by Andrefouet et al. (2006).

e. **Format and storage mode:** Downloadable copies of dataset can be found at: https://doi.pangaea.de/10.1594/PANGAEA.904800

f. **Projection:** WGS_1984_UTM_Zone_1S

g. **Copyright restrictions:** An end user license agreement must be completed in order to use the bathymetry and habitat layers provided by the Khaled bin Sultan Living Ocean Foundation (Purkis *et al.* 2019). A copy of this user agreement is provided in the online archive. Please email the completed form to dempsey@livingoceansfoundation.org.

   For all additional layers it is requested that the original source material is cited either through this manuscript or the Pangaea citation:

   Smallhorn-West, Patrick F; Gordon, Sophie E; Dempsey, Alexandra C; Purkis, Sam J; Malimali, Siolaa; Halafihi, Tuikolongahau; Southgate, Paul C; Bridge, Tom C L; Pressey, Robert L; Jones, Geoffrey P (2020): Tongan socio-environmental spatial layers for marine ecosystem management.
   PANGAEA, https://doi.pangaea.de/10.1594/PANGAEA.904800

h. **Costs:** None.

i. **File details:** Table 1. Filename, size, source and period of study of each layer in the current dataset

Variable	File name	File size	Environmental/ Anthropogenic	Source	Period of study
Bathymetry	Bathymetry.tif	93.89 Mb	Environmental	Purkis et al. (2019) and	2013
				Land Information New Zealand (LINZ)	2019
Coral reef density	ReefDensity_5km.tif	21.77 Mb	Environmental	Current study	2019
	ReefDensity_15km.tif	39.16 Mb			
Distance to deep water	Distance_10mContour.tif	68.37 Mb	Environmental	Purkis et al. (2019) and current study	2013
	Distance_20mContour.tif	77.99 Mb			
Distance to land	Distance_land.tif	38.70 Mb	Environmental/ Anthropogenic	Current study	2019
Distance to major terrestrial inputs	Distance_lagoons.tif	106.84 Mb	Environmental/ Anthropogenic	Current study	2019
Habitat	TONO_MCRM_Habitat_consolidated.shp	681 Kb	Environmental	Purkis et al. (2019) and MCRMP. Also see Allen	2013
	TOHA_20160603_Habitat_classes_consolidated.shp	156.5 Mb		Coral Atlas (https://www.allencoralatlas.org/atlas)	1999-2001
	TOVA_20161017_Habitat-classes_consolidated.shp	79.8 Mb			
Land area	Land_area5km.tif	24.99 Mb	Environmental	Current study	2019
	Land_area15km.tif	61.70 Mb			
Net primary productivity	NPP.tif	66 Kb	Environmental	Yeager et al. (2017)	1979-2020
Salinity	Salinity.tif	194 Kb	Environmental	Sbrocco and Barber (2013)	1959-2010
Sea surface temperature	SST_tif	258 Kb	Environmental	Sbrocco and Barber (2013)	1959-2010
Wave energy	Wave_Energy_tif	21.12 Mb	Environmental	Current study	2019
				University of Guam Marine Laboratory Wave Energy Tool	
Distance to fish market	Distance_to_market.tif	96.58 Mb	Anthropogenic	Current study	2016
Distance to village	Distance_village.tif	101.03 Mb	Anthropogenic	Current study	2016
Fishing pressure	Fishing_Pressure_Null.tif	31.63 Mb	Anthropogenic	Tongan Census Bureau	2016
	Fishing_Pressure_Old.tif	31.55 Mb			
	Fishing_Pressure_Current.tif	31.53 Mb			
Management status	Fish_Habitat_Reserves.shp	20 Kb	Anthropogenic	Tongan Ministry of Fisheries	2019
	Special_Management_Areas.shp	20 Kb			
Population density	Population_Density_5km.tif	15.40 Mb	Anthropogenic	Tongan Census Bureau	2016
	Population_Density_15km.tif	44.07 Mb			
	Population_Density_30km.tif	47.23 Mb			
Socioeconomic development index	Socioeconomic_Development_2km.tif	29.99 Mb	Anthropogenic	Tongan Census Bureau	2016
	Socioeconomic_Development_5km.tif	32.18 Mb			
	Socioeconomic_Development_10km.tif	35.43 Mb			
Villages	Villages.shp	56 Kb	Anthropogenic	Current study	2016

2. <u>Dataset methodology</u>

2.1 Environmental variables

2.1.1 Bathymetry

Depth is both a crucial determinant of marine community structure (Huston 1985, Brokovich et al. 2008), as well as a mitigation factor from anthropogenic activities (Bridge et al. 2013). The bathymetric profile of Tonga was therefore included as a layer in this dataset. Data describing bathymetry between 0 and -20 m at a resolution of 2 m^2 was obtained from Land Information New Zealand (LINZ) for all island groups of Tonga (Hartmann *et al.* 2018). For the island groups of Vava'u and Ha'apai (excluding the Nomuka group) deeper bathymetric data (0 to -60 m) was available from the Khaled bin Sultan Living Ocean Foundation Global Reef Expedition (KSLOF-GRE, Purkis *et al.* 2019) and was therefore used in preference for these areas.

Bathymetry data created by Purkis *et al.* (2019) was derived via spectral derivation of water depth from WorldView-2 (WV2) satellite imagery. Authors used empirical algorithms described by Stumpf et al. (2003) and Kerr and Purkis (2018) to extract bathymetry data from multispectral WV2 imagery and followed methodology by Kerr and Purkis (2018) to map water depth (see Purkis *et al.* 2019 for more details). For full details of LINZ methods see Hartmann *et al.* (2019).

Original layers from both Linz and Purkis *et al.* (2019) were combined and the resolution reduced to 10 m^2 to limit file size. Pixel resolution reduction was completed using the *Resample* tool with the *cubic* function, before applying a smoother to reduce the effects of rogue pixels.

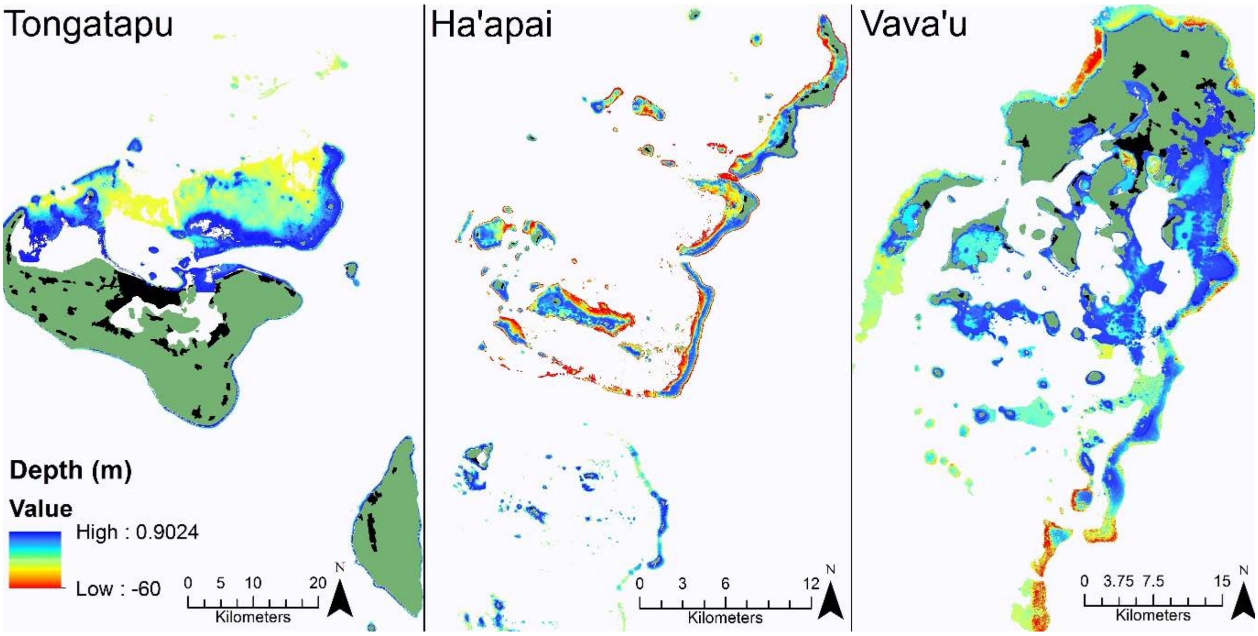


Figure S1. Bathymetric profile of Tonga's shallow water marine environment. Satellite derived bathymetry (SDB) data for Vava'u and Northern Ha'apai were collected by the Khaled bin Sultan Living Ocean Foundation (KSLOF) from 0 – 60 m. Satellite derived bathymetry data for Tongatapu and southern Ha'apai (Nomuka group) were collected by Land Information New Zealand (LINZ) from 0 – 20 m. Green areas represent land and black areas represent villages.

2.1.2 Coral reef density

Coral reef density was calculated as the total area (m^2) of coral reef habitat within a radius from each 10 m^2 pixel defined by a buffer distance of both 5 and 15 km. These distances were selected because they represent the lower and upper range of larval dispersal distances for most reef fish (Green *et al*. 2015) (Fig. S2). Coral reef habitat classification by Purkis et al. (2019) consisted of 36 habitat classes at a resolution of 2 m^2 but was not available for the island groups of Tongatapu or Nomuka (within Ha'apai). For these island groups habitat classification by Andrefouet *et al.* (2006) was used (24 classes, 30 m^2 resolution). While determining the most accurate degree of connectivity between reefs in Tonga will depend on both biophysical modeling of dispersal patterns and genetic parentage analysis, it was beyond the scope of this study to complete a comprehensive assessment of connectivity at this level within Tonga's >15,000 km^2 of reef habitat (Bode *et al.* 2019). These reef density layers therefore represent a first approximation of potential patterns of connectivity.

Reef habitat for Vava'u and Ha'apai was defined from Purkis *et al.* (2019) habitat classification and included the following habitats: shallow fore reef terrace, shallow fore reef slope, reef crest, lagoon pinnacle reefs (massive coral dominated and calcareous red algae conglomerate), lagoon floor bommies, lagoon patch reefs, lagoon fringing reefs, deep forereef slope, back reef pavement, back reef coral framework, and back reef coral bommies. Reef habitat for Tongatapu and Nomuka was defined from Andrefouet *et al.* (2006) habitat classification, and included the following habitats: subtidal reef flat, shallow terrace with constructions, reef flat, forereef on terrace, and fore reef. A raster layer with all included reef layers was generated by assigning a value of 1 to each 10 m^2 pixel containing reef habitat, and a value of 0 for pixels containing non-reef habitat. The *focal statistic* tool was then used to calculate the sum of the number of pixels within a 5 or 15 km radius of each 10 m^2 pixel of reef area in Tonga. The resulting value was then converted to units of m^2.

