Supporting Information for

Low fuel cost and rising fish price threaten coral reef wilderness

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Additional supplementary file (.csv format) is provided of the data used in boosted regression tree models

Wilderness Reefs

Wilderness areas can be defined as natural systems isolated enough from human activities to remain ecologically quasi-intact (Mittermeier *et al*. 2003). However, how "quasi-intactness" can be measured and how isolated an area should be to be considered wilderness are difficult questions whose answers are likely ecosystem-dependant.

For coral reefs in New Caledonia, fish community metrics display asymptotic S-shaped curves along a gradient of human impact (D'Agata *et al*. 2016). Inflections to asymptotic values are reached after 6.5 hours travel time from market for biomass, 7.5 hours for herbivore biomass, 12 hours for apex predator biomass (excluding sharks), 14 hours for species richness, 16.5 hours for functional richness, 21.5 hours for functional diversity, and 25 hours for reef sharks (D'Agata *et al*. 2016; Juhel *et al*. 2018). Thus, any reef in New Caledonia at >16.5 hours travel time from market has reached asymptotic maximum values for at least one fish community metrics, and can thus be considered as "quasi-intact" or in a "natural" status for that or these metrics.

Several wilderness reefs are known in the world (Chagos, remote atolls of Polynesia and New Caledonia, Cocos island, Rowley shoals, Kingman reef, Palmyra (Graham & McClanahan 2013; Jones *et al*. 2018)), and these disparate remote areas tend to have similar characteristics (D'Agata *et al*. 2016b). However, how many are left in the world is unknown, although the calculation of travel time to all reefs of the world suggest that they are very rare. Globally, 58% of coral reefs are <30 minutes from the nearest human settlement, 25% at < 4 h from the nearest major market, and only 31% at more than 12 h from the nearest market (Maire *et al.* 2016).

Using the travel time database for the reefs of the world (Maire *et al.* 2016) and thresholds of 10 and 20 hours travel times for wilderness reefs (D'Agata *et al.* 2016a), we calculate here how many wilderness reefs remain in the world, and how many are in New Caledonia. We report that 5% of world reefs are >10 h travel time from the nearest human settlement (41% from major markets), 2.6% at > 15 h (20% from markets), and only 1.5% at > 20 h (9% from markets). These remaining wilderness coral reefs areas are over-represented in the New Caledonian archipelago, whose waters contain approximately 10% (10 h threshold), 18% (15 h) or 33% (20 h) of remaining wilderness reefs worldwide. Thus, taking the most conservative approach, with functionally quasi-intact reefs at > 20 h travel time from the nearest human settlement (or future market), wilderness reefs are extremely rare, only accounting for 1.5% of global coral reefs, of which one-third are in New Caledonia.

Yield-limited cost of fishing framework

Operating costs (C) are given by the following equation

$$(1) \qquad C= [t_i{\cdot}f_t + t_f{\cdot}f_f] \cdot p + (t_f+t_i){\cdot}w{\cdot}n_w + e$$

Where t_i is the time taken to travel to reef i from the market and return in hours, f_t is the fuel consumption per hour travel, t_f the time spent fishing, f_f the fuel consumption per hour fishing, p is the price of fuel, w is the hourly wage, n_w the number of wages paid, and e a constant covering maintenance and other fixed operating costs (e.g., fishing license). The cost of travel ($t_i{\cdot}f_t$) – can be further broken down into $t_il{\cdot}f_tl$ and $t_is{\cdot}f_ts$ – the time and fuel it takes to travel to reef i by land (l) and by sea (s). Fuel consumption is a function of the engine capacity, type and speed of travel, calculated by the following from the FAO Fisherman's Handbook (Prado & Dremiere 1990):

$$(2) \qquad F = 0.75*P(max)*(S/d)*t* 0.001$$

Where 0.75 is a coefficient, F = fuel consumption in litres, P(max) = engine horsepower, S = specific consumption in grams/HP/hour, d is specific gravity of the fuel, and t = time of engine use (hours). To calculate t_f we use:

$$(3) \qquad t_f = [Y/(B_i \cdot q)] \cdot n_f$$

Where B_i is the biomass of fish at reef i and n_f the number of fishers. We assume that changes in fish biomass that occur because of removal of fish by individual fishing trips are insignificant, and that all species within the fishery are equally catchable

