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LETTER

Low fuel cost and rising fish price threaten coral reef wilderness

Fraser A. Januchowski-Hartley[1,2,3] | **Laurent Vigliola**[2] | **Eva Maire**[4,5] | **Michel Kulbicki**[6] | **David Mouillot**[4,7]

[1]UMR 9190 MARBEC, IRD-CNRS-UM-IFREMER, Institut de recherche pour le développement (IRD), Montpellier, Cedex 5, France

[2]UMR 9220 ENTROPIE, Institut de Recherche pour le Développement (IRD), Centré IRD de Nouméa, Nouméa, New Caledonia

[3]Department of Biosciences, College of Science, Swansea University, Abertawe, UK

[4]UMR 9190 MARBEC, IRD-CNRS-UM-IFREMER, Université de Montpellier, Montpellier, Cedex 5, France

[5]Lancaster Environment Centre, Lancaster University, Lancaster, UK

[6]UMR 9920 ENTROPIE, Laboratoire Excellence LABEX Corail, Institut de recherche pour le développement, Perpignan, France

[7]Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, Queensland, Australia

Correspondence
Fraser A. Januchowski-Hartley, Institut de recherche pour le développement (IRD), UMR CNRS UM IRD IFREMER 9190 MARBEC, CC 093, 34095 Montpellier, Cedex 5, France.
Email: f.a.hartley@swansea.ac.uk

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Abstract

Wilderness areas offer unparalleled ecosystem conditions. However, growing human populations and consumption are among factors that drive encroachment on these areas. Here, we explore the threat of small-scale fisheries to wilderness reefs by developing a framework and modeling fluctuations in fishery range with fuel costs and fish prices. We modeled biomass of four fishery groups across the New Caledonian archipelago, and used fish and fuel prices from 2005 to 2020 to estimate the extent of exploited reefs across three fishing scenarios. From 2012 to 2018, maximum profitable range increased from 15 to over 30 hr from the capital city, expanding to reefs previously uneconomic to fish, including a UNESCO heritage site. By 2020, over half of New Caledonian (∼17% global) wilderness reefs will become profitable to fish. Our results demonstrate that remoteness from humans should not be considered protection for wilderness coral reefs in the context of rising fish prices.

KEYWORDS

coral reef conservation, fisheries management, reef accessibility, small-scale fisheries, South Pacific

1 | INTRODUCTION

Humanity has a global impact on nature through proximate and distant forcing factors on land and at sea (Beyer, Venter, & Grantham, 2019; Jones et al., 2018; Mittermeier et al., 2003), and likely no part of the globe can be considered pristine. Within this Anthropocene era (the current geological age where humans are the dominant influence on climate and environment), the concept of "wilderness" has evolved to refer to natural systems isolated enough from human activities to remain ecologically quasi-intact, providing refugia for critical habitats (e.g., primary forests and coral reefs) and their associated biodiversity (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000). Distance from humans, or low accessibility, can be considered a *de facto* economic barrier to exploitation (Mittermeier et al., 2003; Tickler, Meeuwig, Palomares, Pauly, & Zeller, 2018). For example, intact rainforest areas provide barriers to exploitation due to the difficulty of traversing the terrain (Abernethy, Coad, Taylor, Lee, & Maisels, 2013; Espinosa, Celis, & Branch, 2018; Parry, Barlow, & Pereira, 2014), while in the marine realm distance and travel time, particularly across open ocean can similarly provide barriers to exploitation (Maire et al., 2016). These wilderness areas thus offer unparalleled ecosystem conditions to host the most vulnerable species (e.g., mammals and sharks), and can be considered as benchmarks to evaluate conservation efforts (Cinner et al., 2018; Graham & McClanahan, 2013; Myers et al., 2000). However, rapidly growing human population, per capita consumption, and technological advances are driving unprecedented encroachment upon these areas (Abernethy et al., 2013; FAO, 2018; Jones et al., 2018; Parry et al., 2014; Song, Hoang, Cohen, Aqorau, & Morrison, 2019; Tickler et al., 2018).