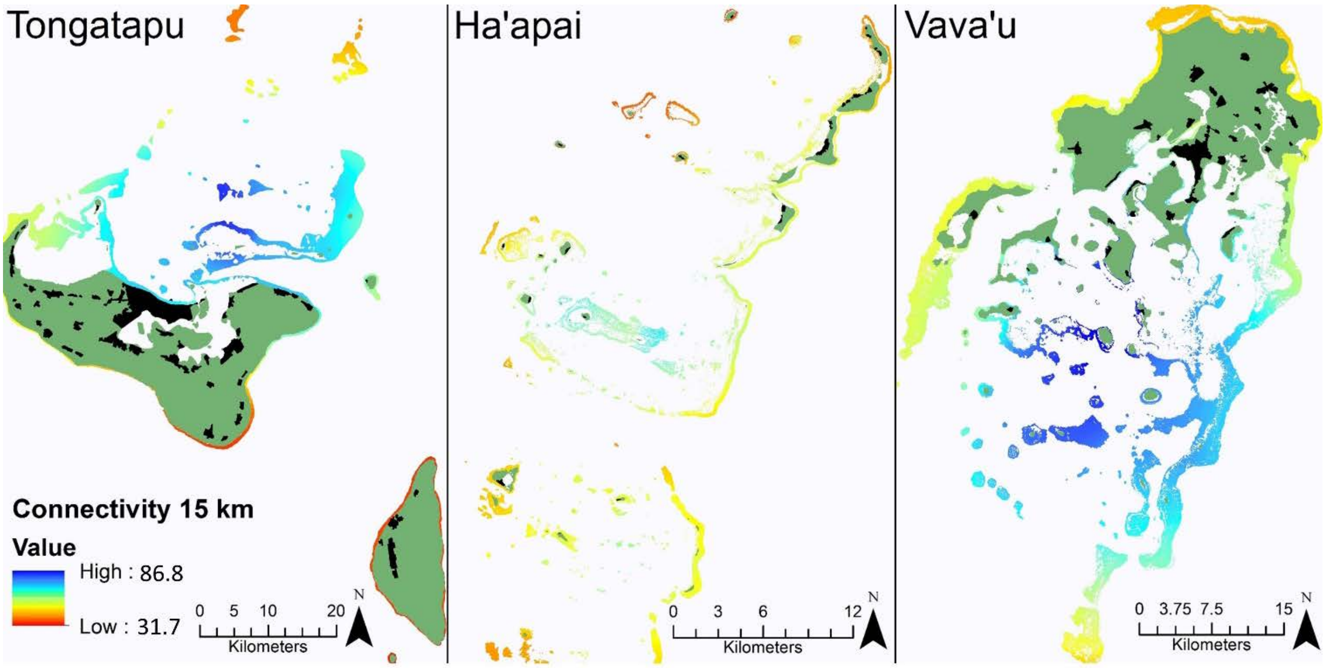


Figure S2. Coral reef density in Tonga measured as the amount of reef habitat in within a 15 km radius of each 10 m^2 reef pixel. An additional layer with a 5 km buffer is also provided in the online data source. Green areas represent land and black areas represent villages.

2.1.3 Distance to deep water

Differences in coral reef community structure can be driven not only by depth, but also the overall depth of the reef system in question (Bak 1977). For example, benthic and reef fish communities at a depth of 4 m in a shallow lagoon may be remarkably different than at the same depth on a deep wall system. Two spatial layers were therefore created describing the distance of each pixel to the 10 and 20 m depth contours respectively (Fig. S3).

First, to minimize the influence of erroneous pixels, the *resample* function (ArcMap V10.4.1) was used to resize bathymetry layers to a resolution of 10 m^2 using the cubic function. A *smoothing* filter was then twice applied twice to further minimize the influence of erroneous pixels on the dataset. The *raster calculator* and *extract by attribute* functions were used to split the bathymetry layers into two layers corresponding to all values shallower and deeper than the specified depth (10 or 20 m). The *Euclidean distance* tool was then used to calculate the distance to the 10 and 20 m depth contour for each pixel shallower than the specified depth. All pixels deeper than the specified depth were designated a value of zero. Lastly, the two resulting layers were merged using the *mosaic to new raster* function. This resulted in a continuous layer with a value of the distance to each depth contour for all pixels shallower than the specified depth, and a value of zero for all pixels deeper than the specified depth.

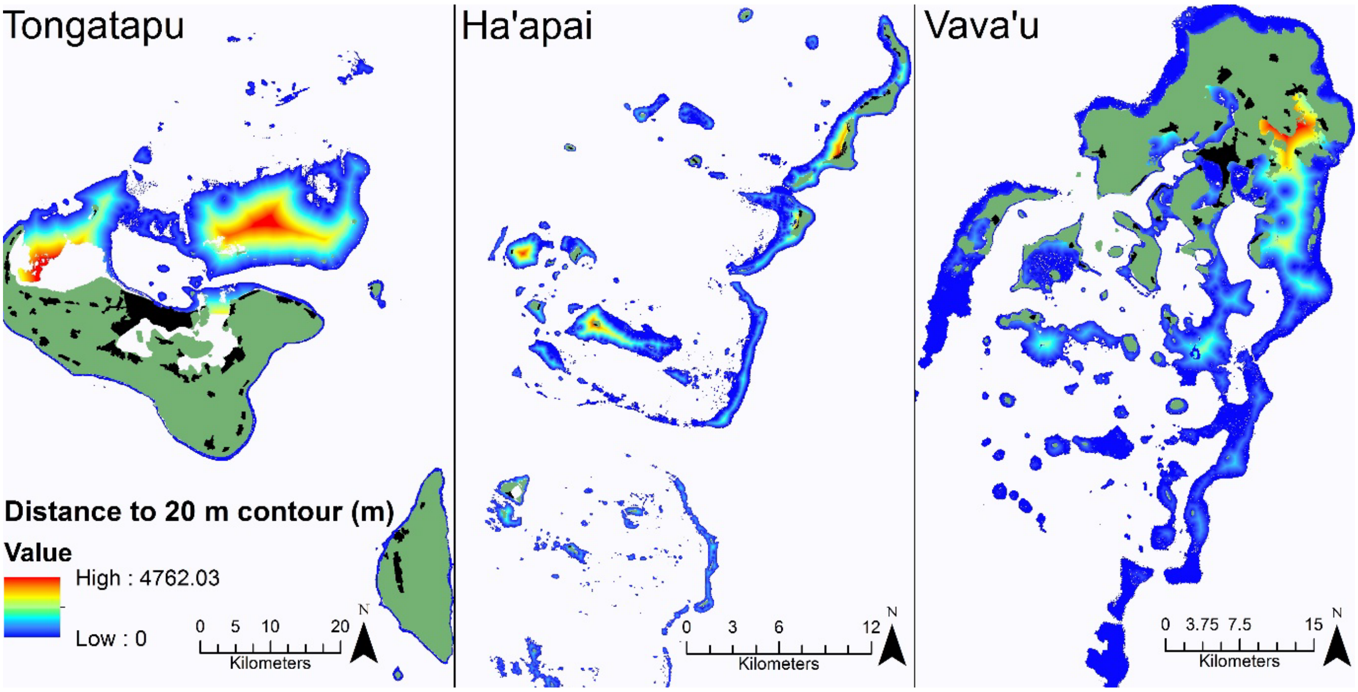


Figure S3. Distance to the 20 m depth contour. Distance to the 10 m depth contour is also provided as an additional layer. Green areas represent land and black areas represent villages.

2.1.4 Distance from land

Distance from land may be an ecologically relevant variable for both environmental and anthropogenic reasons. Firstly, environmental factors such as terrestrial runoff are important drivers in marine processes (Fabricius 2005). In addition, anthropogenic influencesnum may decrease with distance from shore. For example, while most fishing occurs close to villages, fishers in Tonga occasionally set up fishing camps on remote islands. Therefore distance to land, including small islands, could act as a proxy for additional anthropogenic pressures unable to be accounted for by other metrics such as distance from villages or population centres. Distance from land may also be an important consideration for other industries, such as aquaculture, where distance from land may be a more important consideration than distance from village. The distance to the nearest landmass, including small, uninhabited islands was therefore calculated for each 10 m^2 pixel using the *Euclidean distance* function (Fig. S4).

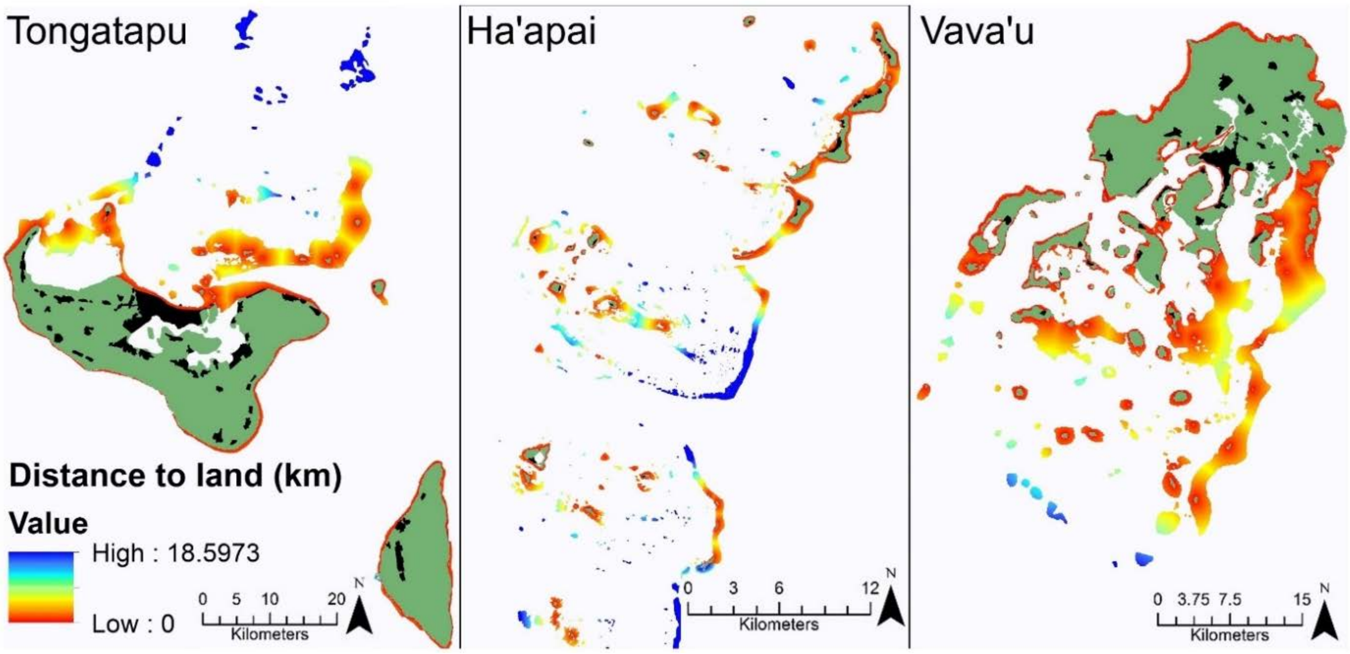


Figure S4. Distance from land for every 10 m^2 pixel of Tonga’s near-shore marine environment. Green areas represent land and black areas represent villages.

2.1.5 Distance from major terrestrial inputs

Terrestrial runoff is a well-established stressor to the marine ecosystem, affecting growth, survival, reproduction, recruitment, and species interactions of a variety marine organisms (Fabricius 2005). Nutrient inputs from land derived sources are commonly detectable in primary producers up to 15 km from shore (Lapointe and Clark 1992; Yeager et al. 2017) and terrestrial-derived dissolved organic nutrients may be detectable 50 km or more from the coast (Delvin and Brodie 2005)

There are five major sources of terrestrial inputs in Tonga. Three large lagoon areas with strong tidal flow occur in Vava'u: near the villages of Taoa, Makave and Koloa, respectively. Two occur in Tongatapu: the main lagoon of Fanga'uta and the tidal flat between villages Puke and Ha'atafu. These five locations are the main sources of terrestrial inputs into the marine environment of Tonga, and likely also sources of both pollution and raw effluent (Aholahi *et al.* 2017). Distance to the nearest major terrestrial input sources was therefore calculated for each 10 m^2 pixel using the *Euclidean distance* function (Fig. S5).