In this yield-limited model, constrained by the size of the fish hold/quota limits, Y can be determined using the standard equation for yield:

$$(4) \qquad Y = qBE$$

Where q is the catchability coefficient, B is the biomass within a given reef area, and E is the effort in number of fisher hours. Catchability can be calculated using previously collected effort/yield data where fish biomass is known, and varies with gear, species, environmental conditions and stock (reviewed by (Arreguín-Sánchez 1996)). Here, we use data collected by one of the authors (F. Januchowski-Hartley) on fishing effort and stock abundance in neighbouring Vanuatu suggesting that between 200kg/hectare a range of q of between 0.002 and 0.007 is appropriate, with higher stock levels in this range resulting in higher value (Januchowski-Hartley et al. 2014). To account for changes in catchability based on exposure to fishing, we used a non-linear logistic relationship between biomass and q.

Gross revenue per trip will fluctuate depending upon the proportion of high versus low value fishes in the catch. Here we assume that each species/fish group will be represented in the catch in proportion to their abundance in the fished area, and total revenues will therefore be:

$$(5) \qquad R = \sum_j Y_j \cdot P_j$$

Where Y_j is the yield of species or group *j* in the catch and P_j is the landing price for that species/group

Data collection and sources

Fish biomass

Reef fishes were surveyed from 2001 to 2015 across New Caledonia, across 556 distance sampling underwater visual census sites spanning ~5° latitude and ~9.5° longitude (Fig. S3). These sites cover a gradient of human pressure from high population density sites close to markets (2,135 people km^{-2}), to isolated and uninhabited sites more than 300 km from the nearest population. For each reef site transects were surveyed on both the reef flat and slope when feasible. Due to lack of spatio-temporal replication in UVC, we were unable to model how biomass would change across time and thus biomass did not vary across years. We limited fish species included in our analysis to 352 species of commercially important fish species. Sharks and rays were removed from the data due to the weaknesses of UVC sampling in assessing their occurrence, and UVC datasets were truncated at a distance of 7m on each side (see D'agata *et al*. 2016a for species list and further details). Fifty-metre long distance-sampling underwater visual census (D-UVC) were conducted at each site, with each transect allowing estimation of fish biomass and density over a 700 m^2 area. This method involves two divers, one on each side of a transect line recording the species abundance, body-length and distance from the transect-line for each fish or group of fish on their side of the line (Labrosse et al. 2006). We estimated the biomass of individual fishes using the allometric length-weight conversion $W = aTL^b$, where parameters *a* and *b* are species-specific constants obtained from Fishbase (Froese & Pauly 2016). Where data was not available for a particular species, we used parameters from a similar sized species in the same genera if possible, or genera mean values.

Anthropogenic variables

Four anthropogenic variables were used to model fish biomass: 1) the human population occurring with a 20 km radius of each reef; 2) the linear distance between each reef and market in Nouméa; 3) the mean travel time of our scenarios to the reef site; and 4) the land-based travel time from Nouméa to each reef site. We calculated travel times as in Maire et al. (2016), using the *accCost* function of the 'gdistance' pack in R (R Development Core Team & Others 2011) to automate calculation for each reef location, using origin and destination points as inputs, and a transition matrix describing the connections between cells across the friction-surface grid. We used the same terrestrial speeds as Maire et al. (2016), but used different speeds for travel over water, 20.9 km/h (~11 knots) and 26.5 km/h (~14 knots) for boats < 5 m and boats < 8 m respectively. These speeds were calculated from the equation for critical speed from the FAO Fisherman's Handbook (Prado & Dremiere 1990):

$$(6) \qquad V(km/h)=(5.4*\sqrt{(L_w)})*1.852$$

Where L_w is the length of the waterline (4m for boats < 5 m,7 m for boats 5 m < 8 m). We were unable to distinguish between open-ocean and travel inside lagoons, and therefore used an average speed of 20 km/h (~ 11 knots) for boats greater than 8 m. For the purposes of this study, we assumed that fishing activities consumed 20% of the fuel of normal travel due to the passive nature of commonly used gears in New Caledonia (Labrosse et al. 2006). We used the following engine sizes and ratios to calculate fuel consumption (Eq 2): 30HP two-stroke for boats < 5 m, 125HP four-stroke for boats < 8 m, 300HP for boats > 8 m, S = 350 for two-stroke, 250 for four-stroke, 185 for diesel engines, specific gravity of 0.72 for gasoline, and 0.84 for diesel).

