Research

Disentangling the complex roles of markets on coral reefs in northwest Madagascar

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ABSTRACT. Rapid degradation of the world's coral reefs jeopardizes their ecological functioning and ultimately imperils the well-being of the millions of people with reef-dependent livelihoods. Ecosystem accessibility is the main driver of their conditions, with the most accessible ecosystems being most at risk of resource depletion. People's socioeconomic conditions can change as they get further from urban centers and can profoundly influence people's relationship with the environment. However, the mechanisms through which increasing accessibility from human societies affects natural resources are still unclear. A plausible mechanism through which markets influence the environment is through the socioeconomic changes that tend to accompany accessibility. We used social and ecological data from 10 coastal communities and 31 reefs in northwest Madagascar to (i) unravel the respective influences of the local fish market and coastal communities on reef fish biomass and (ii) investigate how communities' socioeconomic and resource use characteristics change with increasing proximity to markets. We used generalized additive models to reveal that reef fish biomass is strongly related to the accessibility of both markets and local communities. We also highlight that the ways coastal communities use marine resources changes predictably with market proximity. More precisely, market proximity affects fishing gear (technique effect), wealth, and selling strategies (scale effect) of coastal communities. Our findings emphasize the need to better quantify links between markets and fishing communities through household-level surveys to implement market-based actions that could help to regulate the effect of markets on both fish stocks and fishing communities.

Key Words: *accessibility; coral reef fisheries; fish biomass; market access; social-ecological systems*

INTRODUCTION

Earth's ecosystems are under increasing pressure as globalization connects the world (Liu et al. 2013). Expanding trade, transportation, migration, and technology are altering intertwined dynamics between human and natural ecosystems across space and time (Rockström et al. 2009, Liu et al. 2015). Global trade through interconnected markets or new access to markets can increase accessibility through road networks and infrastructure expansion, which in turn, profoundly shape the exploitation of both terrestrial and marine natural resources (Laurance et al. 2009, Dobson et al. 2010, Mora et al. 2011, Ahmed et al. 2014, Barber et al. 2014, Alamgir et al. 2017). There are growing concerns about the risk of unsustainable resources use due to unregulated trade in those previously isolated areas, with obvious ecological and management implications for those key ecosystems (Berkes et al. 2006, Rockström et al. 2009, Steffen et al. 2011, McCauley et al. 2013, Mora et al. 2016, Tregidgo et al. 2017).

However, research on the potential mechanisms through which increasing market accessibility influences ecological conditions is still nascent. To date, research on market accessibility has primarily examined how increased market access can affect resource users through the obvious mechanism of trade and price changes (Delgado et al. 2003, Schmitt and Kramer 2009, Thyresson et al. 2011, 2013, Januchowski-Hartley et al. 2020). Yet there are other potential mechanisms that have received less attention. Recent research has quantified how people's

socioeconomic conditions, i.e., wealth, educational attainment, and health care utilization, change as they live further from urban centers (Weiss et al. 2018). Certain socioeconomic conditions, such as poverty or islandness, can profoundly influence people's relationship with the environment (Carter and Barrett 2006, Cinner 2011, Coulthard et al. 2017). Thus, a plausible mechanism through which markets influence the environment is through the socioeconomic changes that tend to accompany resource accessibility. As a heuristic to guide this type of exploration, a parallel literature on the impacts of economic development on the environment highlights three causal pathways: (i) a technique effect, whereby societies can use alternative technologies to conserve or exploit resources; (ii) a composition effect, which suggests that the structure of the local economy changes with economic transitions, for example, from a natural resource-based economy to a service-based economy, and (iii) a scale effect, which refers to the size of the economy where wealthier communities exploit more natural resources leading to increasing environmental degradation and potential displacement of exploitation further afield, often in places that are poorer or less regulated (Grossman and Krueger 1995, Cinner et al. 2009a, Lange et al. 2018).

Here, we focus on small-scale fisheries that are an essential source of food, culture, and livelihoods for millions of people around the world (Béné et al. 2007, Bell et al. 2009, Teh et al. 2013). Specifically, we consider artisanal coral reef fisheries of northwest Madagascar. We hypothesize that coral reef ecological conditions

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improve with decreasing accessibility to both markets and coastal communities, and that these relationships depend on the presence and effectiveness of fisheries management. We also evaluate how market access, i.e., the travelling time to the nearest market, affects community-level socioeconomic characteristics of resource use, e.g., fisheries dependence, livelihood diversity, or fishing gear technologies. Specifically, we aim to better understand the entwined relationships between local fish markets (hereafter "markets"), socioeconomic characteristics of coastal communities, and the ecological conditions of coral reefs (Cinner et al. 2009*a*, Tsurumi and Managi 2010, Sugiawan et al. 2017). The objectives of our study are to investigate (i) the relative effects of market access, fisheries management, and key environmental variables on reef fish biomass in the northwest of Madagascar; and (ii) the association between socioeconomic characteristics and markets among coastal communities. We address these questions using ecological data collected in 31 reefs, and socioeconomic information from household-level surveys conducted in 10 coastal communities in northwest Madagascar.

Context and study area
Madagascar relies heavily on the exploitation of natural resources for subsistence and livelihoods (World Bank 2010, Conservation International 2015). The artisanal fishery is a significant economic sector comprising multigear and multispecies fishing activities, where fishers can access reefs directly from the shore or using wooden pirogue canoes (McKenna and Allen 2003, Doukakis et al. 2008, Davies et al. 2009). Artisanal fisheries in Madagascar are vital to food security and livelihoods for coastal communities and support the majority of the Malagasy coastal population (Barnes-Mauthe et al. 2013). This is particularly true along the west coast where agricultural production remains low (FAO et al. 2018) and employment options are limited (Laroche and Ramananarivo 1995, Le Manach et al. 2012).

Coral reefs in northwest Madagascar are recognized for their exceptional biodiversity and their resilience to climate change in the Western Indian Ocean (McKenna and Allen 2003, McClanahan et al. 2011*a*, Obura 2012). The west coast of Madagascar is now considered as a high priority for increased management efforts as a potential "climate refugia" in the Western Indian Ocean (McClanahan et al. 2011*b*, Beyer et al. 2018). Coral reef management actions in Madagascar have mainly focused on strengthening local governance of marine resources that are socially acceptable and can deliver benefits for local economics and biodiversity (Harris 2011, Westerman and Gardner 2013). In rural communities, management actions are based on social conventions known as *dinas* (Rakotoson and Tanner 2006) aimed at increasing fish stocks and biodiversity, protecting cultural heritage, and promoting sustainable socioeconomic development to contribute to poverty reduction (Govan et al. 2009, Jupiter et al. 2014, Rocliffe et al. 2014). More specifically in northwest Madagascar, there are currently three forms of marine resource management: (i) marine protected areas (MPAs) managed by Madagascar National Parks; (ii) MPAs that are managed by local communities recognizing the *dinas* and with the technical and financial support of national or international associations or NGOs; and (iii) locally managed marine areas (LMMAs) managed by local communities based on a legal framework, the *Gestion Locale Sécurisée* (GELOSE), designed to integrate the *dinas* with governmental laws to enable community-based

management of natural resources (Rakotoson and Tanner 2006). Within the MPAs and LMMAs in this area, management typically includes restricted zones where fishing is allowed using certain types of gear and access is restricted to local fishers, and permanent no-take reserves where all fishing activities are prohibited. In addition, beach seining, considered as a destructive fishing practice, has been historically prohibited along most coastal areas through *dinas* and is now nationally prohibited in Madagascar since 2018 (although is still happening in some areas without strong management structures). Shark fishing and sea cucumber harvesting are also regulated in the northwest, as are seasonal closures of some pelagic fisheries, e.g., Indian mackerel *Rastrelliger kanagurta*.