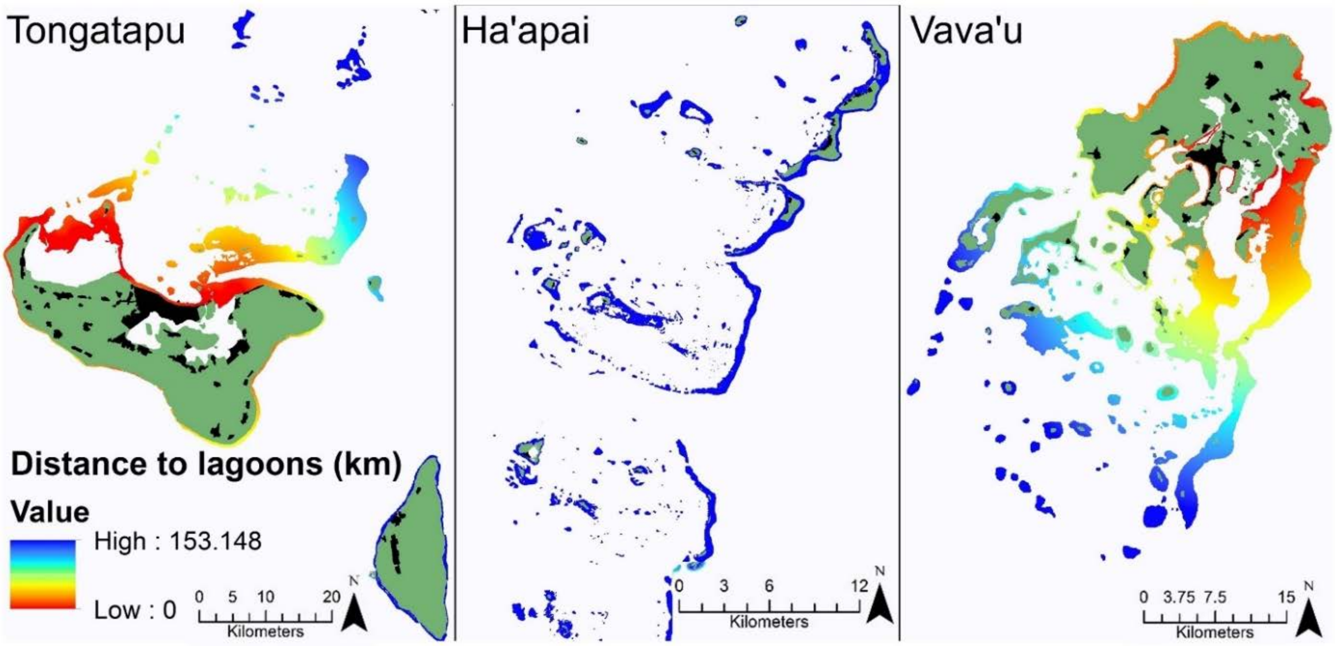


Figure S5. Distance from major terrestrial input sources in meters for every 10 m^2 pixel of Tonga's near-shore marine ecosystem. Green areas represent land and black areas represent villages.

2.1.6 Habitat

Habitat is a crucial determinant of marine ecosystem structure (Coker *et al.* 2014). Marine habitat classification was therefore obtained from Purkis et al. (2019) (Fig. S6) and Andrefouet *et al.* (2006). Purkis et al. (2019) consisted of 36 aggregated map classes at a resolution of 2 m^2 but was not available for the island groups of Tongatapu or Nomuka (within Ha'apai). For these island groups habitat classification by Andrefouet *et al.* (2006) was used (24 classes, 30 m^2 resolution). In addition to the two habitat layers included in this dataset, as of March 2020 the Allen Coral Atlas has also completed habitat maps for Tonga, available to download at: https://www.allencoralatlas.org/atlas

Habitat classification data created by Purkis *et al.* (2019) used eCognition software (v. 5.2, Trimble Inc.) to segment WorldView-2 (WV2) satellite imagery into polygons labelled by zone, structure, and ultimately habitat class. Habitat classification was then calibrated by field observations. Habitat classification by Andrefouet *et al.* (2006) used Landsat 7 ETM+ satellite imagery and habitat classification was determined using image-based criteria to determine geomorphological classes. For a detailed methodology of image acquisition and habitat classification schemes, see Purkis *et al.* (2019) and Andrefouet *et al.* (2006).

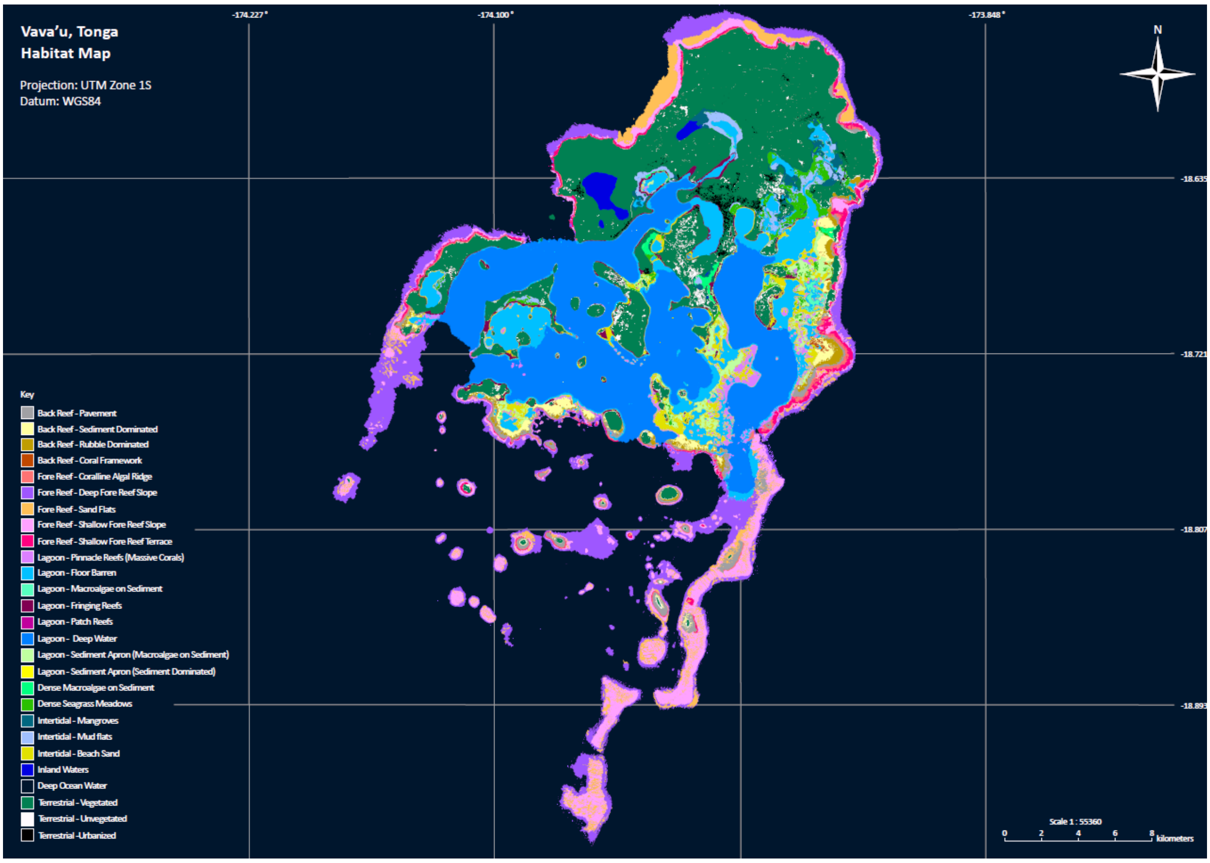


Figure S6. Habitat classification by Purkis *et al.* (2019) for Vava'u. Green areas represent land and black areas represent villages.

2.1.7 Land area

Local marine community structure and productivity may be influenced by terrestrial nutrients and runoff into the marine ecosystem (Fabricius 2005). Total land area, as well as distance from land may therefore also act as a useful metric for the degree of terrestrial influence on near-shore marine ecosystems. The total land area within a 5 and 15 km buffer zone of each 10 m^2 pixel was calculated as an additional proxy for terrestrial influence. Five and 15 km buffers were selected as previous studies found that nutrient inputs from terrestrial sources are commonly detectable in primary producers up to 15 km from shore (Lapointe and Clark 1992). While Yeager et al. (2017) acknowledge that riverine plumes may affect the marine environment up to 50 km from the coast (Delvin and Brodie 2005), in most cases the effects are limited to within ~10 km of shore (Fabricius 2005). A raster layer was generated by assigning values of 1 for all land pixels and values of 0 for all marine pixels. The *focal statistics* tool was then used to calculate the sum of pixel values within a 5 and 15 km radius. Lastly, the *extract by mask* function was used to clip the large resulting layer by the extent of Tonga's near-shore marine ecosystem (Fig. S7).

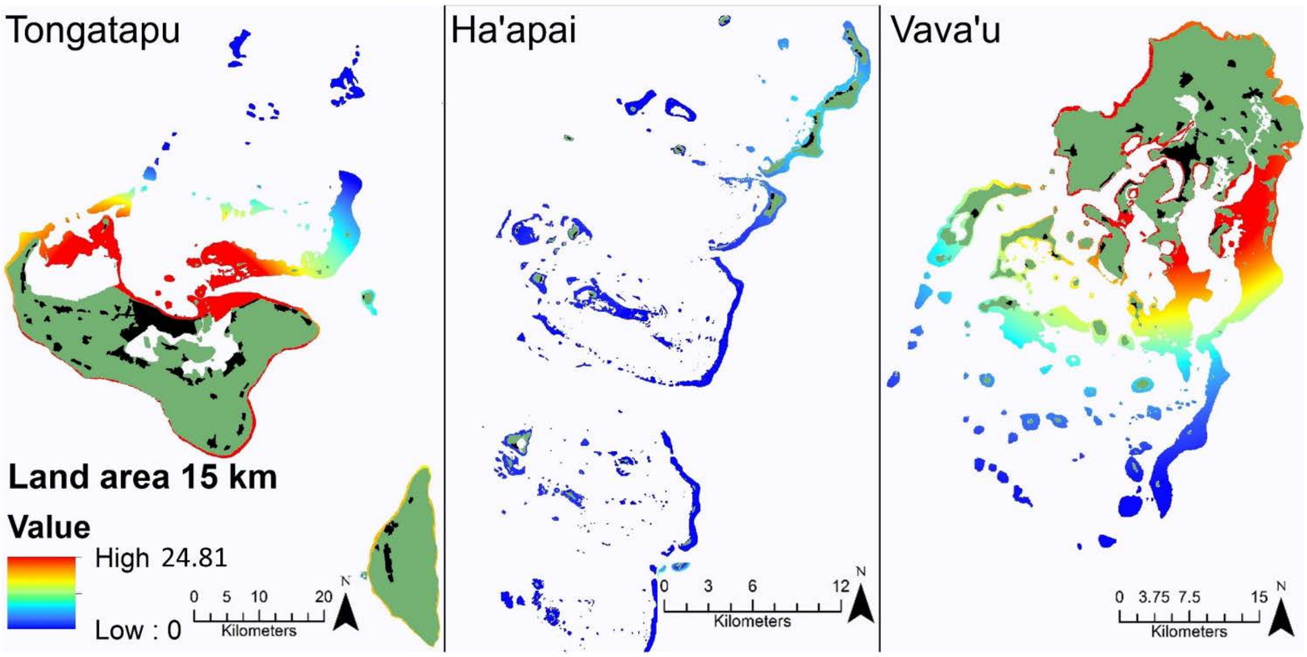


Figure S7. Total land area (km^2) within 15 km of the near-shore marine ecosystem of Tonga. An additional layer with total land area within 5 km is also provided. Green areas represent land and black areas represent villages.

2.1.8 Net primary productivity

Variation in primary productivity can affect the assemblage structure of herbivorous fishes (Mumby et al. 2013) and the total biomass of reef fishes (Williams et al. 2015; Harborne 2016). An oceanic primary productivity layer was therefore extracted from a global layer developed by Yeager *et al.* (2017) to describe the marine ecosystem of Tonga.