Habitat variables

Each reef was assigned to one of four biotopes: coastal fringing (immediately adjacent to the mainland), intermediate lagoon (between the mainland and the New Caledonia barrier reef); back reef (the landward facing part of the barrier reef); and outer barrier reef. We included reef zone (slope or flat) and island type for each reef: high island (island of volcanic origin, including Grand Terre, the main island of New Caledonia, low island (created by sediment or uplift of coral reefs), and atolls.

Sea Surface Temperature

Weekly average Sea Surface Temperature (SST) (5 km pixel) was obtained from AVHRR (Advanced Very High Resolution Radiometer; http://oceanwatch.pifsc.noaa.gov/). We used the *ncdf4*, *raster* and *rgdal* packages in R 3.3 (R Core Team 2017) to calculate the mean sea surface temperature between 1st January 2000 and 19th December 2009 for each pixel which contained a reef site.

Boosted Regression Trees Predictive Modelling

We used fish biomass data from 556 reef sites surveyed between 2001 and 2015 to construct boosted regression tree (BRT) models of total fish biomass, and the biomass of four important categories of catch *Plectropomus* spp., *Naso* spp., Scarinae, and *Lutjanus* and *Lethrinus* spp., using data only for fishes > 20 cm and thus likely recruited to the fishery. Predictor variables included mean travel time, total distance, and linear distance from major market (Nouméa), land travel time, sea surface temperature, population density, reef and island type, reef zone and protection (see above for how these were calculated).

Pairwise relationships between all variables were assessed using Spearman rank correlation. Total distance and mean travel time were highly correlated (> 0.8) and total distance was dropped from further analysis. Cross-validation (CV) deviance and standard error (se) were used to assess model performance (where lower values indicate a better model). Model optimization was achieved by adjusting three parameters: tree complexity (tc – the number of nodes in a tree); learning rate (lr – establishes the contribution of each tree to the model); and bag-fraction (bf – specifies the proportion of data to be selected at each step). All possible combinations of tc (1, 2, 3, 4, 5), lr (0.01, 0.001, 0.005) and bf (0.5, 0.75) were run, and the combination with the lowest deviance was used to fit the final BRT model. Finally, we used the gbm.simplify routine in the *dismo* package (Hijmans et al. 2013) to perform a backward selection that drops variables contributing little (assessed using the average CV error to decide how many variables can be removed from the original model without affecting predictive performance) (Table S1). To predict biomass across the all reefs of New Caledonia, we overlaid a 1 km x 1km grid across the millennium mapping database of coral (UNEP). We selected every grid cell that contained any category of coral reef, and refined this to slope only, because fishers are unlikely to target shallow reef flats. 5466 reef cells remained, for which we calculated predictor variables, before predicting biomass of each reef fishery group for each reef cell.

Distances/travel time, mean SST and population density were all calculated from the centroid of each reef cell.