METHODS

Study area
Our study includes coral reefs along ~150 km of coastline from Nosy Iranja to Nosy Mitsio (Fig. 1). The area is characterized by many small islands off the coast where human settlements are relatively sparse, consisting of dispersed small villages. Most of the fishing vessels are sailing wooden pirogue canoes and the most commonly employed gear are spear guns, gillnets, lines, fish traps (creels and valakira), and beach seines, despite recent legal regulations (Doukakis et al. 2008, Davies et al. 2009, Jadot et al. 2015). This area includes one national park (Nosy Tanikely), officially established in 2011, that encompasses an uninhabited island and surrounding waters where fishing is prohibited and two MPAs (Ankarea and Ankivonjy) that were officially established in April 2015 and are comanaged between local communities and the Wildlife Conservation Society. The two latter MPAs have designated restriction strategies by which local fishers have exclusive access rights to fishing inside each MPA. The management plans for each MPA are based on the existing *dinas* in both areas, and complemented by national policies on flagged species (shark, whales, sea turtles), habitats (mangroves, coral reefs), and gear restrictions, including bans on (i) beach seines, (ii) nets with mesh size under 25 mm, (iii) nets over 500 m long, and (iv) any fishing gear directly entering in contact with the bottom to avoid coral reef destruction. Outside MPAs, only national restrictions apply but the level of compliance is generally poor (Westerman and Gardner 2013). Given the multiplicity of management forms in our study area, we categorized sites based on whether fishing is permitted (open access and restricted reefs) or fishing is prohibited (no-take zones within the two forms of management; Fig. 1). However, we recognize that levels of compliance within the "fishing prohibited" category may vary.

Ecological surveys
We surveyed 31 ecological sites (hereafter "reefs") between April and November 2016, comprising 16 reefs where fishing is permitted and 15 reefs where fishing is prohibited (Fig. 1). Surveys occurred on the main reef types in our study areas, including both fringing reefs of continental islands and complex patch reefs. For each reef, transects were performed on the slope and oriented parallel to the depth contour between 3 and 14 m.

Reef fish survey
Distance-sampling underwater visual census (D-UVC) was used to survey finfishes along 50 m long transects. This method involved two divers, where each diver recorded the species,

abundance, body length, and distance perpendicular to the transect line of each fish or group of fish, while swimming slowly down the line (Labrosse et al. 2002). We included 25 fish families that represent the main reef fish families in the study region (Acanthuridae, Balistidae, Caesionidae, Carangidae, Chaetodontidae, Ephippidae, Fistularidae, Haemulidae, Holocentridae, Kyphosidae, Labridae, Lethrinidae, Lutjanidae, Mullidae, Nemipteridae, Pempheridae, Pomacanthidae, Pomacentridae, Scaridae, Scombridae, Scorpaenidae, Serranidae, Siganidae, Sphyraenidae, and Zanclidae). Transects width were truncated at 5 m on each side allowing for species density estimation on a 500 m² transect (50 x 10 m). The biomass of individual fish was estimated using the allometric length-weight conversion: $W = aTL^b$, where parameters a and b are species-specific constants extracted from FishBase (), TL is the individual total fork length in centimeters, and W is the weight in grams (Kulbicki et al. 2005). Biomass of each transect was further converted to kilograms per hectare of reef area.

Fig. 1. Map of the study area located off the southeast coast of Africa in northwest Madagascar. Surveyed reefs where fishing is permitted (open access and restricted reefs: orange squares) or fishing is prohibited (no-take zones within the two forms of management: green squares), coastal communities (circles), local markets (stars), and cartography of reefs (blue shades) are represented. Each coastal community is colored according to its nearest market (Ambilobe: black; Ambanja: white, Hell Ville: grey).
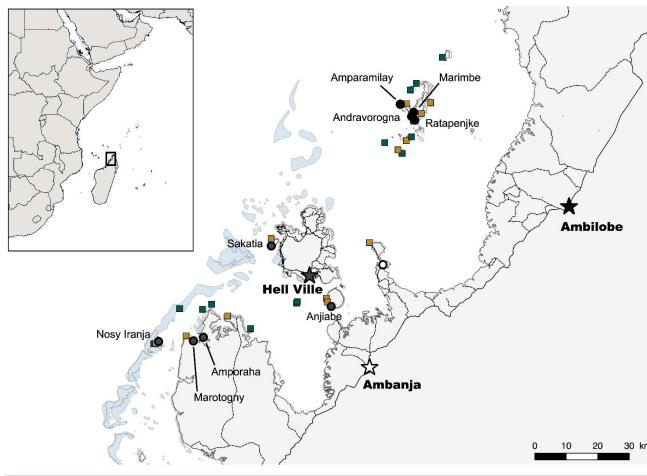
Reef habitat and environmental variables
Point intercept transects (Hill and Wilkinson 2004) were used to assess benthic conditions. This method consists of recording the benthic substrate at 25-cm intervals along a 50-m transect. We estimated the percent cover of live hard coral and macroalgae as major benthic covariates of interest. We also visually measured structural macro-complexity, which was estimated every 5 to 10 m along each transect to provide an average structural complexity score per transect. Scores ranged from 0 (no vertical relief, flat, or rubbly areas) to 5 (Wilson et al. 2007). The mean depth over each transect was also recorded during surveys.

To evaluate the environmental conditions on each reef, weekly average sea surface temperature (SST) and chlorophyll-a

concentration, which provide information on the amount of primary production occurring in the ocean (Huot et al. 2007), were extracted during a 5-year period (2012–2016) at a 4-km resolution from the Geostationary Operational Environmental Satellites and the Polar-orbiting Operational Environmental Satellites (GOES-POES) dataset and the Moderate Resolution Imaging Spectro-radiometer (MODIS; http://oceanwatch.pifsc.noaa.gov/). For each reef, we calculated the weekly average of temperature and ocean primary productivity over a 5-year period (2012–2016) but we did not account for seasonality.

Using a set of six reef habitat and environmental variables, we first performed a principal components analysis (PCA) to describe similarities between our ecological sites while dealing with multicollinearity and we included depth, weekly average SST and primary productivity, reef complexity, percent cover of macroalgae, and live hard coral (Cinner et al. 2013, Maire et al. 2016, McClanahan et al. 2016). We only retained the first two components (representing 56% of the total variance; see Appendix 1) that mix abiotic and benthic conditions as environmental covariates for further analysis.

Travel time to markets
For each reef, we considered two human settlements: (i) the nearest coastal community; and (ii) the nearest market. Travel time was estimated as the shortest time of travelling between each reef and its nearest market and community, respectively, considering the following:

- • Sea travel using wooden pirogue canoes: speed of 7 km.h⁻¹
- • Primary roads using motorized vehicles: speed of 50 km.h⁻¹
- • Track/secondary roads using motorized vehicles: speed of 20 km.h⁻¹

Speed values were estimated from field observation in March-April 2016, road network data was extracted from the OpenStreetMap (OSM) project and was completed by GPS tracks obtained during field campaigns in March-April 2016.

We also assessed the total human population occurring within a 4-km radius of each reef using the WorldPop dataset version 2.0 (Tatem 2017), which estimates human population with national adjustments at a 100-m resolution for the year 2015 (the year closest to 2016, year in which the ecological and social surveys were conducted). We set the cut-off at 4 km to reduce spatial overlap between reefs. All social and environmental variables considered in the study and expected to influence reef fish biomass are described in Table 1.