Here, we present a framework to explore the potential threat of increasing access to wilderness areas using the lens of a small-scale coral reef fishery between 2005 and 2020, assessing the geographic extent of fishery profitability. We further discuss the roles that governance institutions can play to mitigate this exploitation of wilderness. Over the past 50 years, fishing fleets have consistently traveled further in the hunt for fish, and, through the support of subsidies, have potentially expanded their spatial reach to over 66% of continental shelves, and approximately 90% of ocean area (Kroodsma et al., 2018; Sala et al., 2018; Tickler et al., 2018). Fishing activities are unique among large-scale food industries in that expenditures on fuel represent a large proportion (75–90%) of total costs (Parker & Tyedmers, 2015). Contraction of artisanal and small-scale fisheries was expected to follow the increase in fuel prices, limiting fleets to accessible, likely over- or fully exploited areas, increasing food insecurity for much of the world's poor (Parker & Tyedmers, 2015; Pelletier et al., 2014; Popova et al., 2019). However, after a sustained price of over $100/barrel between 2008 and 2015, oil price fell to below US$40/barrel at the end of 2015 (constant 2015 USD). Although there was an increase between 2016 and 2018, oil price has declined by ∼20% over the course of 2019, and is expected to remain below the peaks seen in 2012–2014 up to 2050, due to decreased demand, improved energy efficiency, and alternate energy supplies (EIA, 2019). In parallel, fish prices have steadily increased this century, even as the total volume of fisheries and aquaculture production has risen (FAO, 2018; Tveterås et al., 2012). With fish resources near markets often severely depleted (Cinner, Graham, Huchery, & Macneil, 2013; D'agata, Mouillot et al., 2016), these dynamics are potentially encouraging artisanal and small-scale fisheries to exploit wilderness areas owing to their emerging profitability.

2 | METHODS

2.1 Cost of fishing framework

Our conceptual framework has two major components: the operational cost of fishing and catch revenue for a given fishing campaign. Capital costs are an important factor when considering entering or exiting a fishery (Pradhan & Leung, 2004), but here we concentrate on operational costs because they are immediately consequential for fishery range. We present a constant-yield model where operational cost is a function of travel time, fishing time, salaries, and fixed costs, while revenue is a function of total yield and the proportion of high- versus low-value fish in the catch. Recent studies suggest that travel time from human population explains fish biomass better than distance (Cinner et al., 2018; Juhel et al., 2018; Maire et al., 2016), and thus we considered operational costs as a function of time—both of travel and time spent fishing. Fishes are often landed distant from market, prior to transport by road, which can have significantly lower costs per km travel than sea transport, and by using time rather than distance, we are more accurately able to represent costs (Maire et al., 2016).

In our yield-limited model of operational costs, we assume that biomass increases nonlinearly with distance from market, and that total time is not constrained, minimum profitable travel occurs at the lowest travel time for which fishing costs and travel costs are below expected revenue, while maximum profitable travel is at the highest travel time for which this is the case (Figure 1). Optimal travel time (maximization of profit) will likely occur at a lower travel time than that taken to reach pristine reefs, despite increases in fishing efficiency beyond this point. Once optimal travel time is exceeded, cost increases are primarily due to travel, because fishing is likely more efficient with increasing fish biomass. Coral reef fisheries are multispecies fisheries, with different species and groups valued differently, and higher trophic level and

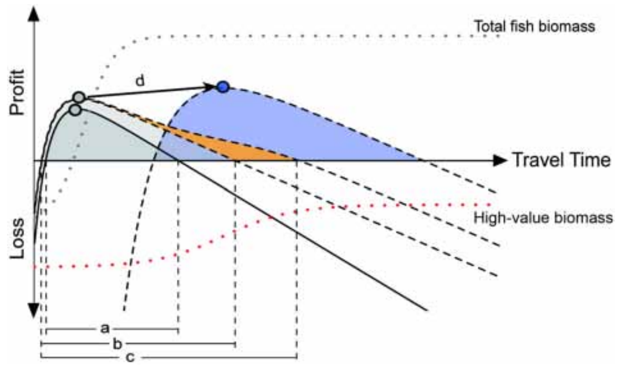


FIGURE 1 Conceptual diagram linking fisheries profitability to travel time from market, fuel cost, and fish price. Black lines are fishery profit–loss curves under low (solid) and high (dashed) fish price scenarios, horizontal line is cost–revenue equilibrium, dotted lines indicate fish biomass, and the gray/blue shaded areas represent profitable fisheries (assuming fixed yield). Gray and blue dots are travel time where profits are maximized for each scenario. Fishing is profitable between a minimum time, where fish become abundant enough to fish, and a maximum beyond which travel becomes too costly (a). If fuel price decreases, or fish price increases, maximum travel time will increase (b). If a high-value species biomass increases with distance from humans at a slower rate than total biomass (red dashed line), decrease in travel costs coupled to increase in fish prices may result in significantly greater maximum travel time, dependent on the rate of increase of the high-value species (c). Similarly, fishery specialization to high-value species will increase both maximum profitable travel time and profits (d)

more-valuable species biomass will increase more slowly with travel time from market. Although minimum travel time to reach profitable reefs may not change, depending on relative abundance and time spent fishing, maximum profitable travel time can increase substantially (Figure 1).