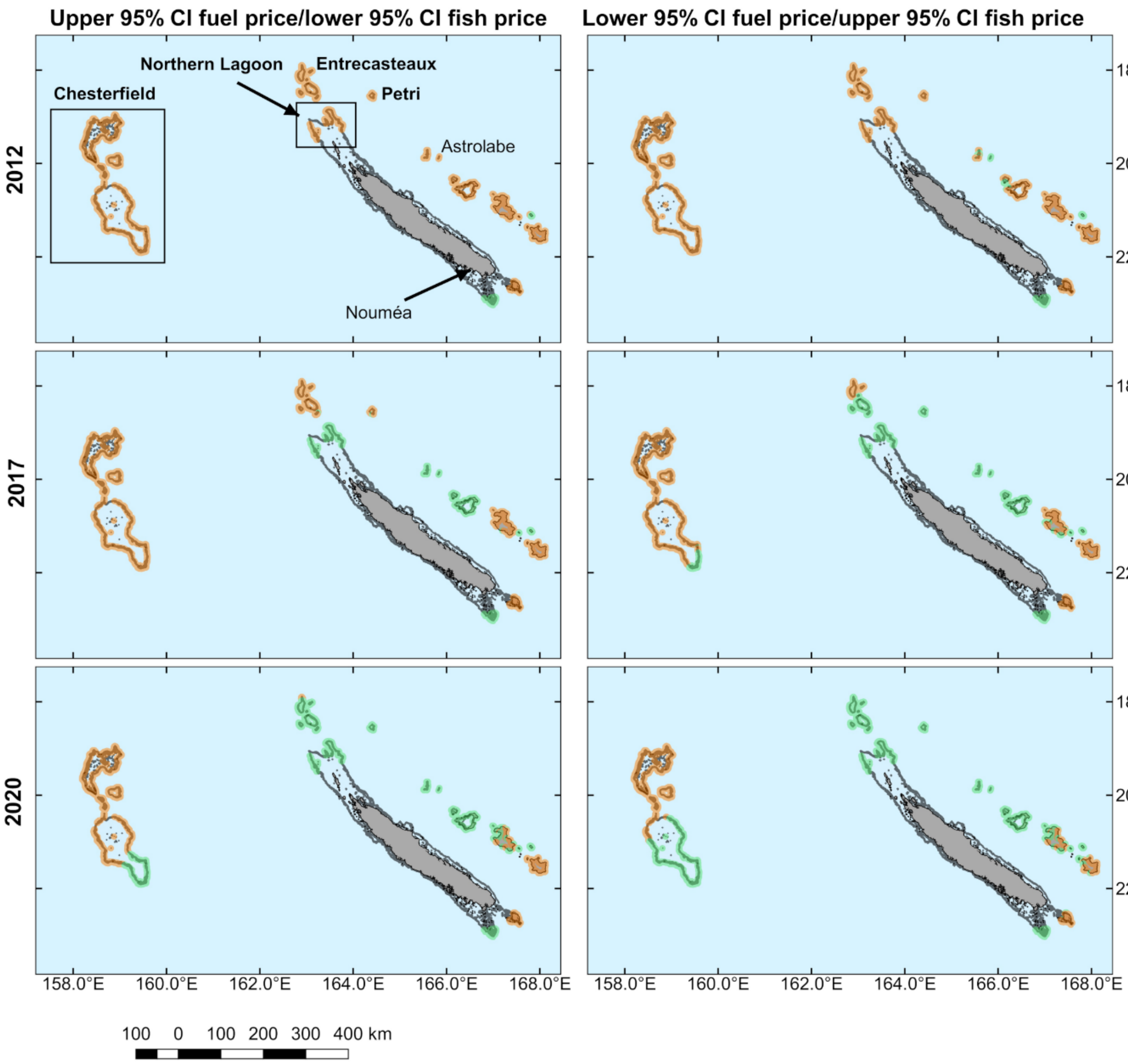

Fig. S2. Profitability maps of New Caledonian reefs for vessels > 8 m in length under lower 95% CI mean annual fuel cost, and upper 95% CI mean annual fish prices.