Yeager et al. (2017) global layers were developed from 8-day composite layers from 2003-2013 produced by NOAA Coast Watch (http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdPPbfp28day.graph?productivity). The NPP layer was modelled on a 2.5 arcmin grid based on satellite measurements of photosynthetically available radiation (NASA's SeaWiFS), SST (NOAA's National Climactic Data Center Reynolds Optimally-Interpolated SST), and chlorophyll a concentrations (NASA's Aqua MODIS; http://coastwatch.pfeg.noaa.gov/erddap/griddap/erdPPbfp28day.html) (Behrenfeld and Falkowski, 1997). Remotely sensed estimates of productivity over shallow water are confounded by bottom reflectance, so grid cells with a minimum depth of <30 m were filtered out based on the STRM30 plus bathymetry layer (0.5 arcmin resolution, http://topex.ucsd.edu/WWW_html/srtm30_plus.html) following Gove et al. (2013). The values for cells with missing data following filtering were interpolated from the three closest surrounding cells within a 125 km search radius.

The primary productivity of benthic communities can vary at small scales because of differences in wave exposure, light intensity and nutrient concentrations (Harborne 2016). However, high resolution NPP of reef habitat is not possible from remotely sensed data. The Yeager et al. (2017) NPP layer captures larger-scale patterns in productivity across the region and this layer is therefore supplied at a coarse resolution and covers Tonga's nearby oceanic system (approximately 220 km east-west by 330 km north-south (Fig. S8).

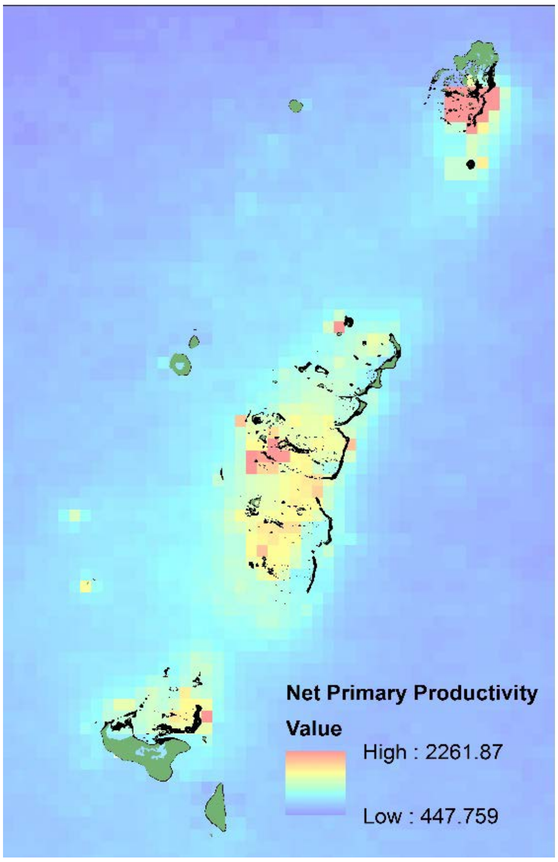


Figure S8. Net Primary Productivity (NPP) of Tonga's marine environment.

2.1.9 Salinity

Environmental fluctuations in salinity strongly affect the physiological functions of marine organisms (e.g. marine bivalves, Lucas 2008) and may structure species assemblages (Barletta et al. 2005). The global layer of sea surface salinity developed by Sbrocco and Barber (2013) shows a small increase in salinity from north to south across Tonga's waters. Despite the minor difference in salinity, this layer was still included to address potential needs of end users. Due to the coarse resolution, the extent of this layer therefore details a broader marine area than previous layers and also includes Tonga's nearby oceanic system (approximately 220 km East-West by 330 km North-South) (Fig. S9).

Measurements of salinity were extracted from the Sbrocco and Barber (2013) global layer of mean sea surface salinity. These values were obtained by Sbrocco and Barber (2013) from in situ oceanographic observations compiled by NOAA's World Ocean Atlas 2009 (WOA09; Antonov et al. 2010). The authors calculated monthly means (measured in practical salinity units) by averaging five "decadal" climatologies at 1 arc-degree resolution for the time periods from 1955 to 2006. These were subsequently smoothed by Sbrocco and Barber (2013) in ArcMap to 30 arc-second grids. The final MARSPEC layer included was the mean annual sea surface salinity in psu at 1 km resolution. Further details can be found in both Sbrocco and Barber (2013) and (Antonov et al. 2010).

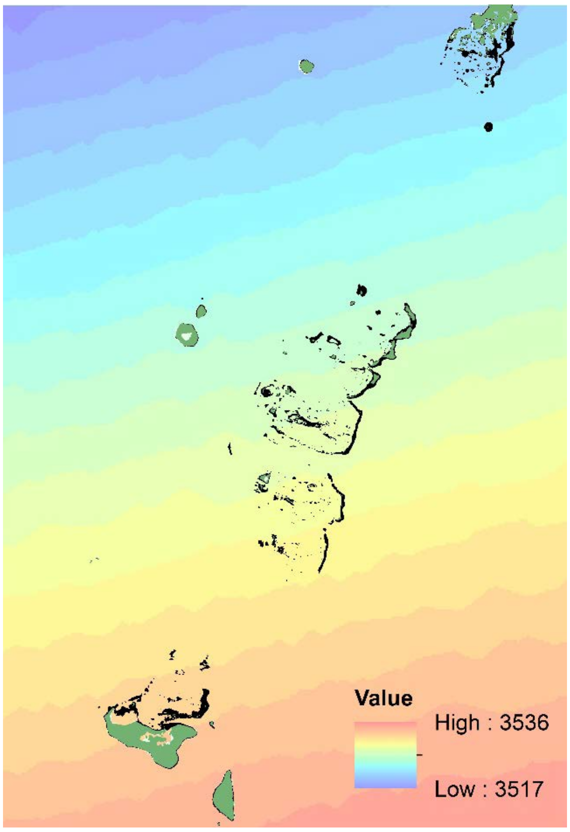


Figure S9. Mean annual salinity of Tonga's marine environment measured in practical salinity units (psu).

2.1.10 Sea surface temperature

Temperature is a primary abiotic factor affecting the physiology of marine organisms (Brett 1971; Harborne 2016), including algal productivity (Hatcher 1990) and thus potentially the demographics of herbivorous fishes (Harborne 2016). The recurrent mass bleaching of coral reefs globally is also directly linked to variability in sea surface temperature (Hughes et al. 2017). Consequently, general patterns of mean sea surface temperature across Tonga were also included in this dataset (Fig. S10).

Coral bleaching events are primarily associated with variability in sea surface temperature, and the metric Degree Heating Weeks (DHW) is commonly used as a proxy for heat stress events. While nine SST variability layers are available from the NOAA coral reef watch website (https://coralreefwatch.noaa.gov/product/thermal_history/index.php), including average time between stress events and number of stress events since 1985, at DHW0, DHW4 and DHW8 respectively, these were not included in the present study.

Mean annual sea surface temperature (SST) was extracted from Sbrocco and Barber (2013) MARSPEC global ocean layers. Sbrocco and Barber (2013)obtained satellite measurements of SST at 2.5 arc-minute resolution (approximately 4 km^2) from Aqua-MODIS 4-micron night-time SST level 3 standard mapped image products, downloaded from NASA's Ocean color website (*http://oceancolor.gsfc.nasa.gov/).* Monthly climatological means from September 2002 to August 2010 were used to calculate mean annual SST. As with NPP and salinity, global layers were clipped by the extent of Tonga's nearshore oceanic environment. Temperature is presented in degrees Celsius.

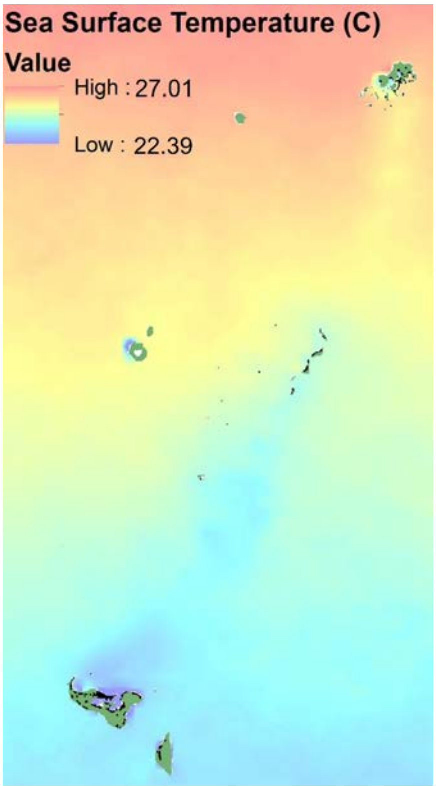


Figure S10. Mean annual sea surface temperature (SST) of Tonga's marine environment in degrees Celsius.

2.1.11 Wave energy

Wave exposure is an important variable structuring coral reef communities (Fulton et al. 2005) and can have significant effects on both fish assemblages and benthic habitat types. Mean wave energy, calculated as joules per square meter, was calculated using the University of Guam Marine Lab (UOGML) Wave Energy Tool (Fig. S11). A detailed description of methodology is provided in Jenness and Houk (2014) and Ekebom et al. (2003). Mean wind speed and direction were calculated from weekly wind speed and direction obtained from QuikSCAT satellite scatterometer data. Land and reef flat habitat layers from Andrefoeut *et al.* (2006) were then used to calculate fetch to the nearest landmass, reef flat or reef crest. Mean wave energy was then calculated using wind speed, direction, fetch and linear wave equations (Ekebom et al. 2003). While this data only accounts for surface wave exposure, it is likely to be a good estimate of the exposure experienced in each cell, since this project is designed for use in shallow-water, near-shore habitats. Due to extended processing times, grid cell size was set to 200 m^2, then outputs smoothed twice using the *filter* function and *resampled* to 10 m with binary weighting to produce a 10 m^2 resolution.

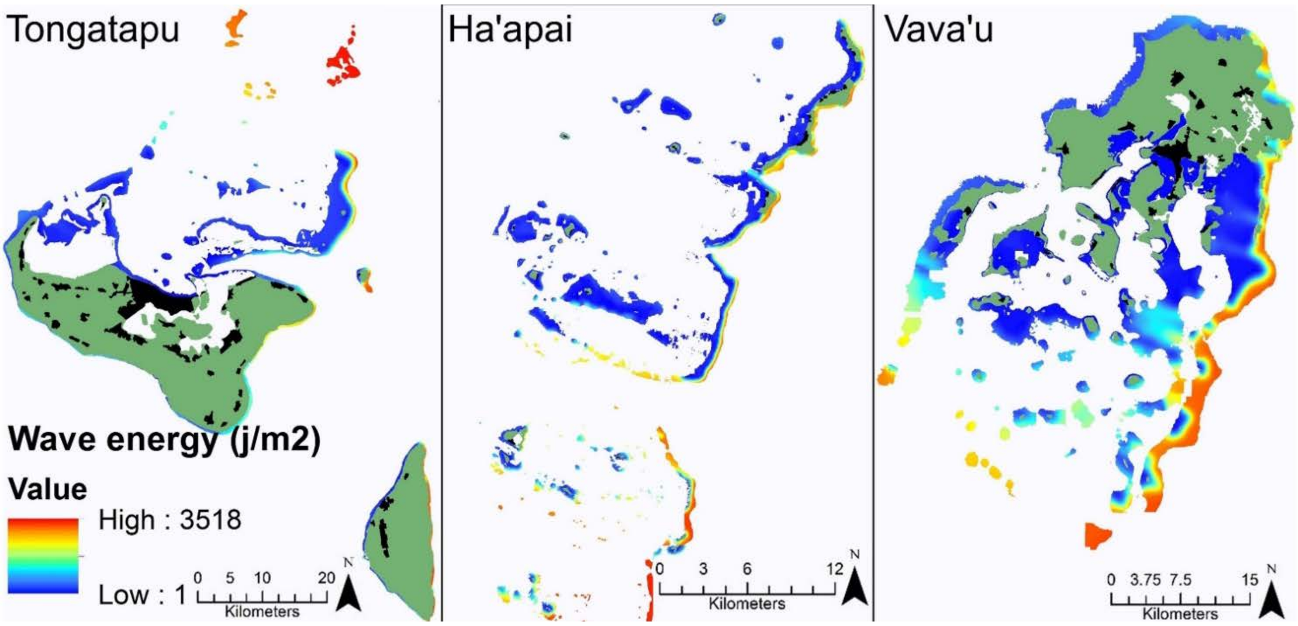


Figure S11. Mean wave energy, calculated as joules per m^2, for each 10 m^2 pixel of Tonga's near-shore shallow marine environment. Green areas represent land and black areas represent villages.