Socioeconomic surveys
Semistructured questionnaires were conducted at 10 coastal communities (Fig. 1) to collect information on socioeconomic characteristics, fishing and farming activities, resource use, and management. Surveys were conducted across three districts in northwest Madagascar from November to December 2016 by trained and experienced Malagasy interviewers (Fig. 1, Appendix 2). For communities with less than 50 households, all households were surveyed; in larger communities, 50 households were randomly chosen when possible. In total, 354 household surveys were conducted across the 10 communities (Appendix 2). All survey activities were approved by the Wildlife Conservation

Table 1. Name and description of human, environmental, and habitat variables considered to influence total reef fish biomass. References and statistical transformation are also described for each variable.

Category	Name	Description	References	Transformation
Human	Human population size	Number of inhabitants in a 4-km buffer around the reef extracted from WorldPop 100-m resolution dataset version 2.0	Mora et al. 2011, Brewer et al. 2012	Log transformed and standardized
Human	Travel time from the nearest market	Travel time between each reef and the nearest market	Brewer et al. 2012, Cinner et al. 2013, D'Agata et al. 2016, Maire et al. 2016	Standardized
Human	Travel time from the nearest community	Travel time between each reef and the nearest coastal community		Standardized
Human	Management type	Whether fishing is permitted or prohibited	McClanahan et al. 2016, Cinner et al. 2018	/
Environment	Sea surface temperature (SST)	Weekly average SST over 2012–2016 extracted from GOES-POES 4-km resolution dataset	Williams et al. 2015	Reduced as two PCA components and standardized
Environment	Primary productivity	Weekly average chlorophyll-a concentration over 2012–2016 extracted from MODIS-Aqua 4-km resolution dataset	Williams et al. 2015	Reduced as two PCA components and standardized
Habitat	Depth	Mean depth along the 50-m transect	Srinivasan 2003, Brokovich et al. 2008	Reduced as two PCA components and standardized
Habitat	% Live hard coral	Sum of the percentage of the corresponding category within the 200 points along the 50-m transect. Estimated during ecological surveys and following the Point Intercept Transect 25-cm (PIT25) procedure described by Hill and Wilkinson (2004).	Luckhurst and Luckhurst 1978, Roberts and Ormond 1987, Bellwood et al. 2004, Norström et al. 2009, Stella et al. 2011	Reduced as two PCA components and standardized
Habitat	% Macro algae			Reduced as two PCA components and standardized
Habitat	Reef complexity	Score from 0 (no vertical relief, flat, or rubbly areas) to 5 (exceptionally complex relief with numerous caves and over hangs) along the 50-m transect. Estimated during ecological surveys and adapted from Wislon et al. (2007)	McCormick 1994, Nash et al. 2013, Ferrari et al. 2016	Reduced as two PCA components and standardized

Society Institutional Review Board as part of a global social-ecological monitoring framework designed to monitor the impact of conservation and management interventions (Gurney and Darling 2017).

We adapted indicators of the technique, composition, and scale effects to the fishery of northwest Madagascar (Table 2). As indicators of the technique effect, we examined fishing gear use (Brewer 2013, Stevens et al. 2014) by considering gear diversity and the nature of the main gear (spear, line, and gill net) used by households. As an indicator of the composition effect, we examined livelihood diversification (number of livelihood activities; Cinner and Bodin 2010, Chaves et al. 2017, Kramer et al. 2017) with a focus on fishing activity (proportion of households who rank fishing as primary activity). As indicators of the scale effect, we examined both fish demand and displacement of environmental footprints. More precisely, fish demand was analyzed through the wealth of coastal communities using a material style of life index (Pollnac and Crawford 2000) and fish consumption. Displacement of environmental footprints was assessed through the proportion and the degree to which people sold their catch, either directly to local markets or to middlemen who sold fish outside the village. For all indicators, we calculated an average community-level mean to use in our analyses (see details in Table 2).

Data analysis
To explore how proximity to markets and communities affect reef fish biomass beyond ecological and human population size effects, we built generalized additive models (GAMs) considering the two environmental covariates provided by PCA, human population size, travel time from human settlements and markets, and management. All covariates were standardized before modeling (Table 1). GAMs have the property of exploring nonlinear relationships using smooth functions, thus there is no need to make any a priori assumption on the shape of the relationship (Hastie and Tibshirani 1990). All terms used a reasonable spline smoothed function ($k = 3$) given the limited number of data. We considered all the possible submodels, i.e., all the possible combination of variables, including travel time from the nearest market and the nearest community, and management type (fishing permitted or prohibited). We also considered interactions between management and market or community. Because all these models are nested, we performed a likelihood ratio test (LRT) to determine which human variables significantly improved model fit (Wood 2006). We also assessed model fitting and parsimony by using AICc, Akaike Information Criterion corrected for small data samples (Hurvich and Tsai 1989). Prior to modeling, biomass response variable was log+1 transformed. We also checked for collinearity among our covariates using bivariate correlations (all coefficients were < 0.7)

Table 2. Description of the 10 indicators measured for the 10 coastal communities to investigate the association between socioeconomic characteristics and markets among coastal communities. Markets can affect communities through three causal pathways: (i) a technique effect, (ii) a composition effect, and (iii) a scale effect. Theory and references for each effect are also described.

Market mechanism	Theory	References	Indicator	Description	Survey method	Sample size
Technique effect	New or altered technologies are more likely to occur near markets resulting in higher gear diversity and changes in fishing practices	Brewer 2013, Stevens et al. 2014	Gear diversity	The mean number of gear types that household used	Fishers only	164
			Spear	% of households who ranked spear as main gear	Fishers only	164
			Line	% of households who ranked line as main gear	Fishers only	164
			Gill net	% of households who ranked gill net as main gear	Fishers only	164
Composition effect	Households near markets may be involved in more activities and have reduced dependence on fishing	Cinner and Bodin 2010, Charlton et al. 2016, Chaves et al. 2017, Kramer et al. 2017	Livelihood diversity	The mean number of livelihood activities that households are involved in	All households surveys	353
			Fishing activity	% of households who ranked fishing as primary activity	All households surveys	353
Scale effect	Demand: Relatively wealthier communities may be located closer to markets and may have increased demand for fish	Grossman and Krueger 1995, Cinner et al. 2009*a*, Lange et al. 2018	Material Style of Life (MSL)	A composite measure of wealth based on household possessions	All households surveys	353
			Fish consumption	the proportion of households consuming fish at least once a day	All households surveys	353
	Displacement: Economic opportunities increase near markets and may affect the way fish are sold	Grossman and Krueger 1995, Cinner et al. 2009*a*	Fish sold	% of fish catch sold to other people	Fishers only	164
			Selling strategy	(i) Other people in the village, (ii) fish trader/middleman selling outside the village, (iii) local market	Key informants	20

and the variance inflation factor (VIF) estimates (VIF < 5). We then performed control procedure to check whether the smoothness selection criterion (k = 3) was appropriate and detected outliers (Wood 2006). We lastly examined homoscedasticity and normality of residuals.

To explore the social characteristics of communities and mechanisms of technique, composition, and scale, we performed a PCA to explore correlations between the 10 social characteristics of coastal communities (Table 2) and travel time from the nearest market. Because the distance of community from a market was confounded with the presence of management (i.e., remote communities further away from markets were located within MPAs, whereas communities closer to markets were not associated with fisheries management), we included one supplementary variable to take into account the increased presence of management further away from markets. We checked the loadings of variables to identify which variables have the largest effect on each component and the score of each coastal community to quantify how communities are described by different components.