2.2 New-Caledonia case study

New Caledonia is a South Pacific archipelago, approximately 1,200 km east of Australia. The main island of "Grande Terre" has one of the largest barrier reefs in the world, covering 24,000 km^2, and there are extensive atoll reefs (Chesterfield, Entrecasteaux, Astrolabe), three large high islands (the Loyalty Islands) and several smaller islands, and wilderness coral reef areas are over-represented (Supplementary Material). One third of the population lives in Grand Terre's southwest, in and around Nouméa, the capital (~98,000 people) (ISEE, 2019). Here, we estimated the potential geographic extent of profitable small-scale and artisanal reef fisheries across New Caledonia from 2005 to 2018, and forecasted spatial expansion of profitable fisheries to 2020 using fuel and fish price trends.

We used the following scenarios: (a) boats <5 m length traveling up to 50 km from the nearest population; (b) boats between 5 and 8 m length traveling up to 150 km from the nearest population; and (c) boats >8 m length fishing only reefs more than 50 km from the nearest population. The first two scenarios include a "land" component, while vessels >8 m travel entirely by sea, using appropriate passages through the reef (Juhel et al., 2018). For scenarios 1 and 2, each boat was crewed by two nonsalaried fishers, while in scenario 3 each boat was crewed by four fishers with a salary of $60/day/fisher (2015 US$). These scenarios are based on boat size distributions, fisher numbers, and approximate salary from Province Sud fisheries department data, Guillemot, Léopold, Cuif, and Chabanet (2009), and Gontard and de Coudenhove (2013) as representative of fishing vessels in New Caledonia. For scenarios 1 and 2, fishers traveled to a launch site, conducted four fishing trips, and then returned to Nouméa to sell their catch. We calculated revenue by predicting biomass of reef fish using boosted regression trees (BRT) for all species combined and for four catch categories (Coral trout—*Plectropomus* spp., Unicornfish—*Naso* spp., Parrotfish—*Scarinae*, and Emperors and Snappers—*Lutjanus* and *Lethrinus* sp.). These groups were chosen based on prominence in the fish market in Nouméa and occurrence within transects (i.e., rare but valuable species, such as *Bolbometapon muricatum*, were not included because of insufficient representation in data to create accurate models). All analysis was conducted in R (R Core Team, 2017). For details on BRT models, see the Supporting Information.

To estimate the potential upper and lower ranges of profitable travel time, we calculated 95% confidence intervals of annual means in fish and fuel prices and applied these to our framework. Predictor variables were chosen based on previous studies (D'agata, Mouillot et al., 2016; Maire et al., 2016). Data on fish and fuel prices between 2005 and 2015 were obtained from the New Caledonia Direction des Affaires Maritimes and provincial fisheries departments, and downloaded from the website of the New Caledonia Direction de l'Industrie, des Mines et de l'Energie (www.dimenc.gouv.nc), respectively. See the Supporting Information for further technical details.

3 | RESULTS

The increasing cost of fuel between 2005 and 2012 (33% ± 4% for gasoline and 47% ± 2% for diesel—Figure 2a) induced a contraction in both the maximum time a vessel could travel to reach profitable reefs (Figure 2b) and the proportion of reefs accessible to each vessel type that could be profitably fished (Figures 2c–4). For boats greater than 8 m length, maximum travel time to reach profitable reefs decreased from over 22.7 hr in 2005 (range uncertainty: 17.1–23.0 hr) to 14.3 hr in 2008 (range uncertainty: 14.3–22.7 hr), and returned to 22.7 (range: 4.3–22.7) in 2012. However, the percentage of