2.2 Anthropogenic variables

2.2.1 Distance from markets

Globally, distance to fish markets has a strong explanatory role in the structure of reef fish biomass (Brewer et al. 2012; Cinner et al. 2013). Market access can also be a better predictor of the condition of reef fish fisheries than the density of local human populations alone (Cinner and McClanahan 2006). Three main fish markets exist in Tonga, associated with the capital of each island group. The Tongatapu fish market is located at the small boats harbor near the Nuku'alofa wharf. The Vava'u fish market is situated at the main commercial wharf in Neiafu. While not permanent, in Ha'apai most reef fish are sold commercially at the Pangai wharf. The distance from the nearest of these three locations to each 10 m^2 pixel (marine extent defined by Andrefouet *et al.* (2006), see extent description in section 2.1.6 Habitat) was calculated using the *Euclidean distance* function (Fig. S12).

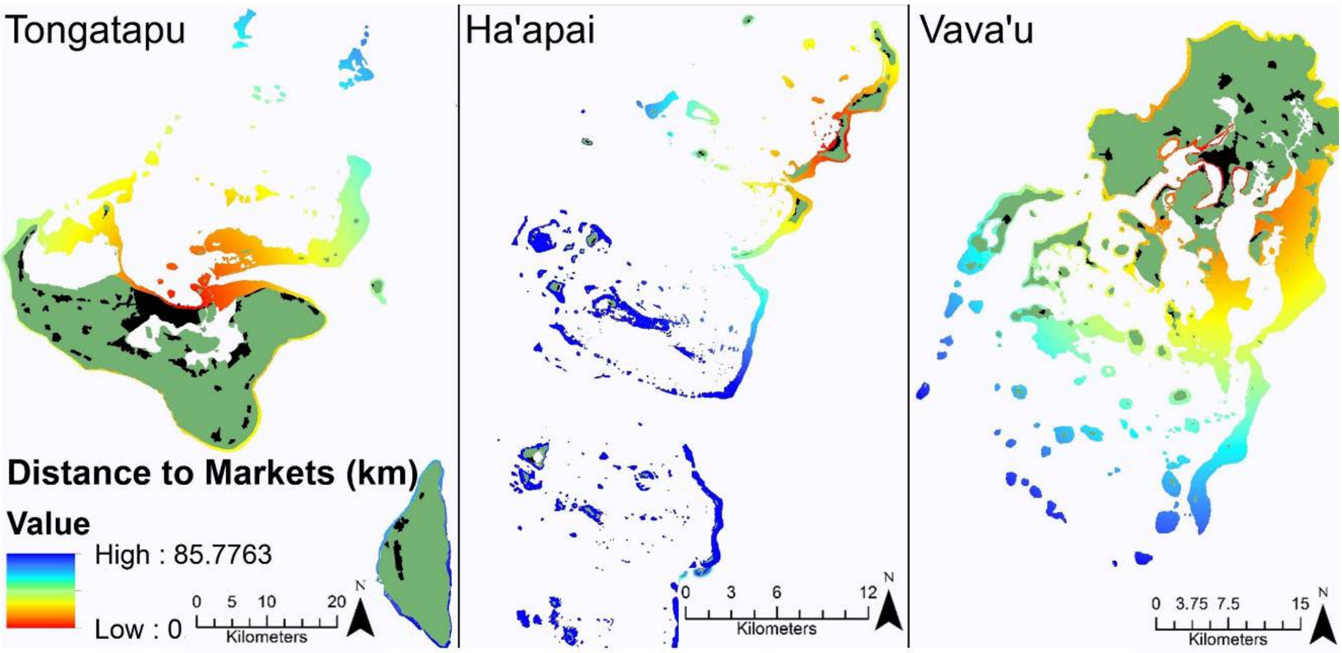


Figure S12. Distance to the three main fish markets for each 10 m^2 pixel of Tonga's near-shore marine environment. Green areas represent land and black areas represent villages.

2.2.2 Fishing pressure

Reef fish fisheries in Polynesia are critical for maintaining livelihoods and food security (Kronen 2004). Fishing pressure is a strong determinant of many metrics of reef health, and one of the most direct ways that humans interact with coral reefs (Cinner et al. 2018). Metrics of fishing pressure are often calculated using fisheries-dependent data (e.g. catch data). However, while some catch data are available from Tonga, they lack the spatial and temporal resolution, wide spread coverage and detail required to build an accurate model of fishing pressure for the entire region. Furthermore, current fishing activities may not be an accurate reflection of long-term trends, as fishers will likely change fishing grounds as stocks become depleted (Ochiewo 2004).The current study therefore used a combination of census data and key informant interviews to build a historical model of relative fishing effort across the reef fish fishing grounds of Tonga (Fig. S13, S14). This model represents a unit-less value of relative fishing effort that assumes fishers minimize travel time and only extend their range as closer stocks become depleted.

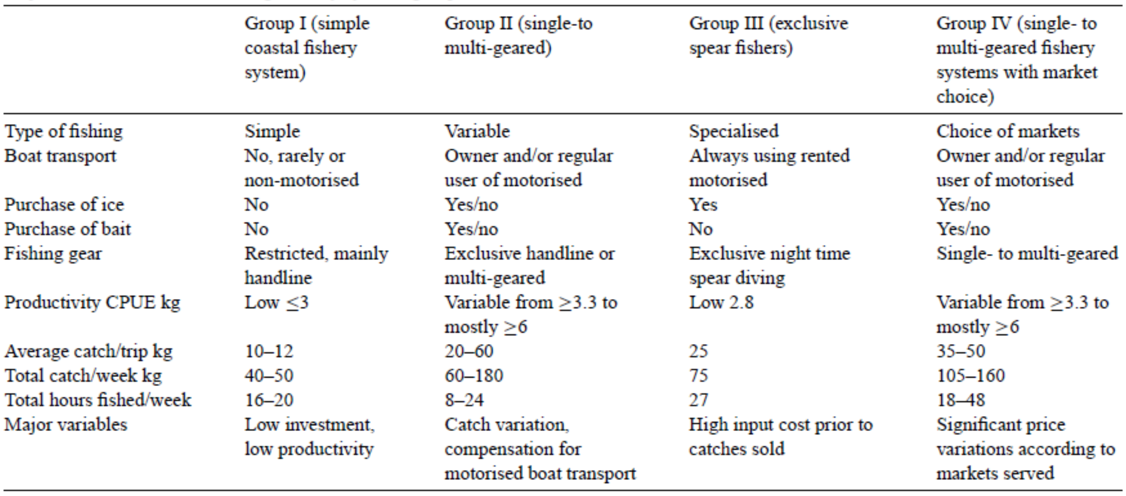
The reef fish fishery in Tonga can be broadly divided into commercial and subsistence fishing, each with different patterns of resource use and behavior (Kronen 2004). Key informant interviews were used to ascertain the specific details of both fishing practices, and took place during regular training meetings between Ministry of Fisheries staff and communities implementing new management areas. Interviews were conducted with both Ministry of Fisheries staff as well as local fishers (who classified themselves as either mostly commercial or mostly subsistence fishers). Twelve fishers from four villages agreed to participate in short informal interviews to discuss their fishing practices (Smallhorn-West et al. 2019). Fishers were asked the type of fishing they engage in, the methods employed and if willing, to outline on a map their fishing grounds.

The 2016 national census reported 2301 individuals in Tonga who identify as fishers. Of these, 1868 fish mainly for subsistence, while the remaining 433 reported fishing predominantly for commercial purposes (Statistics Department Tonga, 2016). Commercial fishing in Tonga is an organized profession, in which groups of fishers go out in boats at night time to fish an area of reef (Kronen 2004, Smallhorn-West *et al.* 2019). Following a night of fishing commercial fishers generally travel to the main fish markets and sell their catch to middlemen who run stalls in town and on roadsides. While commercial fishers also often engage in subsistence fishing, it is rare for subsistence fishers to fish commercially (Kronen 2004, Smallhorn-West *et al.* 2019). Subsistence fishing is here defined as ‘fishing mainly for personal consumption or for that of family or gifts.’ In contrast, subsistence fishing is much more opportunistic. Subsistence fishing is generally shore based and practiced close to the villages, with fishers swimming out from shore (Kronen 2004, Smallhorn-West *et al.* 2019).

Census data and key informant interviews were used to build a model of fishing pressure for Tonga, using similar methodology to Smallhorn-West *et al.* (2019). While village level population data was available from the 2016 national census, only district level data was available on fishing practices. Therefore, the village level abundance of commercial and subsistent fishers targeting reef fish was calculated by: 1) dividing the district level population of commercial and subsistence fishers by the population of each village; 2) multiplying the resulting value by the district level proportion of fishers who target reef fish, and 3) multiplying each value by a constant representing the proportional difference in total catch for each type of fishing, to account for differences in total catch between commercial and subsistent fishers.

An economic assessment of fisheries types in Tonga by Kronen (2004, Table S2) suggested that there was no clear economic distinction between commercial and subsistence coastal fisheries, however both national census data and key informant interviews suggested that fishers consistently identify themselves according to these categories. We therefore categorized Kronen (2004) Group 1 individuals as ‘subsistence’ and Group 3 as ‘commercial’ (Table 2). Group 1 individuals are predominantly shore based and align with subsistence practices. Group 3 fishers are exclusively spear fishers, fishing predominantly at night, which align with key informant interview findings of commercial practices. The proportional difference in catch between groups was calculated using total catch week^{-1} (kg) values of 40 and 75 kg respectively (Kronen 2004, Table S2). The abundance of commercial and subsistence fishers in each village was then multiplied by the proportional difference between these values, centered around 1 (1.30 commercial, 0.695 subsistence). The values for each village therefore represent the number of commercial or subsistence fishers who target reef fish, weighted by proportional differences in total catch (kg week^{-1}).

Table S2. Major characteristics of four Tonga fishery systems groups from Kronen (2004).