RESULTS

Influence of travel time and management on fish biomass
Among all the models tested, the best model (LRT's *p*-value = 0.02 and lowest AICc = 14.9) explained up to 83% (adjusted *R²*) of the variability observed in log fish biomass (Table 3 and Appendix 3). This model integrated travel time from community in interaction with management, as well as the effect of travel time from the nearest market (Table 3). Accessibility from human settlements (nearest market p-value = 0.001 and community p-value = 0.04), local human population size (p-value = 0.003), and management (p-value = 0.003) were the most important predictors while only one environmental covariate (Env2 p-value = 0.02) was important (Table 3). We found that log human population size had a significant negative influence on fish biomass in both reef categories, i.e., fishing permitted and fishing prohibited, at the same rate (Fig. 2c) while biomass increased further away from market until reaching a maximum at approximately 6–7 h from a market (Fig. 2b, Table 3). In the same vein, fish biomass increased nonlinearly with increasing travel time from the nearest community in reefs where fishing is permitted, with a sharp increase at approximately 1.5 hours (Fig. 2a). Conversely, fish biomass showed no relationship with travel

Table 3. Significance table of all covariates included in the best-fit model of fish biomass (R² adj = 0.83). The two first components (Env1 and Env2) of the principal component analysis (PCA) performed with habitat and environmental variables, human population size, travel time from the nearest market, and travel time from community in interaction with management (fishing permitted vs fishing prohibited) provided the best-fit model. Estimates and standard errors (SE) of estimates of fixed terms while estimated degree of freedom (edf) of smooth terms are provided with corresponding significance test.

	Variable	Estimate	SE	t	Pr(>|t|)
R²(adj) = 0.83	Fixed terms				
	Intercept	2.58	0.077	33.7	< 2e-16
	Management (Fishing banned)	0.41	0.12	3.41	0.003
	Smoothed terms (k = 3)	edf		F	p-value
	Env1	1.00		0.89	0.4
	Env2	1.00		6.73	0.02
	Population	1.00		11.1	0.003
	Travel time market	1.82		10.4	0.001
	Travel time village	0.67		6.63	0.04
	Travel time village : Management (Fishing allowed)	1.50		1.97	0.1
	Travel time village : Management (Fishing banned)	0.83		6.54	0.02

Fig. 2. Partial effects of each socioeconomic covariate predicting log fish biomass in the model while considering the other predictor variables are held constant. Relationships between fish biomass and travel time from the nearest community (a), travel time from the nearest market (b), human population size (c), and management (d) for reefs where fishing is permitted (orange) or fishing is prohibited (green).
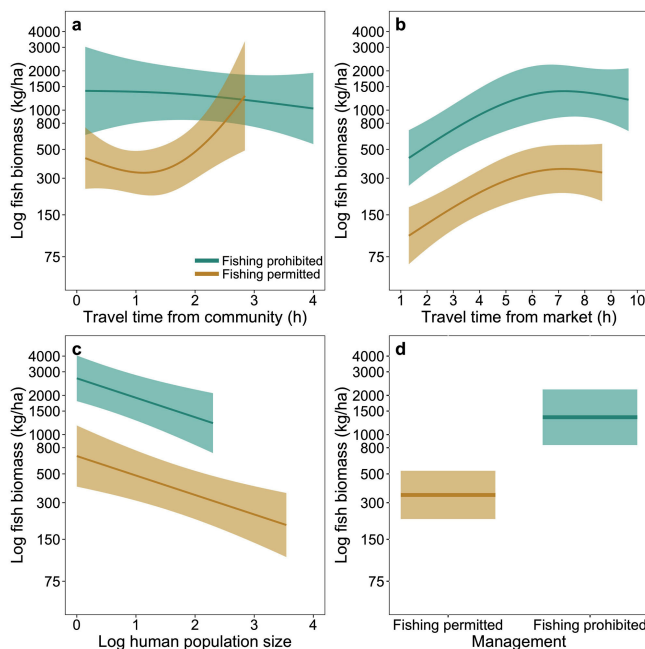
time from the nearest community in reefs where fishing is prohibited (Fig. 2a, Table 3).

Overall, reefs where fishing is permitted and located near markets and communities had lower reef fish biomass than their

counterparts in no-take zones (Fig. 2b-d), demonstrating that marine reserves exert effective controls of fishing pressure in northwest Madagascar. It also suggests some local benchmarks for reef fish biomass can be attained in the absence of fishing at 1235 kg.ha⁻¹ (Fig. 2d). Fish biomass in reefs where fishing is permitted increased beyond one-hour travel time to reach comparable level of biomass than reefs where fishing is prohibited at more than 2.5 hours from the community (Fig. 2a).

Socioeconomic characteristics of coastal communities
We found that 46% (range: 24–67%) of households ranked fishing as their primary livelihood activity (Table 4), and that households were associated with two livelihoods activities on average (range at community level: 1.6–2.3; range of household responses: 1–4). Indicators of the technique effect showed that more than one-half of fishing households (96 out of 164 so 58%) relied on only one gear type for their fishing activities (mean at community level: 1.5; range of household responses: 1–4). However, we highlighted a diversity of fishing practices where line fishing is the main gear type for ~48% of households included in this survey (range across communities: 3–86%), while 25% of households reported gill net as a primary gear (range across communities: 0–87%) and 11% of households reported spear gun as the primary gear (range across communities: 0–37% of households).

We also examined fish demand and displacement of environmental footprints as indicators of the scale effect. We found that 51% of households consumed fish at least once a day (range at the community level: 38–65%) while the material style of life (MSL), measuring the possessions of households, i.e., housing materials and electricity, showed two distinct subgroups because three communities had high MSL, i.e., wealthier communities, while seven communities had less assets (Table 4). Overall, all communities sold ~85% of their catch (range: 71–93%). Although the 10 communities sold fish to other people in the village, key informants reported that seven communities regularly sold fish to middlemen, two sold to both local markets and middlemen, and only one sold fish exclusively within the community (Table 4).

Table 4. Descriptive statistics of the socioeconomic indicators measured for the 10 coastal communities. Travel time from the nearest market and the presence of management actions are also provided.

| Coastal community | Composition effect | | Technique effect | | | | Scale effect | | | | Travel time from market (h) | Management |
	% of hh engaged in fishing activities	Mean number of livelihoods	Mean gear diversity	% using gill net as main gear	% using spear as main gear	% using line as main gear	Material style of life (MSL)	% of hh consuming fish daily	% of fish catches sold	Middle-men†		
Amparamilay	66.7	2.3	1.3	0	37.5	50.0	-0.07	60.0	92.1	II	7.8	Ankarea MPA
Andravorogna	61.1	1.9	1.6	0	18.2	54.5	-0.12	50.0	92.5	II	6.4	Ankarea MPA
Marimbe	40.0	1.9	1.5	36.4	9.1	36.4	-0.08	64.0	81.2	I	8.5	Ankarea MPA
Ratapenjke	52.9	2.0	2.1	0	7.1	85.7	-0.06	38.2	90.3	II	6.4	Ankarea MPA
Amporaha	42.4	1.8	1.4	35.3	5.9	58.8	-0.09	48.5	89.3	II	6.7	Ankivonjy MPA
Marotogny	50.0	1.8	1.5	11.8	11.8	41.2	-0.06	65.0	90.1	II	6.7	Ankivonjy MPA
Nosy Iranja	25.6	1.6	1.3	11.1	0	55.6	-0.09	51.3	70.9	0	7.9	Ankivonjy MPA
Anjiabe	34.0	2.0	1.3	62.5	8.3	25.0	0.02	42.0	78.6	II	1.9	open-access
Antafiambotry	62.0	1.6	1.6	86.7	0	3.3	0.01	50.0	92.4	I	1.9	open-access
Sakatia	24.5	2.1	1.3	8.7	8.7	69.6	0.03	42.9	77.5	II	0.8	open-access

†(I) if first buyer,   (II) if not first buyer and   (0) if absent

Association between market proximity and community characteristics

We also investigated whether proximity to market is related to communities' socioeconomic and resource use characteristics. Correlations from PCA showed that increasing travel time from the nearest market was associated with the following: fewer material assets (communities with lower MSL scores); higher fish consumption (scale effect); more spear and line fishing and less gill net fishing (technique effect); and increasing management (Fig. 3a, Appendix 4). We found that market access did not have a strong effect on the economic structure of households (composition effect) as the proportion of households engaged in fishing and livelihood diversity did not vary much across the communities, i.e., all communities were highly dependent on fishing livelihoods (Fig. 3a, Appendix 4). Finally, there was no significant association between gear diversity (technique effect) and market access (Fig. 3a, Appendix 4).