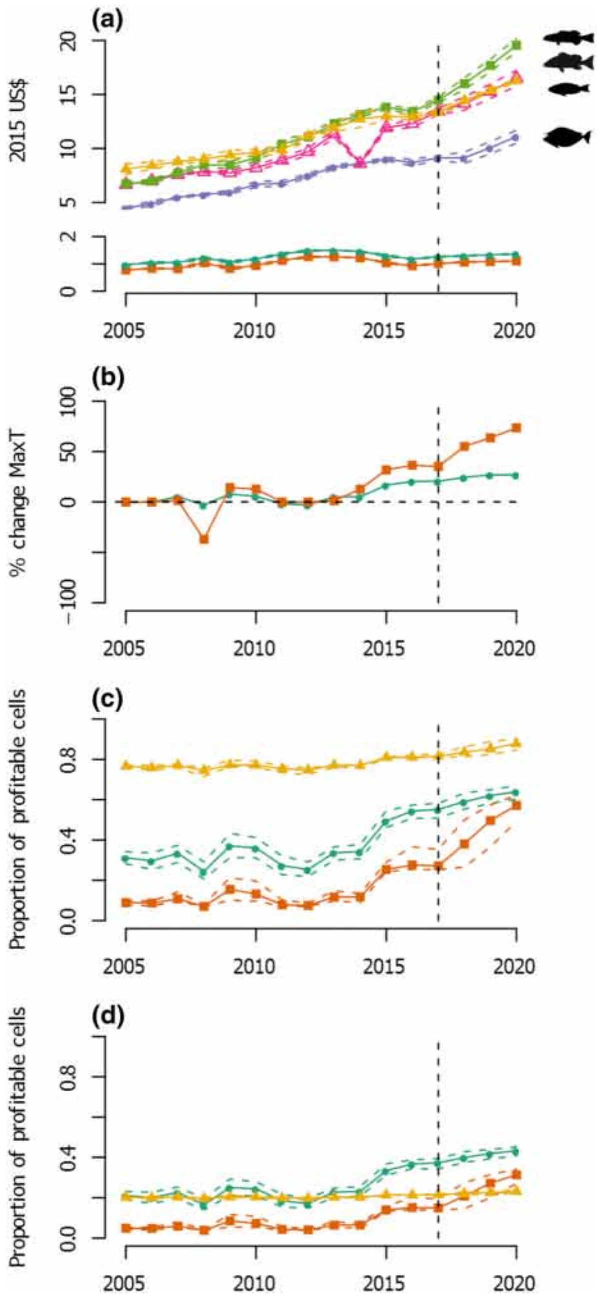


FIGURE 2 Change in fuel costs, fish prices, time to reach profitable reefs, and proportion of profitable reefs of New Caledonia over the time scale of this study (2005–2020). (a) Annual mean price per kilogram of the four main groups of coral reef fish species (from top to bottom: coral trout (squares), snappers and emperors (closed triangles), parrotfish (open triangles), and unicornfish (circles)) and fuel price (green circles—petrol and orange squares—diesel). Shaded areas are 95% confidence intervals of annual means. (b) Percentage change in maximum profitable travel time for each vessel type (size in meters) compared to the 2005 baseline. Orange squares—boats >8 m and green circles—boats >8 m <12 m (boats <5 m not shown). (c) Proportion of profitable accessible reefs for each vessel type across the New-Caledonian archipelago (yellow triangles—boats <5 m). (d) Proportion of all reefs across the New-Caledonian archipelago profitable for each vessel type. Trends to the right of vertical dashed line are predictions post 2017

profitable reefs decreased from 9.0% (7.6–9.6) to 7.9% (7.3–9.7) in 2008 and 7.5% (7–8.6%) in 2012 (Figure 2c). For boats 5–8 m in length, maximum travel time under which fishing was profitable decreased slightly, from 11.4 hr (11.8–13.0) to 10.8 hr in both 2008 and 2012 (range: 10.3–10.8 both years), and percentage of profitable reefs from 31.1% (28.2–34.4) to 24.4% in 2008 (range: 20.7–29.0) before increasing again to 25.3% (range: 22.0–29.0) in 2012 (Figure 2c). Boats <5 m could fish to the limits of their range throughout these years, and the proportion of accessible profitable reefs remained around 75% (range: 71.4–75.7 across all years and uncertainty).

In 2017, it was profitable for vessels >8 m to fish almost 30% of accessible reefs (range: 25.2–35.3), including the northern reefs of the New Caledonia lagoon, Petri, and Astrolabe at travel times of up to 35.1 hr from Nouméa (Figures 2 and 3b), and potentially even Southern Chesterfield atolls (Figure S1). By 2020, if rates of change in fuel and fish price over the past decade remain constant, these vessels will be able to travel up to 40 hr from Nouméa (range 37.2–42.2) and still find profitable fishing grounds, across 57.2% of accessible reefs (range 49.2–62.2). This includes the majority of reef cells in the Southern Chesterfield atolls (Figure 3 and Figure S1). For smaller boats (5–8 m length), there was an increase in maximum range within which fishing was profitable from 10.8 hr in 2012 to 13.8 hr across all fish and fuel price combinations in 2020 (the limit of this scenario's range from Nouméa), and an increase in the amount of profitable reef cells from 25.3% to 63.9% (range 63.3–70.0). Only depauperate reefs near Nouméa would remain not profitable to fishing in 2020 (Figure 3; Figure S2 and S3). Most coral reefs immediately surrounding the main island of New Caledonia are reachable by small vessels, resulting in lower fish biomass near the main city of Nouméa. This pattern is particularly true for higher value species, such as coral trout (Figure S1). If fuel prices return to 2012 prices, it is likely that the majority of reefs will still be profitable for most fishers, assuming no concurrent fall in fish prices (Figures 2 and 4).