	Group I (simple coastal fishery system)	Group II (single-to multi-geared)	Group III (exclusive spear fishers)	Group IV (single- to multi-geared fishery systems with market choice)
Type of fishing	Simple	Variable	Specialised	Choice of markets
Boat transport	No, rarely or non-motorised	Owner and/or regular user of motorised	Always using rented motorised	Owner and/or regular user of motorised
Purchase of ice	No	Yes/no	Yes	Yes/no
Purchase of bait	No	Yes/no	No	Yes/no
Fishing gear	Restricted, mainly handline	Exclusive handline or multi-geared	Exclusive night time spear diving	Single- to multi-geared
Productivity CPUE kg	Low ≤ 3	Variable from ≥ 3.3 to mostly ≥ 6	Low 2.8	Variable from ≥ 3.3 to mostly ≥ 6
Average catch/trip kg	10–12	20–60	25	35–50
Total catch/week kg	40–50	60–180	75	105–160
Total hours fished/week	16–20	8–24	27	18–48
Major variables	Low investment, low productivity	Catch variation, compensation for motorised boat transport	High input cost prior to catches sold	Significant price variations according to markets served

To extrapolate fisher abundance across the reef fish fishing grounds of Tonga, polygons of each village (142 total) were created and converted to points. The fishing grounds for reef fish in Tonga are defined as all reef habitat from Andrefouet *et al.* (2006) and Purkis *et al.* (2019). The *heatmap* function (QGIS V.2.14) was then used to create separate decay kernels that extrapolated the weighted abundance of commercial and subsistence fishers across the reef habitat of Tonga. Key informant interviews established that commercial fishers fish every part of their island group, from inner to outer islands. The decay kernel extent was therefore set to 30 km, corresponding to the outer extent of each island group. Subsistence fishing is generally limited to the waters close by each village, and

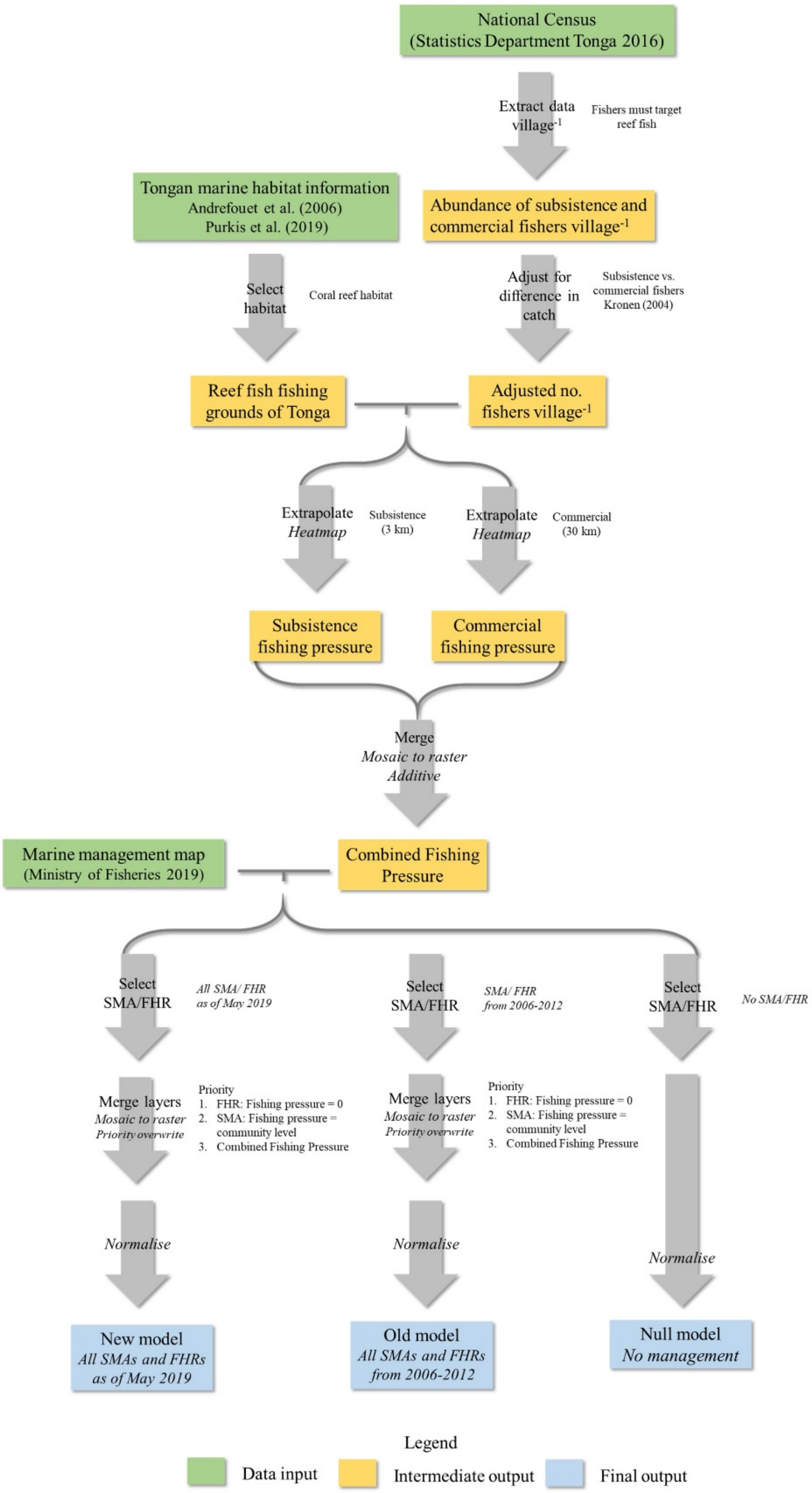


Figure S14. Flow chart representing the steps used to build three fishing pressure models for Tonga.

therefore the kernel extent was set with a cut-off of 3 km around each village. This distance is based on the maximum distance identified as fishing grounds by subsistence fishers during key informant interviews. All values of fishing pressure in Fish Habitat Reserves (FHRs) were set to 0, and Special Management Areas (SMA) values set to the sum of commercial and subsistence fishers from each corresponding SMA. This model therefore assumes full compliance by fishers. One caveat in this model is that many SMAs and FHRs have only been implemented recently and therefore values created might not represent accurate long term trends in fishing effort. The current study therefore also created two additional fishing pressure layers: 1) raw fishing pressure, values without any adjustments for management practices (Null model), and; 2) a layer only including SMAs/FHRs implemented more than five years previously (Old model).

Commercial and subsistence fishing pressure heatmaps, as well as specific fishing pressure values for each FHR and SMA were merged using the *mosaic to new raster* function (ArcMap V10.4.1). This function added commercial and subsistence values together, but overruled them if the area corresponded to an SMA and/or FHR. This raster layer was subsequently clipped by the coral reef habitat of Tonga using the *extract by mask* function. Lastly, these values were normalized to provide values ranging between 0 and 100.

The final fishing pressure metric represents a unit-less value of relative fishing effort throughout the region. This metric assumes that, all else being equal, fishers preferentially select sites closer to home and extend their range as close locations become exhausted. While the model is therefore likely decoupled from current fishing effort, it is nonetheless useful in that it constitutes the historical impact of fishing on reef fish assemblages in Tonga.

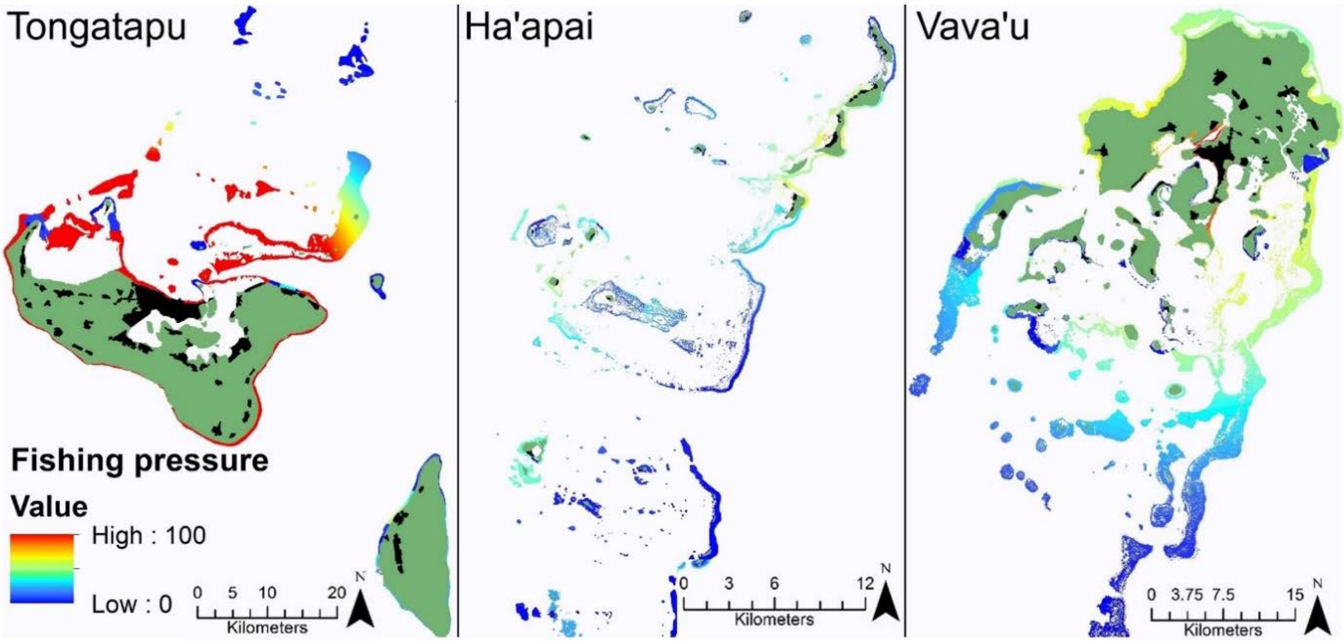


Figure S14. Relative fishing pressure for Tonga's coral reef ecosystem measured as the catch adjusted village level abundance of commercial and subsistence fishers extrapolated across the fishing grounds of Tonga. This figure represents the Current model, which includes all SMAs and FHRs as of 2019. Green areas represent land and black areas represent villages.

2.2.3 Management status

Extensive literature now demonstrates the global importance of marine protected areas as a way to reduce fishing pressure and change coral reef community structure (Lester et al. 2009; Edgar et al. 2014). Historically fishing in Tonga has been open access. In 2002, amid concerns over the depletion of the reef fish fishery, the Tongan Ministry of Fisheries implemented the Special Management Area (SMA) program (Gillett 2017). Special management areas are locally managed marine protected areas comprised of two management components: 1) an exclusive access zone in which only members of the SMA community can fish, and; 2) a permanent no-take Fish Habitat Reserve (FHR) in which no one can fish. While the extent of each SMA is defined by the Ministry of Fisheries, the size and location of the FHR within is determined by the community itself (represented by the SMA committee). It is the responsibility of each community to manage and enforce compliance of fishers within their SMA and FHR. While between 2006 and 2014 only seven SMAs were implemented, recently community demand has increased rapidly, with over 40 new SMAs gazetted in the past five years. Separate polygon layers were created to define the location of SMAs and FHRs, with the area (km^2), perimeter length (km) and year established of each SMA and FHR embedded in the spatial layer (Fig. S15; Table S3).

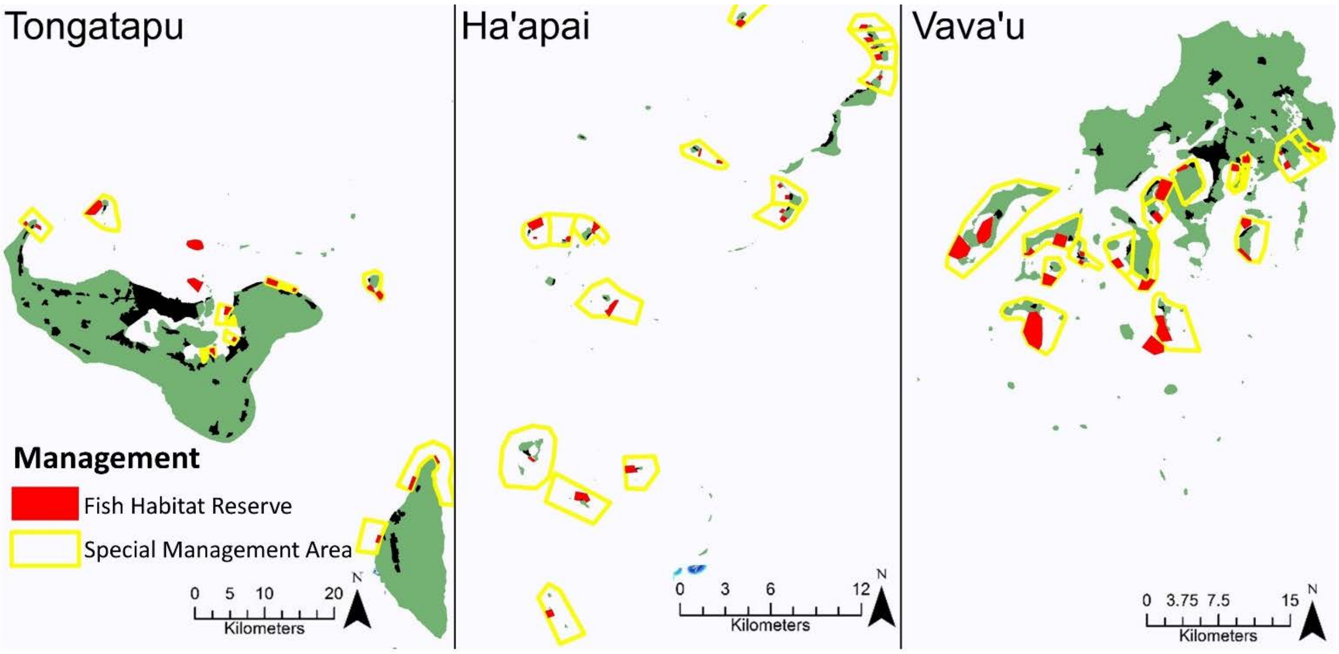


Figure S15. Configuration of Special Management Areas and Fish Habitat Reserves in Tonga. Green areas represent land and black areas represent villages.