All communities sold a high proportion of their catches, and there was not a clear relationship between the proportion of fish catch sold and accessibility to markets (Table 4). Although greater travel time from the nearest market was not strongly associated with middleman as a preferred buyer, selling strategies were associated with market proximity (scale effect) (Fig. 3, Appendix 4). We found that fishing households from distant communities (up to two hours from market) did not reach the nearby market to sell fish catches but sold preferentially to their own community or to middlemen who occasionally collected seafood products in those remote communities (Fig. 3b). Similarly, a low proportion of fishing households (in two coastal communities) sold their catch directly to market only if their community was located at less than two hours (Fig. 3b). Overall, middlemen's influence was widespread in the region since they collected seafood products from very close (at less than two hours) but also to more distant communities from markets (up to eight hours) (Fig. 3b, Table 4).

Overall, six communities were properly represented (cos2 > 0.4) by the first two components (PC1 and PC2) of the PCA (Fig. 3, Appendix 5). Surprisingly, we found that communities tended to be distributed through space according to the market (Hell Ville, Ambanja, or Ambilobe) they were nearest to (Fig. 3). Thus, not

only travel time from the nearest market but also differences between markets could affect the communities' socioeconomic characteristics (Fig. 3a).

DISCUSSION

Our study shows how the accessibility of markets and local communities can affect both reef fish biomass and the socioeconomic characteristics of coastal communities. Our analysis also reveals interesting nonlinear patterns between accessibility and fish biomass. We found that fish biomass increases as reefs are further away from the market in both reef categories, i.e., fishing permitted and fishing prohibited (Fig. 2b), but that this effect levels off at about six hours from markets. Alternatively, we found that reefs where fishing is permitted remained relatively depleted when they were < 1.5 hours from the nearest community, but biomass began to increase after 1.5 hours (Fig. 2a). Our results are broadly consistent with previous studies conducted at larger scales, i.e., national and global, highlighting that market integration is a major driver of fish biomass (Brewer et al. 2012, Cinner et al. 2013, D'Agata et al. 2016, Maire et al. 2016). However, the mechanisms associated with this market effect remain poorly understood.

To examine potential explanations for these relationships, we investigated how the socioeconomic and resource use characteristics of coastal communities change with proximity to markets through three strategies: (i) the change in techniques people used to harvest fish (called the technique effect); (ii) the composition of the economy (called the composition effect); and (iii) the scale at which people act as a consequence of economic growth (called the scale effect). Our findings suggest that market proximity in northwest Madagascar can affect coastal communities mainly through the technique and the scale effects, and that these effects could vary according to the characteristics of the nearest market.

First, we found that market proximity influenced the fishing techniques used by coastal households. In small-scale fisheries, gear diversity is generally high and increases over time as the number of fishers increases and economic development is more likely to bring new technologies or new materials that increase

Fig. 3. Associations between market proximity and (a) socioeconomic characteristics of communities through a principal components analysis and (b) selling strategies. (a) Ten socioeconomic indicators were assessed for each of the 10 coastal communities: the mean number of gear types (Gear div.), the proportion of fishing households who ranked gill nets (Gill net), spear (Spear), and line (Line) as main gear, the proportion of households who ranked fishing as primary activity (Fishing), the mean number of livelihood activities that households are involved in (Livelihood div.), a composite index of community wealth (MSL), the proportion of households consuming fish at least once a day (Fish consumption), the proportion of fish sold (Fish sold), and the importance of middlemen (Middlemen) in fish selling that were related to market access (Travel time from market). Social indicators were associated with the composition (green), the technique (orange), or the scale (purple) effect. Because market accessibility and management actions had confounding effects in the study area (marine reserves are disproportionately located far from markets) we included one supplementary variable (Management) to take into account this effect. The 10 coastal communities are represented as colored dots according to which nearest market they are associated with (Ambilobe: black; Ambanja: white; Hell Ville: grey) and are in bold when the community is well represented by the first two components (Cos2 > 0.4, see Appendix 5). Most variables were properly represented (in bold) by the two first components except fish consumption, livelihood, and gear diversity (see Appendix 5). (b) When fish sold, we also looked at the relationship between the preferred buyer: own community, middlemen from other communities, or local market and market access. At least part of fish catch was sold directly within the community, but fish was also sold to middlemen or at the local market. Middlemen were widespread in the region and seemed to buy seafood products from very close (< 2 hours) to more distant communities from markets (up to 8 hours). Distributions are represented using 95% confidence intervals when possible.
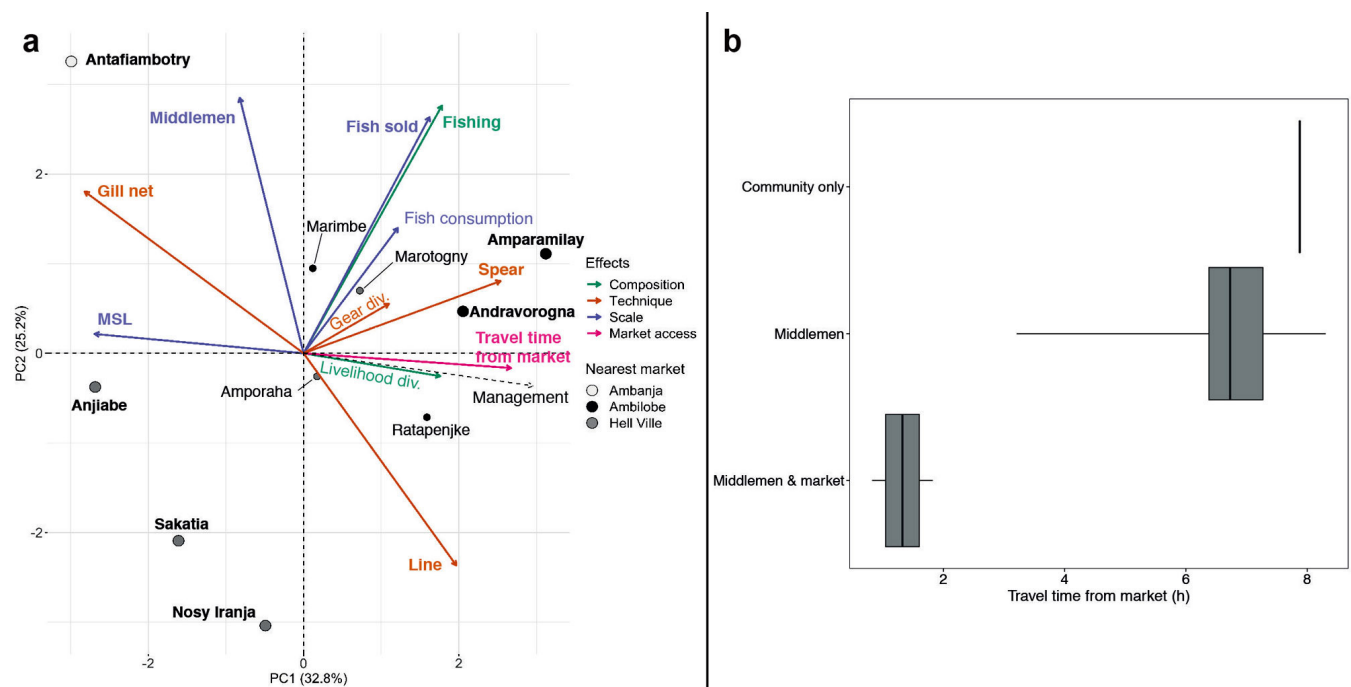
gear longevity (Brewer 2013, Teh et al. 2013, Stevens et al. 2014, Selgrath et al. 2018). In northwest Madagascar, more than one-half of fishing households (96 out of 164, or 58%) only use one gear type while the maximum gear diversity is four, which is consistent with previous results from the Philippines showing that most artisanal fishers rely on only a few gear types (Selgrath et al. 2018). Although there is a confounding effect between gear restrictions (beach seines, mesh size < 25 mm, and nets > 500-m long) and market accessibility (MPAs with gear restrictions are located away from markets), we show that the use of spearfishing and, to a lesser extent, line fishing increase in poorer communities located in MPAs further away from markets while gill nets (mesh size > and < 5 mm) were dominant in relatively wealthier communities close to markets and with no management plan (Fig. 3a). It suggests that future changes in wealth related to market