4 | DISCUSSION

Small-scale fisheries are often overlooked within global analyses of fishing effort (e.g., Kroodsma et al., 2018). Our results demonstrate that these fisheries may, due to the divergent trajectories of fuel cost and fish price, threaten wilderness resources. Although initially increasing travel costs resulted in contraction of the fishery, the drop in fuel prices in the context of rising fish prices (notably we did not account for subsidies here) has resulted in a marked increase in profitability of the fishery. A *de facto* economic barrier dissuading exploitation has been breached for some reefs over the

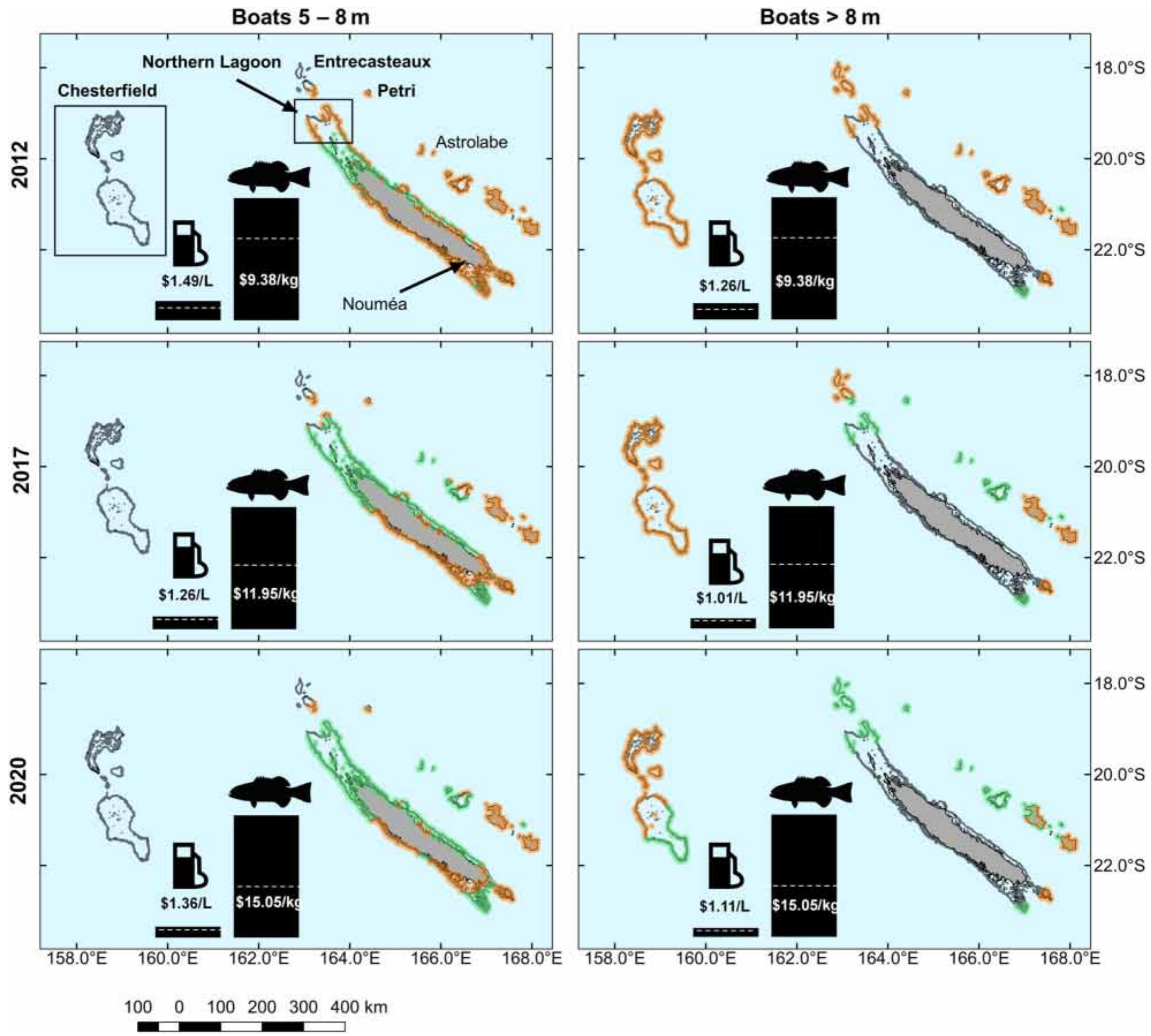


FIGURE 3 Profitability maps of New Caledonian reefs for vessels 5–8 m, and vessels >8 m in length. Black bars indicate fuel price (gasoline for 5–8 m boats and diesel for boats >8 m) and mean fish price at the Nouméa market for each year. Dashed lines indicate 2005 fuel and fish prices. All values in 2015 US$ equivalent. Orange represents unprofitable reef cells, and green represents profitable reef cells