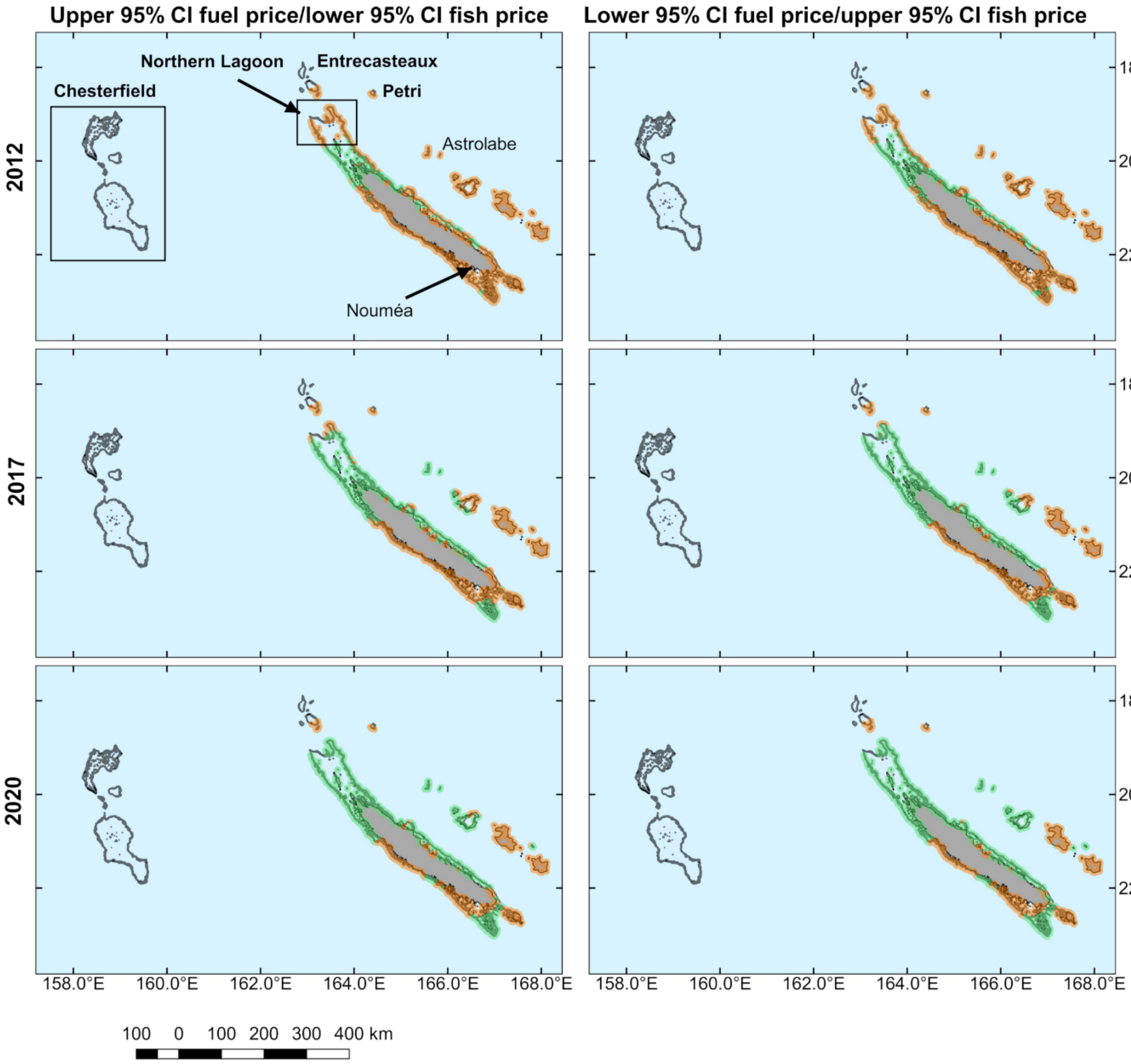

Fig. S3. Profitability maps of New Caledonian reefs for vessels 5- 8 m in length under lower 95% CI mean annual fuel cost, and upper 95% CI mean annual fish prices.