access may affect fishing techniques being used independently of gear restrictions. Moreover, there is large amount of variation in how fishing gear differentially targeted the proportion, number, and functional traits of species (Cinner et al. 2009*b*, Mbaru et al. 2020). Lines mainly target large and high trophic-level species whereas spears generally target larger individuals of both herbivore and carnivore fishes (McClanahan and Mangi 2004, Davies et al. 2009). Such fishing techniques may induce changes in the structure and functioning of coral reefs through missing trophic cascades and top-down controls (Bozec et al. 2016, Rasher et al. 2017) but some functional roles performed by fishes can be replaced by other taxa, for instance, herbivores by sea urchins (Graham et al. 2017). Gill nets generally have highest catch per fisher, a low species selectivity, i.e., catch a wide range of species and functional diversity, but high size selectivity according to the

mesh size (McClanahan and Mangi 2004, Davies et al. 2009, Mbaru et al. 2020). Gill nets capture a significant proportion (13–33%) of key herbivores (Cinner et al. 2009b) such as grazers and scrapers/excavators that have been identified as critical to the resilience of coral reefs (Bellwood et al. 2004, Mumby et al. 2006) but also remove high proportions of juveniles (McClanahan and Mangi 2004, Mangi et al. 2007) that jeopardizes the ability of fish populations to replenish. Conversely, ecological conditions can affect gear effectiveness and gear with low selectivity such as nets can be particularly successful on degraded reefs that are dominated by herbivores (Hicks and McClanahan 2012). An understanding of the gear selectivity in northwest Madagascar would allow for effective gear-based strategies that can act as complementary strategies to existing restrictions. New or altered technologies are more likely to occur near markets and are driven by resource demand (Brewer 2013, Stevens et al. 2014). However, innovation and access to more efficient technology can generate inequality and poverty (Pauly 2006), which can lead to "social-ecological traps" where the most impoverished fishers are spurred to use destructive techniques (Cinner 2011). Last, fishing practices can reflect fishers' preference for different types of fish, i.e. species or families, which could be sold at different markets according to demand. We suggest that better understanding the links between markets and fishing communities is crucial to implementing effective market-based actions that could help to regulate the effect of markets on fish stocks and fishing communities.

Second, we found that market proximity can also affect communities through the scale effect, and more specifically through both demand and displacement aspects. Relatively wealthier communities (assessed by material assets and a higher MSL score) are located closer to markets, which is consistent with other studies showing how access to major cities can change the economic, educational, and health status of societies (Weiss et al. 2018). We found that relatively wealthier communities tended to consume less fish, a finding that contrasts with previous studies showing that fish consumption is generally lower in poorer compared to wealthier households (Kawarazuka 2010). One likely explanation for our contrasting results is that we examined trends at a community, rather than household scale. Moreover, all of our study communities sold a high proportion of their catches, often directly to markets or to middlemen (Table 4, Fig. 3b, Appendix 6). Indeed, middlemen operate throughout our study region, collecting seafood products from less than two hours to eight hours away from markets (0b). In many coral reef fisheries, middlemen are essential intermediaries, collecting sea products directly from fishers and providing new trade opportunities and links to markets (Crona et al. 2010, Brewer 2013, Fröcklin et al. 2013, Dacks et al. 2018). Fish prices greatly vary over time and space (quality, seasonality, local preference, seller, buyer) however it has been shown that fish prices are generally higher close to markets (Schmitt and Kramer 2009, Brewer 2011). Middlemen can contribute to fishing income generation in remote communities while fishing households close to markets can increase their incomes by selling their catch directly to markets (Brewer 2011), especially women (Singleton et al. 2019). Most fishers lack information about market prices thus middlemen may drive fish prices down when competition is high prompting households to fish more to ensure stable incomes especially close to markets. However, we were not able to measure whether

demand from middlemen influenced fishing practices or targeted fish species. Although right-based management actions, i.e., locally managed marine areas that preferentially provide access to local users, can control harvesting pressure from "outsiders," this does not prevent right holders from increasing fishing pressure to unsustainable levels. Beyond the negative influence of markets, a further investigation of the role of middlemen through the fish value chains in small-scale fisheries in Madagascar could improve the governance of fish stocks and the sustainability of coastal social-ecological systems (Crona et al. 2010, Thyresson et al. 2013, Wamukota et al. 2014, Cinner et al. 2016). Furthermore, although home ranges of fishing vessels can be used to measure the ability of fishermen to travel further away to catch more fish (Cinner et al. 2009a), all fishing vessels in our study were unmotorized. Most fishing communities in Madagascar commonly use small dugout canoes for one to four persons that are unsafe for high sea fishing, de facto restricting fishing trips' duration and geographical influence on surrounding reefs. However, increased market demand and relatively higher economic development close to markets might lead fishers to access more powerful and larger boats to expand their fishing grounds to more remote areas to maintain catch, as already demonstrated in Solomon Islands (Albert et al. 2015). Such changes could exacerbate the effect of markets and call for greater consideration of technology introductions and improvements as a consequence of economic development.

Finally, market proximity had no strong influence on the livelihood composition of coastal communities (composition effect) because we found generally low livelihood diversity (two activities per household on average) and that remote communities had no more or less livelihoods compared to communities closer to markets (Fig. 3a, Table 4). Even fishing households were generally engaged in other activities such as farming (when possible) or tourism. Our results contrast with a previous study in the Pacific islands where market proximity has been found to be positively correlated with increased income and reduced dependence on fishing (Charlton et al. 2016). One probable explanation for our contrasting results is that we considered a small coastal area rather than the whole country, where artisanal fishing remains a major contributor to food security and income of the Malagasy coastal population (Barnes-Mauthe et al. 2013). Additionally, our case study of northwest Madagascar provides new insights into how livelihoods and fishery dependence are related to this specific social-ecological context.