past decade, and will be for the most remote New Caledonian reefs in the near future. By 2020, over 50% of New Caledonian (~17% of global) wilderness reefs could become profitable to fish. Fishing these more remote reefs (Astrolabe, Chesterfield, Entrecasteaux—a UNESCO World Heritage Site—and Petrie) requires fishers to cross open ocean (100–500 km; > 15 hr travel time), a significant economic barrier to the artisanal fishing fleet. Previously, high travel costs were not sufficiently compensated by reduced fishing time, or increased likelihood of capturing more valuable species. However, increasing relative abundance of valuable fishery species with distance from market (Cinner et al., 2013; D'agata, Mouillot et al., 2016; MacNeil et al., 2015), and rising fish prices have increased profitable range for all sectors of our case-study post-2012.

Our framework, demonstrated in the context of a small-scale reef fishery, can be applied not only to other artisanal fisheries (e.g., small-scale temperate fisheries), but also to other kinds of resource extraction and use in other ecosystems. The operational costs, or accessibility axis of our framework, embedded in the concept of travel time may be, for instance, applied to the bushmeat trade in the Amazon and central Africa (Lindsey, Romañach, Tambling, Chartier, & Groom, 2011; Parry et al., 2014). Similar to fisheries, the bush meat trade extracts resources, with little capital costs or infrastructure requirement with the resulting meat, transported to the nearest market for sale. As roads from logging and other activities expand to untouched areas (Espinosa et al., 2018; Laurance, Sloan, Weng, & Sayer, 2015), travel times will decrease, while hunting success may increase due

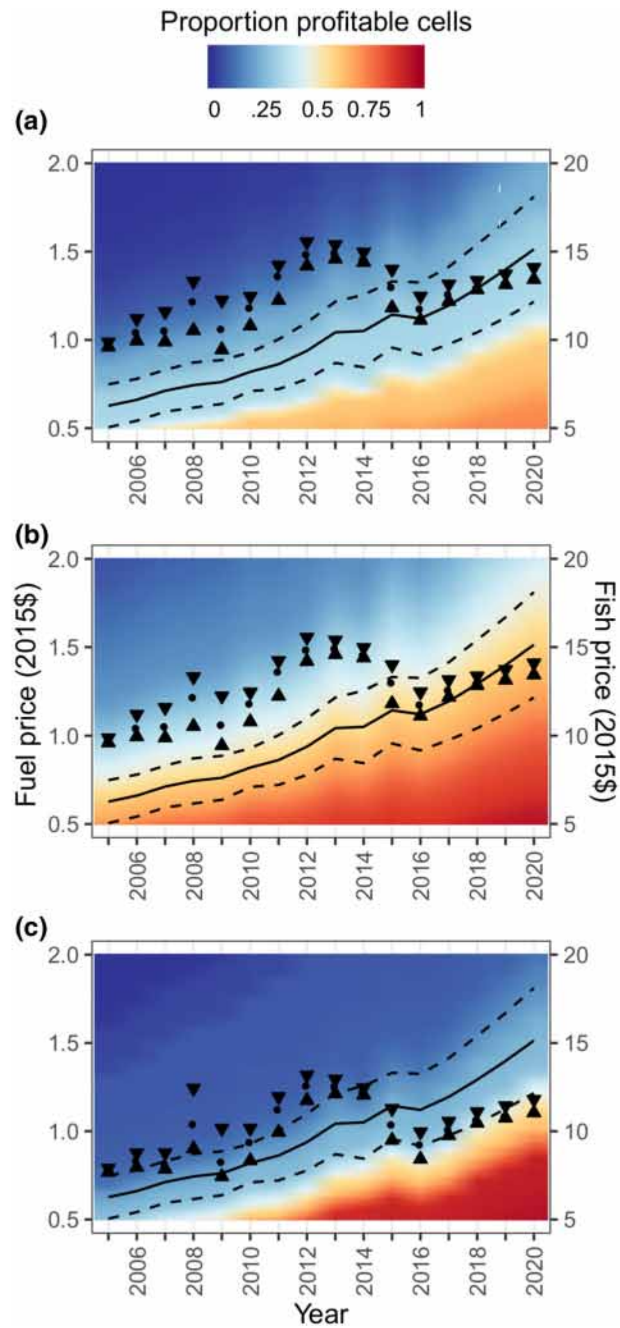
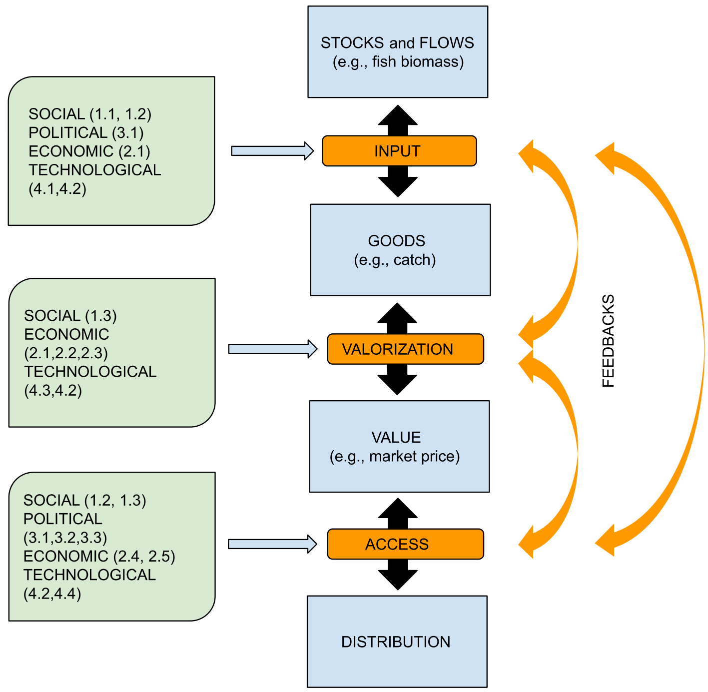