Table S3. All special management areas and fish habitat reserves in Tonga as of May 2019.

Name	Island group	Year Established	Area (km2)	Perimeter (km)
Atata FHR	Tongatapu	2008	1.54	5.48
Atata SMA	Tongatapu	2008	8.40	11.46
Eueiki FHR Vavau	Vava’u	2017	1.19	4.37
Euiki FHR 1 Tongatapu	Tongatapu	2008	0.50	2.80
Euiki FHR 2 Tongatapu	Tongatapu	2008	0.37	2.73
Euiki SMA	Tongatapu	2008	3.75	8.36
Fafa FHR	Tongatapu	2014	1.59	4.99
Fakakakai FHR	Ha’apai	2018	0.94	3.93
Fakakakai SMA	Ha’apai	2018	10.74	13.96
Faleloa FHR 1	Ha’apai	2018	0.45	2.72
Faleloa FHR 2	Ha’apai	2018	0.25	2.22
Faleloa SMA	Ha’apai	2018	15.83	16.50
Falevai FHR	Vava’u	2017	0.36	2.49
Falevai SMA	Vava’u	2017	3.98	8.06
Felemea FHR 1	Ha’apai	2008	0.44	2.78
Felemea FHR 2	Ha’apai	2008	0.74	3.51
Felemea SMA	Ha’apai	2008	17.10	17.99
Fonoi FHR	Ha’apai	2017	1.91	6.20
Fonoi SMA	Ha’apai	2017	22.33	18.44
Ha'afeva FHR 1	Ha’apai	2007	0.44	2.75
Ha'afeva FHR 2	Ha’apai	2007	0.95	4.12
Ha'afeva SMA	Ha’apai	2007	14.30	16.69
Ha'ano FHR	Ha’apai	2018	0.87	4.23
Ha'ano SMA	Ha’apai	2018	11.96	17.27
Ha'atafu FHR 1	Tongatapu	2017	0.17	1.62
Ha'atafu FHR 2	Tongatapu	2017	0.24	2.14
Ha'atafu SMA	Tongatapu	2017	5.35	9.58
Holoeva FHR	Vava’u	2019	0.25	2.55
Holoeva SMA	Vava’u	2019	1.50	10.13
Holonga FHR	Tongatapu	2017	0.30	2.42
Holonga SMA	Tongatapu	2017	0.93	5.74
Houma FHR 1	Eua	2019	0.58	3.62
Houma FHR 2	Eua	2019	0.23	2.27
Houma SMA	Eua	2019	17.48	26.75
Hunga FHR 1	Vava’u	2017	1.46	4.84
Hunga FHR 2	Vava’u	2017	1.32	4.77
Hunga SMA	Vava’u	2017	20.73	21.40
Kapa FHR	Vava’u	2019	0.58	3.49
Kapa SMA	Vava’u	2019	2.33	11.60
Kelefesia FHR	Ha’apai	2018	1.31	4.61
Kelefesia SMA	Ha’apai	2018	32.72	24.31
Koloa FHR 1	Vava’u	2017	0.06	0.99
Koloa FHR 2	Vava’u	2017	0.20	1.82
Koloa SMA	Vava’u	2017	4.52	8.42
Kolonga FHR 1	Tongatapu	2015	0.15	1.57
Kolonga FHR 2	Tongatapu	2015	0.70	3.65
Kolonga SMA	Tongatapu	2015	1.64	7.96
Kotu FHR 1	Ha’apai	2015	3.02	7.54
Kotu FHR 2	Ha’apai	2015	0.19	1.92
Kotu SMA	Ha’apai	2015	16.86	15.73
Lapaha FHR	Tongatapu	2016	0.19	1.68
Lapaha SMA	Tongatapu	2016	1.10	4.41
Lape FHR	Vava’u	2017	0.58	3.15
Lape SMA	Vava’u	2017	1.98	5.57
Lofanga FHR 1	Ha’apai	2018	0.36	3.08
Lofanga FHR 2	Ha’apai	2018	0.45	2.77
Lofanga SMA	Ha’apai	2018	14.83	18.20
Makave FHR 1	Vava’u	2019	0.23	1.91
Makave FHR 2	Vava’u	2019	0.25	2.12
Makave SMA	Vava’u	2019	1.68	11.62
Mango FHR	Ha’apai	2017	2.78	7.53
Mango SMA	Ha’apai	2017	39.75	27.51
Matamaka FHR 1	Vava’u	2019	0.10	1.30
Matamaka FHR 2	Vava’u	2019	0.09	1.29
Matamaka SMA	Vava’u	2019	2.09	7.11
Matuku FHR	Ha’apai	2017	0.55	3.08
Matuku SMA	Ha’apai	2017	16.89	17.00
Muitoa FHR	Ha’apai	2018	0.72	3.71
Muitoa SMA	Ha’apai	2018	10.81	16.04
Nomuka FHR	Ha’apai	2011	0.53	3.26
Nomuka SMA	Ha’apai	2011	68.20	30.40
Nuapapu FHR 1	Vava’u	2019	0.19	2.09
Nuapapu FHR 2	Vava’u	2019	0.69	3.34
Nuapapu SMA	Vava’u	2019	5.83	11.62
Nukuleka FHR	Tongatapu	2016	0.51	3.04
Nukuleka SMA	Tongatapu	2016	2.63	9.16
Ofolanga FHR 1	Ha’apai	2018	1.80	5.35
Ofolanga FHR 2	Ha’apai	2018	1.20	4.47
Ofolanga SMA	Ha’apai	2018	40.70	26.88
Ofu FHR 1	Vava’u	2017	0.29	2.82
Ofu FHR 2	Vava’u	2017	0.38	2.41
Ofu SMA	Vava’u	2017	4.93	8.55
Oua FHR	Ha’apai	2006	2.16	7.32
Oua SMA	Ha’apai	2006	41.68	27.26
Ovaka FHR	Vava’u	2008	2.60	6.38
Ovaka SMA	Vava’u	2008	9.21	13.31
Pangaimotu FHR	Tongatapu	2017	1.40	5.06
Pukotala FHR	Ha’apai	2018	0.23	2.33
Pukotala SMA	Ha’apai	2018	5.68	12.47
Talihau FHR	Vava’u	2017	0.36	2.47
Talihau SMA	Vava’u	2017	2.52	6.16
Taunga FHR	Vava’u	2013	1.21	5.10
Taunga SMA	Vava’u	2013	7.74	11.78
Tufuva FHR	Eua	2018	0.33	2.45
Tufuva SMA	Eua	2019	7.24	11.16
Uiha FHR 1	Ha’apai	2018	0.37	2.51
Uiha FHR 2	Ha’apai	2018	0.46	2.74
Uiha SMA	Ha’apai	2018	17.09	17.45
Utulei FHR	Vava’u	2017	0.21	2.18
Utulei SMA	Vava’u	2017	4.16	7.99
Utungake FHR	Vava’u	2017	1.08	4.22
Utungake SMA	Vava’u	2017	2.34	6.54

2.2.4 Population density

Globally, human population pressure is one of the strongest drivers of ecological and anthropogenic patterns on coral reefs (Cinner et al. 2018), driving changes in fishing, pollution and other destructive practices. While spatial layers describing metrics of fishing pressure and pollution were supplied in the current dataset, raw human population pressure may also be a useful metric required by end users. Human population density within 5, 15 and 30 km of all 10m^2 pixels of near-shore marine habitat was therefore calculated using uniform kernel heatmaps (QGIS V.2.14) and village level population data from the 2016 census.Resulting heatmaps were subsequently clipped by the extent of the near-shore marine environment of Tonga (as defined by Andrefouet *et al.* (2006) using the *extract by mask* function (ArcMap V10.4.1) (Fig. S16). Distance cut-offs for population pressure followed that of previous studies utilizing radiuses of 5 km (Stallings 2009, Cinner et al. 2013), 15 km (Williams et al. 2008), and 30 km (Halpern et al. 2008, Mora et al. 2011).

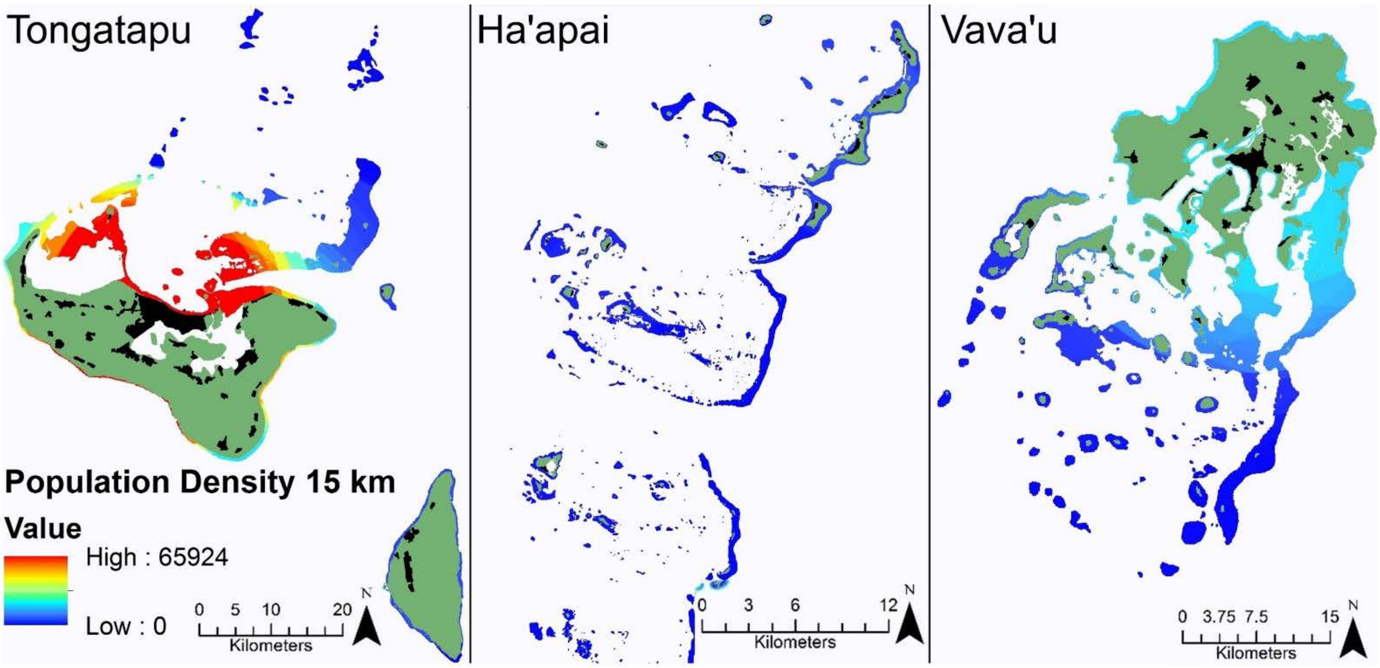


Figure S16. Population within 15 kilometers of each 10 m^2 pixel of Tonga's near-shore marine ecosystem. Additional layers with population density within 5 km and 30 km are also provided. Green areas represent land and black areas represent villages.