The importance of management to support remote communities
MPAs are advocated as a critical tool to conserve marine resources (Edgar et al. 2014, Sala et al. 2018). Consistent with other studies from Madagascar (Komeno and Randriamanantsoa 2013), our study found that fish biomass was higher in reefs where fishing is prohibited compared to reefs where fishing is permitted, even though these marine managed areas (MPAs and LMMAs) were only recently established (2011 and 2015). We did not conduct before and after studies, so there are potential site selection effects observed here, i.e., sites could have been selected for reserves because they have higher initial fish biomass. Interestingly, we found fish biomass in no-take zones decayed with proximity to markets at the same rate as in areas where fishing is permitted. Similarly, a global-scale study also found that even in high compliance MPAs, fish biomass decreased along a gradient of

human impact, suggesting there are impacts of surroundings seascapes on local resources, particularly for small MPAs (Cinner et al. 2018). In our study area, there is also a strong confounding effect between management and market accessibility because two marine managed areas (out of three) were located away (> six hours) from markets. This is consistent with previous studies showing that protected coral reefs around the world are disproportionately farther from main cities and markets (Maire et al. 2016, Cinner et al. 2018). These patterns are exacerbated by the momentum toward large offshore MPAs that target low-conflict ocean areas to rapidly meet international conservation targets (O'Leary et al. 2018), but can also jeopardize prioritizing management activities in coastal areas where overexploitation can threaten the sustainability of marine resources. Effective governance of marine managed areas is necessary to achieve biodiversity conservation objectives and socioeconomic development (Watson et al. 2016). Shared governance involving nongovernmental organizations (NGOs) and local communities may help the expansion of Madagascar's protected area system but has shown mixed results regarding conservation effectiveness (Gardner et al. 2018). Thus, future policies will face the challenge described in the Sustainable Development Goals (Rees et al. 2018) mixing nature conservation and human development.

Limitations of the study
The recent establishment of Ankarea and Ankivonjy MPAs could suggest that fish biomass was initially higher in those areas, and that this higher biomass might be more attributed to its long-lasting isolation from markets and relatively lower human population rather than the effect of protection per se. Moreover, there has not been an assessment of the level of compliance in these MPAS and we do recognize that levels of compliance within the "fishing prohibited" category (no-take zones within Ankarea and Ankivonjy MPAs and Nosy Tanikely National Park) may vary. However, we found that fish biomass was much higher in reefs where fishing is prohibited than in reefs where fishing is permitted (Fig. 2d) suggesting that compliance is relatively high in all no-take zones.

Although our findings suggest that the effects of market proximity could vary according to the characteristics of the nearest market, we could not find any relevant aspect. The three markets considered in our study (Ambanja, Hell Ville, Ambilobe) have similar demographic and economic aspects. We can assume that middlemen have strong links with specific fishers and also preferred markets to sell fish. Further work is needed to better understand how middlemen operate and how they affect marine resource exploitation in our study area.

Although recent studies have suggested that higher catches in remote communities might be because of the presence of middlemen (Dacks et al. 2018), we could not unravel the direct effects of middlemen on coastal resources in our study. Also, there is a strong confounding effect between management actions and market accessibility because the two community comanaged MPAs (Ankarea and Ankivonjy) under study were located away from markets and no open-access areas were found far from markets. Although it was difficult to disentangle the relative effect of management and accessibility on communities' characteristics, we provide some evidence on the role of markets in shaping the fishing practices of local communities while also accounting for

management. Further work is therefore needed to assess how fishing strategies in coastal communities are shaped by remoteness and limited access to markets, particularly in developing countries.

CONCLUSION
Community characteristics, management, and market access influenced fish biomass in this case study of northwest Madagascar. We found that market proximity and characteristics affected coastal communities mainly through the technique and the scale effects, which ultimately can lead to changes in the exploitation and sustainability of marine resources. Markets also shaped reef fish biomass independently of management while the effect of fishing communities interacted with management. Understanding the human-environmental interrelations relies on a scaling-down to highlight the drivers of resource use and governance by considering households behaviors and decision making. A better assessment of how human societies and markets can influence social-ecological characteristics of sustainability is thus a critical step toward long-term management of the coral reef fisheries.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.
php/11595

Data Availability Statement:

Data and code used for the analyses are freely available and can be found at https://github.com/EvaMaire/Markets_NWMadagascar

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Appendix 1. Associations between environmental and benthic conditions of reefs through a Principal Component Analysis and corresponding loadings. The two first components (PC1 and PC2) mix both environmental and benthic variables and explain 56% of the variation observed between reefs. PC1 mostly reflects hard coral cover and complexity (i.e., reef condition and habitat quality) and PC2 mostly describes macroalgae and depth, two factors that can affect fish composition and biomass. PC1 and PC2 reflect potential ecological drivers of reef fish biomass and, as such, are important to retain in the models.
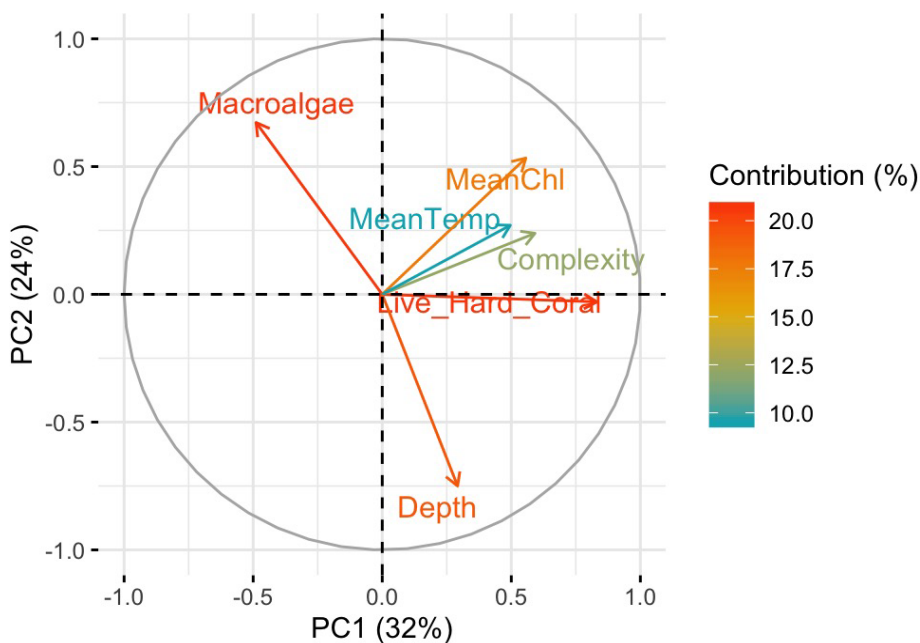
|	PC1	PC2	PC3	PC4	PC5
Depth	0.21	-0.63	0.43	0.07	0.25
Live_Hard_Coral	0.6	-0.02	-0.11	0.31	-0.72
Macroalgae	-0.35	0.56	0.27	0.44	-0.08
Complexity	0.43	0.2	-0.53	0.34	0.6
MeanChl	0.4	0.45	0.16	-0.72	0.04
MeanTemp	0.36	0.23	0.65	0.27	0.23

Appendix 2. Proportion of households surveyed and total estimated number of households in each community.

| Village	Estimated number of households	Number of households interviewed
Amparamilay	16	16
Amparoha	30	30
Andravorogna	23	23
Anjiabe	188	50
Antafiambotry	215	50
Marimbe	25	25
Marotogny	111	40
Nosy Iranja	105	40
Ratapenjke	33	30
Sakatia	290	50
	Total	354

Appendix 3. Comparison of all the nested models to determine the best combination of human variables to explain fish biomass. The two first components (Env1 and Env2) of the Principal Component Analysis (PCA) performed with habitat and environmental variables, human population size provided initial model M0. AICc and Likelihood Ratio (LR) test performed against nested reference (ref) model determined the best combination of human variables. The best model (M3B) combined management, travel time from market and travel time from community in interaction with management.