FIGURE 4 Heat maps of profitability across a range of fuel prices 2005–2020 in New Caledonia. (a) Boats l<5 m in length; (b) boats 5 - 8 m length (fuel: gasoline); and (c) boats >8 m length (fuel: diesel). Icons represent mean (circles), minimum (triangles), and maximum (inverted triangles) annual fuel prices, solid line is mean annual fish price (all species), and dashed lines 95% confidence intervals

to increased abundance of prey. Similarly, the impacts of recreational activities, such as wilderness tourism (Saarinen, 2019), can be assessed through the same travel time framework, although valorization of the ratio between "time in wilderness" versus "time to travel to wilderness" is necessary.

Within the context of increasing economic viability of exploiting wilderness resources, the potential of societal and governmental actors' interactions to protect and manage these economic sectors is essential to maintain both intact wilderness and sustainable usage of the environment. In Steenbergen et al. (2019), an analytical framework whereby governing systems influence the system to be governed at various stages was proposed to recognize the diverse way institutions can both emerge and take effect. Here, we integrate this framework with a conceptualization by Daw et al. (2016) of ecosystem service provision as a chain of elements (Figure 5). Governing relationships between elements within this chain are processes, such as levels of human inputs, and valorization processes. These "multipliers" are where governance institutions may act to regulate exploitation, use and benefits gained from ecosystems, using a guiding set of "sustainability attributes" covering the social, economic, political, ecological, and technological realms (Steenbergen et al., 2019).

Human input to harvest a resource can be managed through political attributes, such as tenure and property rights that control access (3.1 in Figure 5). These are closely integrated with social attributes, whereby access to social networks and relationships with traders can control levels of fishing, access to the stock, and overall health of the stock. In New Caledonia, this takes the form of middlemen or "colporteur" who transport fish from villages to Nouméa (Gontard & de Coudenhove, 2013—1.1 and 1.2 in Figure 5). Additionally, economic and technological attributes influence input through dependence on the resource (2.1 in Figure 5). Harvest efficiency and yield can vary due to changes in fleet capacity, through changes in gear and techniques, for example, regulatory changes in gear use and catch share (Watson et al., 2018), adjusting fishing practices to fish for pelagic species during longer, oceanic trips, or the adoption of newer technologies (fish finders, access to predictive modeling of fish presence, e.g., here or in D'agata, Mouillot et al., 2016). Governance institutions may also take affect through the "valorization" process, which sets the price of the good (in this case fish). In addition to supply-side strategies, such as through reviewing subsidies toward fishing to prevent costs being externalized (Sala et al., 2018; 4.1 in Figure 5), social factors, such as cultural affiliation toward the resource—such as in New Caledonia particular cultural affinities toward "Dawa" (unicornfish) and "Saumonée" (grouper) (1.3 in Figure 5), and economic factors, such as dependence and export markets (2.1 and 2.3 in Figure 5), or consumer choice (social education—4.3 in Figure 5), can also be leveraged to control fish prices (such as through bans, as in the case of the Philippines Life Reef Fish trade). It is notable though that such measures may increase prices at international destinations, potentially driving increased illegal fishing by extra-national "blue-boats" (wooden boats with blue hulls from Vietnam and other East Asian countries—Song et al., 2019). At the "access" stage, social and cultural affiliations toward the resource (e.g., determining "who" can fish), end enforcement by government