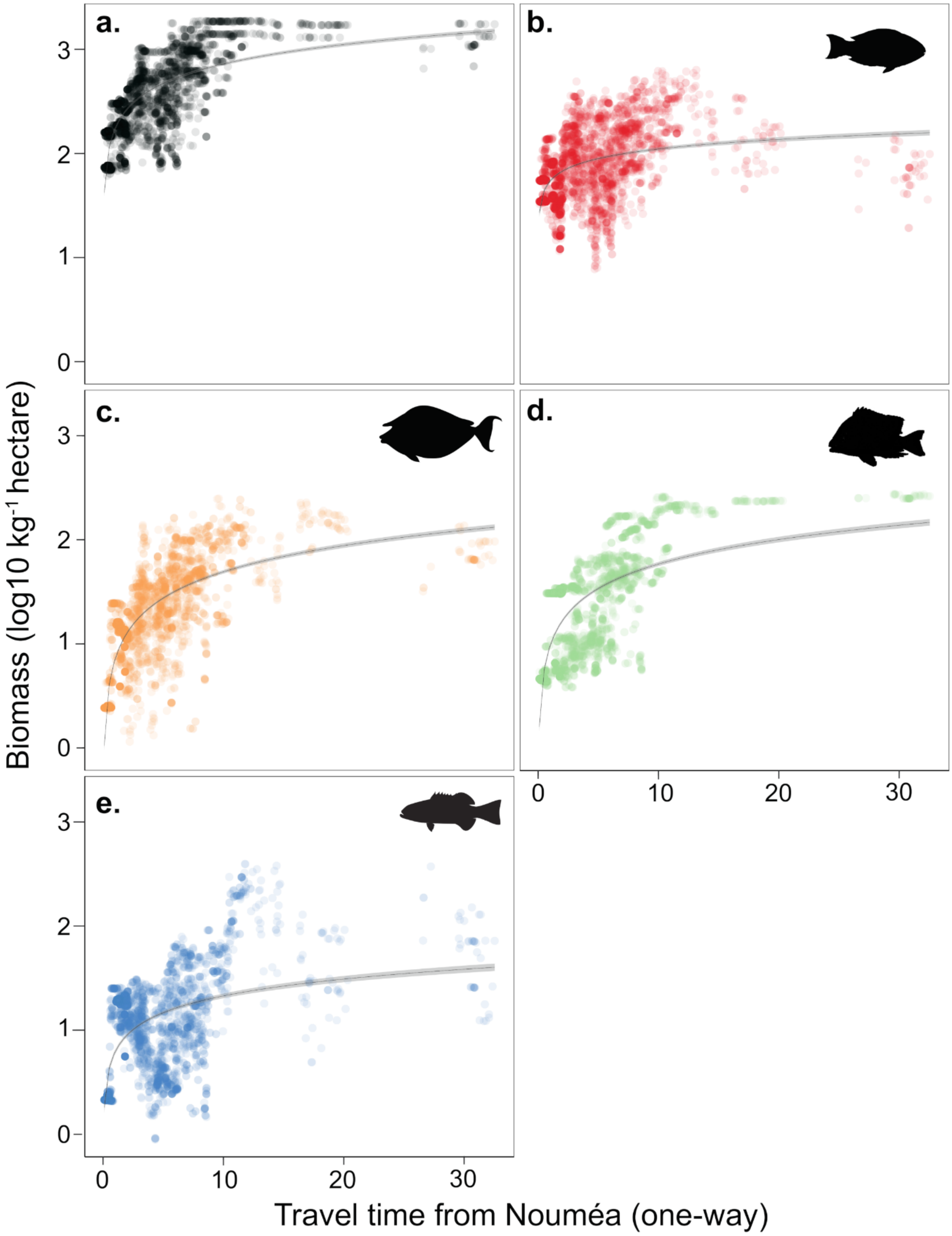

Fig. S1 Predicted reef fish biomass for (A) – all fish; (B) – parrotfishes; (C) – Naso spp.; (D) – Lethrinids and Lutjanids; and (E) – Plectropomus spp. plotted against mean travel time

Table S1. Boosted regression tree model statistics

Group	# predictor variables	lr	TC	Bag-fraction	# of trees	Mean total deviance	Residual deviance	CV deviance (SE)	CV correlation	Training data correlation
Total Biomass	5	0.005	2	0.75	1050	0.522	0.281	0.32 (0.021)	0.638	0.683
Parrotfish	7	0.005	3	0.5	1800	0.606	0.334	0.448 (0.028)	0.511	0.679
Naso spp.	5	0.005	5	0.5	1250	0.926	0.440	0.625 (0.029)	0.574	0.732
Lethrinus & Lutjanus	5	0.001	5	0. 5	2550	1.044	0.523	0.632 (0.024)	0.63	0.715
Plectropomus spp.	5	0.01	5	0. 5	800	0.863	0.344	0.533 (0.043)	0.617	0.781