Model	Covariates	Interaction	AICc	LR test
M0 (ref)	Env1 + Env2 + Population	/	25.0	
M1	Env1 + Env2 + Population + Management	/	18.4	0.002 **
M1 (ref)	Env1 + Env2 + Population + Management	/	18.4	
M2	Env1 + Env2 + Population + Management + Market + Village	/	16.3	0.02 *
M2 (ref)	Env1 + Env2 + Population + Management + Market + Village	/	16.3	
M3A	Env1 + Env2 + Population + Management + Market + Village	Management * Market	21.0	0.6
M3B	Env1 + Env2 + Population + Management + Market + Village	Management * Village	14.9	0.02 *

Appendix 4. Correlogram showing correlations between the ten socioeconomic indicators of coastal communities and market access.
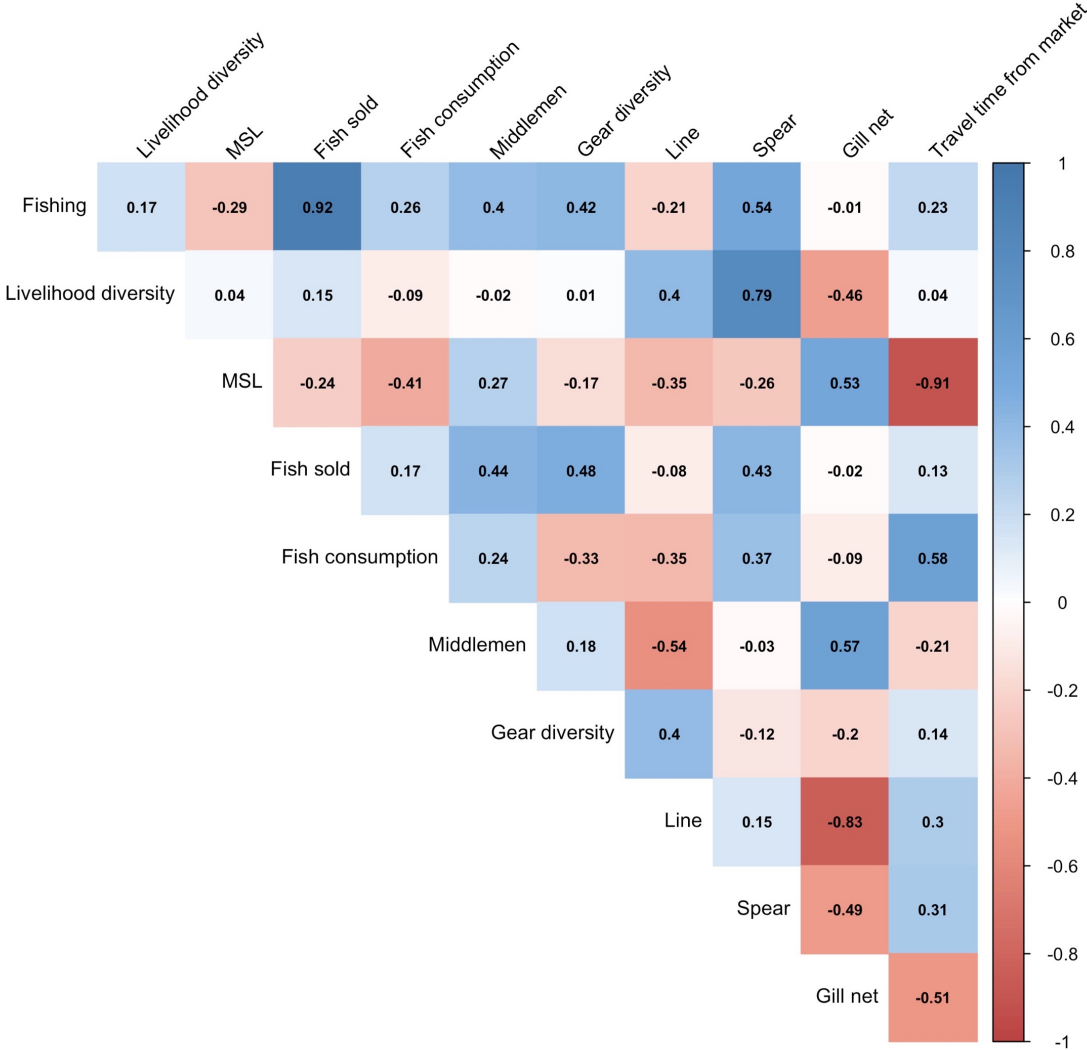
Appendix 5. Scores (cos2) of (a) each variable and (b) community integrated in the PCA linking market access and social characteristics of coastal communities. Ten socioeconomic indicators were assessed for each of the 10 coastal communities: the mean number of gear types (Gear diversity), the proportion of fishing households who ranked gill nets (Gill net), spear (Spear) and line (Line) as main gear, the proportion of households who ranked fishing as primary activity (Fishing), the mean number of livelihood activities that households are involved in (Livelihood div.), a composite index of community wealth (MSL), the proportion of households consuming fish at least once a day (Fish consumpt.), the proportion of fish sold (Fish sold) and the importance of middlemen (Middlemen) in fish selling that were related to market access (TT market). The supplementary variable (Management) was also represented. Most variables were properly represented (cos2 > 0.4) by the two first components (PC1 and PC2) except fish consumption, livelihood and gear diversity. Six communities were properly represented (cos2 > 0.4, in bold) by the two first components (PC1 and PC2).
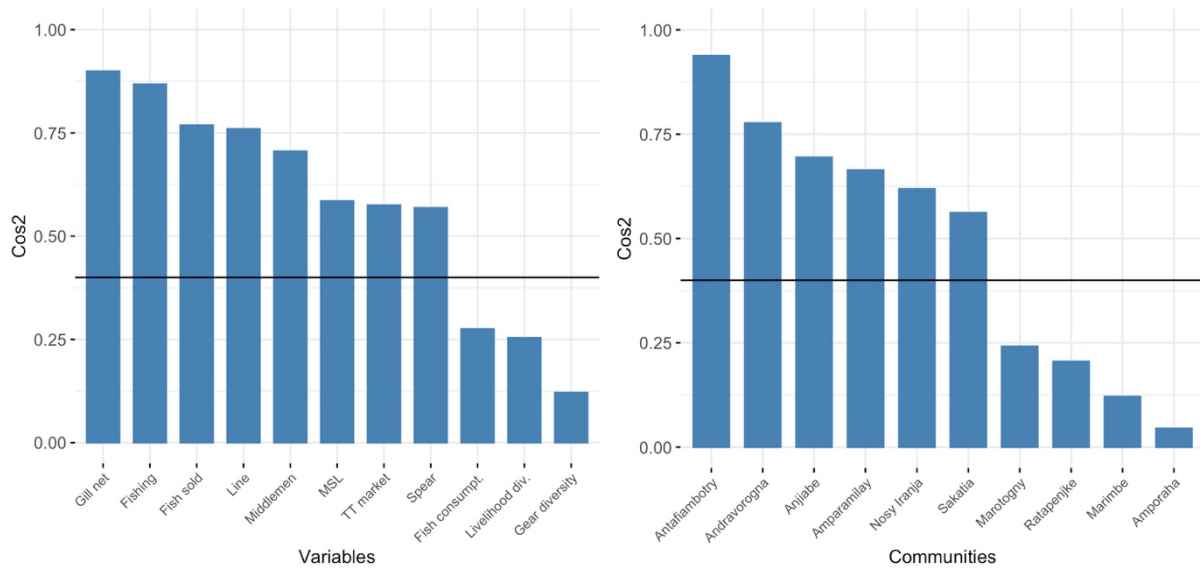
Appendix 6. Associations between market proximity and selling fish catches. We looked at the relationship between the preferred buyer: own community, middlemen from other community or local market and the proportion of fish sold. All communities sold a high proportion of their catches (>71%) but communities regularly sold on average 90% (range: 81 − 93) of fish catch when middlemen were the only buyer, 78% (range: 78 − 79) to both middlemen and market and 71% to their own community when no external buyer was present.