2.2.5 Socioeconomic development index

The level of socioeconomic development of a region may affect the marine environment in a variety of ways. There exists the potential for a both an increase (e.g. greater effluent runoff associated with higher population density) and a decrease (e.g. reduced rubbish dumping associated with increased access to waste management services)) in some harmful activities in areas with higher levels of socioeconomic development (Brewer et al. 2012, Harborne et al. 2016). Data from the 2016 national census (Statistics Department Tonga, 2016) was used to calculate the population density, population growth rate, mean age, education level and level of unemployment for each village in Tonga. Rather than using each variable separately, these data were combined using multivariate analysis to create a composite index of socioeconomic development for each village in Tonga (following Harborne 2016) (Fig. S17).

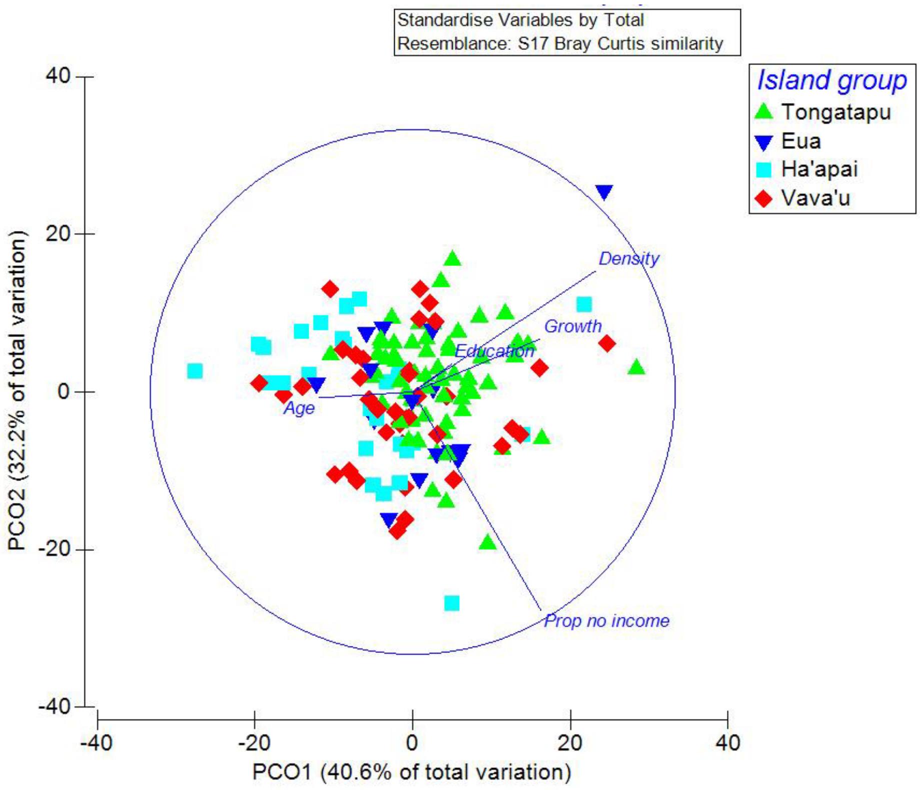


Figure S17. Principal component ordination of five indicators of socioeconomic development for all 142 villages in Tonga.

Population density was calculated by: 1) using satellite images to create polygons for each village in Tonga, and; 2) dividing each villages' population by the area of the polygon. Population growth rate was calculated using the yearly difference in population between the 2016 and 2011 census. Highest level of education was divided into six categories (preschool, primary, lower and higher secondary, technical and tertiary), which were classified on a 12 point scale, to calculate mean education level for each village. The proportion of each village not engaged in work as their main income source was defined as categories ‘no income’ and ‘remittance’ from the occupation section of the 2016 national census (Statistics Department Tonga, 2016). All values were weighted equally prior to analysis. Principal component ordination (PCO) was used to calculate the distance between villages relative to the axis accounting for the greatest amount of data variability. Axis 1 explained 40.6% of variation between villages, with higher values on this axis representing villages with higher population density, faster growth, greater levels of education and a younger mean age.

Values from the primary axis were used as a metric of socioeconomic development for each village. The subsequent socioeconomic indices were then extrapolated across 10 m^2 pixels of the near-shore marine ecosystem of Tonga (Fig. S18). Heatmaps using a uniform kernel shape and a radius of 2, 5 and 10 km were generated (QGIS V.2.14) and subsequently clipped by the Andrefouet *et al.* (2006) defined habitat extent. All raster cells that exceeded the specified radius (e.g 2, 5 or 10 km) were left blank (no data). Pixels with positive values represent areas within the sphere of influence of communities with a high socioeconomic development indices, while negative values represent areas influenced by communities with low socioeconomic development.

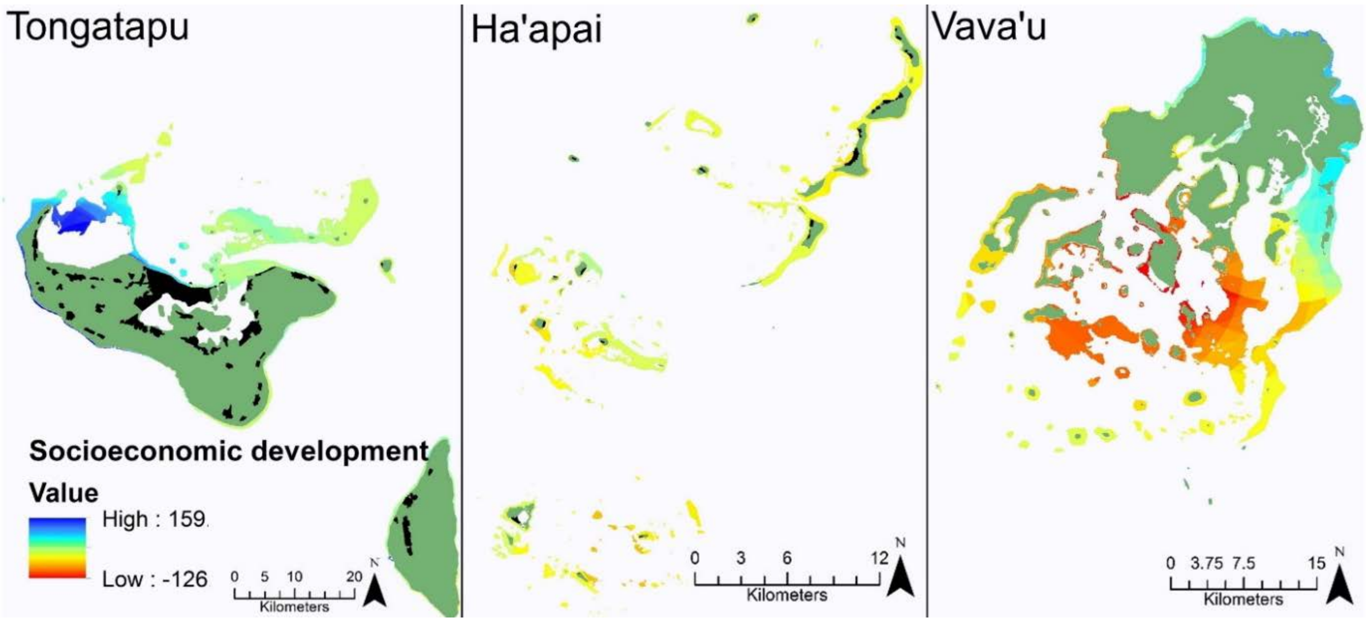


Figure S18. Socioeconomic development axis 1, explaining 40.6% of total variation between villages. Larger values represent 10m^2 pixels within the sphere of influence of communities with higher population densities, growth and mean education level and younger mean age. This layer represents values extrapolated to 10 km, but additional layers with socioeconomic development within 2 km and 5 km are also provided. Green areas represent land and black areas represent villages.

2.2.6 Distance from village

The distance from each 10 m^2 pixel to the nearest village was also included as a layer within this dataset (Fig. S19). While other factors such as population pressure and fishing pressure may be stronger drivers of ecological processes, distance from village may be useful for other applications by end users. For example, distance from village may be an important determinant of marine traffic intensity or may aid in identify the location of a new marine industrial project. . The distance from each 10 m^2 pixel of near-shore marine environment to the nearest village was therefore calculated using the *Euclidean distance* function (ArcMap V.10.4.1) and subsequently clipped by the habitat extent defined by Andrefouet *et al.* (2006).

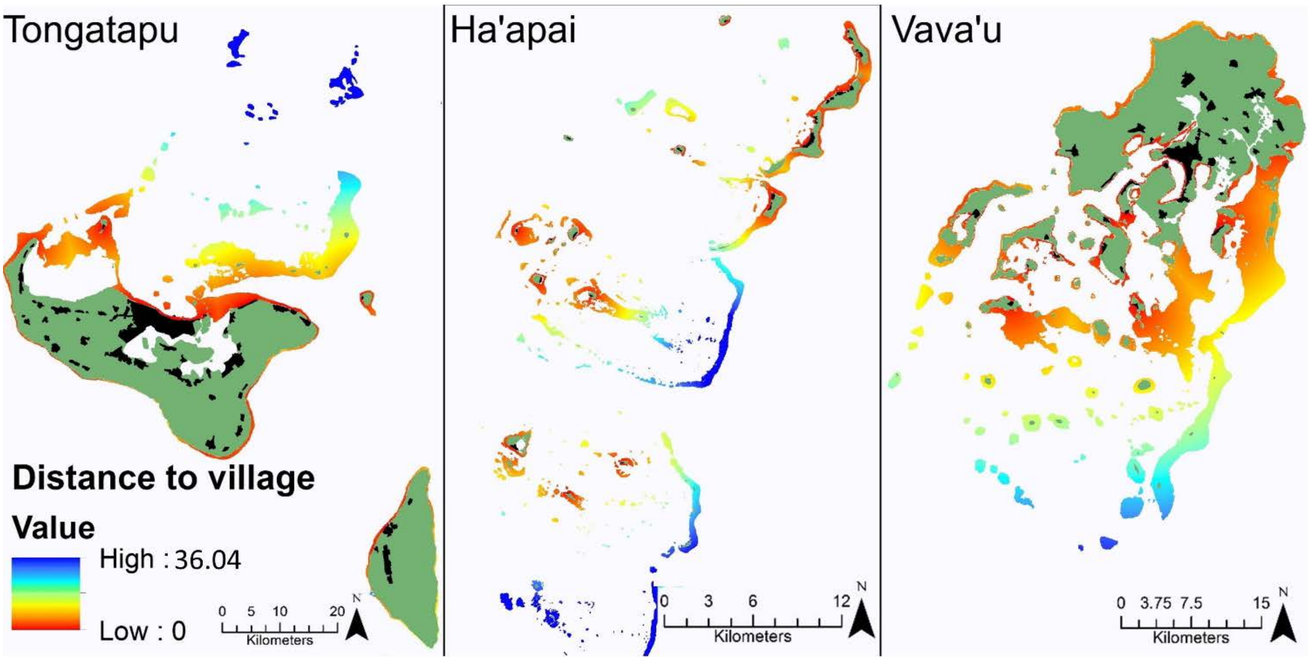


Figure S19. Distance from the nearest village for each 10 m^2 pixel of Tonga's near-shore marine environment. Green areas represent land and black areas represent villages.

2.2.7 Village

Polygons were created from outlines of each village (142) in Tonga using satellite imagery. The subsequent layer is supplied with the village-associated data from the 2016 national census (Statistics Department Tonga, 2016) embedded within the file. This village-associated data was used as inputs to generate fishing pressure, population density and socioeconomic development index spatial layers in the current dataset. Data included within the attribute table are: village name, area, population, population density, weighted number of commercial fishers, weighted number of subsistence fishers, socioeconomic development score, education score, population growth, mean age, proportion of population not engaged in work, island group, district, and village block.

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