1.0 Social

1.1 Strength of social network: extent of social resilience, social group support, and sharing of risk/skills/knowledge

1.2 Interdependent relationships (producers, traders, consumers): the extent of equitable (cultural and social) benefitdistribution

1.3 Cultural affiliation toward the resource: The extent of cultural value and rules associated with to resource use/trade/consumption

2.0 Economic

2.1 Dependence on resource: the extent of dependence on the resource (and trade) for livelihood and income

2.2 Differential nature of product: the extent of distinct commodity value and symbolic value

2.3 Export markets: the extent of the commodity's market chain length

2.4 Marketing system: the extent of openness or exclusiveness of a market.

2.5 Equity of economic benefit distribution: the extent of equitable (monetary and material) benefit distribution

3.0 Political

3.1 Tenure and property rights: the extent of recognized tenure and property rights

3.2 Leadership legitimacy: the extent of effective and legitimate leadership

3.3 Equity of regulated access: the extent of equitable and regulated entry to the SSF/trade

3.4 Just rule of law: the extent of legitimate control, management and regulation, and breadth of inclusion in decision making

4.0 Technological

4.1 Fleet capacity in relation to resource: the extent of catching capacity (technology and investment) of a fleet/SFF

4.2 Exclusion technology: the extent of processing activities,technology and distributive capacity enhancing exclusiveness

4.3 Consumer/Buyer choice: the extent of knowledge by consumers and retail buyers to make informed purchase

4.4 Traceability: the extent of traceability of product source/trade/processing along market chains

FIGURE 5 Conceptual diagram of governance interfaces with wilderness resource use. The description of attributes is drawn from Steenbergen et al. 2019). Individual attributes of the governance system may control several multipliers within this framework, and feedback upon each other

through access restrictions, such as quotas and licenses have been shown to both improve stocks and reduce effort (Watson et al., 2018), are potential levers through which the government and multistakeholder engagement systems can act. In a wilderness context, the ability to exclude users from resources may necessitate trans-national co-operation (4.1 and 4.2). Other "soft" attributes, such as confidence in leaders (3.2, Gutiérrez, Hilborn, & Defeo, 2011), may help convey legitimacy on steps taken to restrict exploitation as can technological attributes, such as exclusion technology (monitoring boats through vessel monitoring systems and overflights) or assigning requirements traceability of the resource (4.4 in Figure 5).

With 95% of reefs globally within 10 hr travel time from the nearest population (Maire et al., 2016), only the 1.5% of reefs more than 20 hr from human population are likely to exhibit quasi-intact ecological conditions (D'agata, Vigliola et al., 2016; Juhel et al., 2018). These isolated protected areas are some of the few reef areas with the potential to fully support a wide range of functional groups (Krueck et al., 2018). For example, the important South Pacific fishery species *Naso unicornis* supports a unique functional role (cropping macroalgae that overgrows coral) with low redundancy on many reefs (D'agata, Vigliola et al., 2016). The isolation and extent of coral reef wilderness (such as Chesterfield, the Chagos Archipelago, Quirimbas Archipelago, and Aldabra—Jones et al., 2018) provides practical challenges to effective enforcement (McNulty, 2013). With many wilderness reefs protected under global treaties or through intergovernmental designations (e.g., Entrecasteaux and Aldabra as UNESCO World Heritage Area and Aldabra as a RAMSAR site), multinational discussions on how to manage these remote reefs under a new fisheries paradigm are necessary to share financial and logistical burdens of enforcement. We argue that remoteness from economic activities is not sufficient protection of wilderness areas (Jones et al., 2018; Mittermeier et al., 2003), and against complacency in enforcement.

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AUTHOR CONTRIBUTIONS

F.A.J. and D.M. conceived the study with support from L.V. F.A.J. and E.M. developed and implemented the analyses. F.A.J. led the manuscript, and all other authors contributed data and made substantive contributions to the text.

DATA ACCESSIBILITY

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper (specifically raw underwater visual census data) can be requested from L.V. (laurent.vigliola@ird.fr) or F.A.J. (f.a.hartley@swansea.ac.uk).

COMPETING INTERESTS

The authors declare that they have no competing interests.

ORCID

Fraser A. Januchowski-Hartley https://orcid.org/0000-0003-2468-8199

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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