References

Arreguín-Sánchez, F. (1996). Catchability: a key parameter for fish stock assessment. *Reviews in Fish Biology and Fisheries*, 6, 221–242. Doi: 10.1007/BF00182344

D'agata, S., Mouillot, D., Wantiez, L., Friedlander, A.M., Kulbicki, M. & Vigliola, L. (2016a). Marine reserves lag behind wilderness in the conservation of key functional roles. *Nat. Commun.*, 7, 12000. doi: 10.1038/ncomms12000.

D'agata, S., Vigliola, L., Graham, N.A.J., Wantiez, L., Parravicini, V., Villéger, S., Mou-Tham, G., Frolla, P., Friedlander, A.M., Kulbicki, M. & Mouillot, D. (2016b). Unexpected high vulnerability of functions in wilderness areas: evidence from coral reef fishes. *Proc. Biol. Sci.*, 283. doi: 10.1098/rspb.2016.0128.

Froese, R. & Pauly, D. (2016). Editors. FishBase. [WWW Document]. www.fishbase.org

Graham, N.A.J. & McClanahan, T.R. (2013). The Last Call for Marine Wilderness? *Bioscience*, 63, 397–402. doi: 10.1525/bio.2013.63.5.13.

Guyard, S., Apithy, L., Bouard, S., Sourisseau, J.M., Passouant, M., Bosc, P.M. & Bélières, J.F. (2010). L'agriculture des tribus en Nouvelle-Calédonie. *Résultats d'une enquête de.*

Hijmans, R.J., Phillips, S., Leathwick, J. & Elith, J. (2013). dismo: Species distribution modeling. *R package version 0. 8-17.*

Januchowski-Hartley, F.A., Cinner, J.E. & Graham, N.A.J. (2014). Fishery benefits from behavioural modification of fishes in periodically harvested fisheries closures. *Aquat. Conserv.*, 24, 777–790. doi: 10.10.1002/aqc.2388.

Jones, K.R., Klein, C.J., Halpern, B.S., Venter, O., Grantham, H., Kuempel, C.D., Shumway, N., Friedlander, A.M., Possingham, H.P. & Watson, J.E.M. (2018). The Location and Protection Status of Earth's Diminishing Marine Wilderness. *Curr. Biol.*, 28, 2683. doi: 10.1016/j.cub.2018.07.081.

Juhel, J.-B., Vigliola, L., Mouillot, D., Kulbicki, M., Letessier, T.B., Meeuwig, J.J. & Wantiez, L. (2018). Reef accessibility impairs the protection of sharks. *J. Appl. Ecol.*, 55, 673–683. doi: 10.111/1365-2664.13007.

Labrosse, P., Ferraris, J. & Letourneur, Y. (2006). Assessing the sustainability of subsistence fisheries in the Pacific: The use of data on fish consumption. *Ocean Coast. Manag.*, 49, 203–221. doi: 10.1016/j.ocecoaman.2006.02.006.

Maire, E., Cinner, J., Velez, L., Huchery, C., Mora, C., Dagata, S., Vigliola, L., Wantiez, L., Kulbicki, M. & Mouillot, D. (2016). How accessible are coral reefs to people? A global assessment based on travel time. *Ecol. Lett.*, 19, 351–360. doi: 10.111/ele.12577.

Mittermeier, R.A., Mittermeier, C.G., Brooks, T.M., Pilgrim, J.D., Konstant, W.R., da Fonseca, G.A.B. & Kormos, C. (2003). Wilderness and biodiversity conservation. *Proc. Natl. Acad. Sci. U. S. A.*, 100, 10309–10313. doi: 10.1073/pnas.1732458100.

Prado, J. & Dremiere, P.Y. (1990). *Fisherman's workbook*. Food & Agriculture Organization of the United Nations, Fishing News Books, Oxford.

R Development Core Team. (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.