ECOLOGY LETTERS

Ecology Letters, (2016) **19**: 351–360 doi: 10.1111/ele.12577

IDEA AND PERSPECTIVE

How accessible are coral reefs to people? A global assessment based on travel time

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Abstract

The depletion of natural resources has become a major issue in many parts of the world, with the most accessible resources being most at risk. In the terrestrial realm, resource depletion has classically been related to accessibility through road networks. In contrast, in the marine realm, the impact on living resources is often framed into the Malthusian theory of human density around ecosystems. Here, we develop a new framework to estimate the accessibility of global coral reefs using potential travel time from the nearest human settlement or market. We show that 58% of coral reefs are located < 30 min from the nearest human settlement. We use a case study from New Caledonia to demonstrate that travel time from the market is a strong predictor of fish biomass on coral reefs. We also highlight a relative deficit of protection on coral reef areas near people, with disproportional protection on reefs far from people. This suggests that conservation efforts are targeting low-conflict reefs or places that may already be receiving *de facto* protection due to their isolation. Our global assessment of accessibility in the marine realm is a critical step to better understand the interplay between humans and resources.

Keywords

Accessibility, coral reefs, marine protected areas, social–ecological, travel time.

Ecology Letters (2016) **19**: 351–360

INTRODUCTION

Natural resources, such as forests and fisheries, are becoming severely depleted; especially those that are more accessible to people (Mora *et al.* 2011; Cinner *et al.* 2013; Barber *et al.* 2014). For example numerous studies have linked increased accessibility through road building to deforestation (Laurance *et al.* 2009) and biodiversity erosion (Ahmed *et al.* 2014). Accessibility is also shown to be a main driver of ecosystem recovery. Distance to primary roads enhances recovery of secondary forests after abandonment of agriculture in Puerto Rico (Crk *et al.* 2009). In terrestrial systems, there is thus considerable attention on accessibility management, mainly via road networks at both local (Dobson *et al.* 2010) and global scales (Laurance *et al.* 2014).

In contrast, considerably less research has focused on accessibility in marine ecosystems, though it has been shown to strongly determine their conditions (e.g. fish biomass and biodiversity) and functioning (Morato *et al.* 2006; Cinner *et al.* 2013). For example in Nicaragua, the development of a road into a remote fishing area altered both price and price variability of fish, which led to more intensive overexploitation (Schmitt & Kramer 2009). Likewise, several studies have shown proximity to market to be the strongest predictor of overfishing on coral reefs (Cinner & McClanahan 2006; Cinner *et al.* 2012, 2013).

Measuring the extent to which global marine resources are accessible to humans has been generally limited to examining the linear distance between fishing grounds and markets or ports (e.g. Watson *et al.* 2015). However, for most coastal ecosystems and artisanal fisheries, this linear distance does not capture ragged coastlines, road networks and other features that can affect the time it takes to travel to a fishing ground. The availability of new analytical tools and high-resolution geo-referenced landscape data now allows for global travel time analyses.

Here, we undertake the first global assessment of the human accessibility of an entire marine ecosystem: coral reefs. Coral reefs are an important study system for exploring accessibility because millions of people depend on their resources (Teh *et al.* 2013; Cinner 2014) and because their services are valued more than for any other ecosystem on earth; on average at \$350,000/ha/year (De Groot *et al.* 2012). Yet reefs are located on varied coastal and oceanic places with different levels of infrastructure development (roads, markets) and thus are likely to show great variability in their degree of accessibility

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by people. Using a novel metric of 'potential travel time' between people and reefs we ask the following questions: (1) How accessible are the world's coral reefs to people? (2) Is accessibility to people through travel time a better predictor of reef fish biomass than classical measures of human impact? (3) Are marine conservation efforts representatively protecting reefs near and far from people?

GLOBAL ACCESSIBILITY OF CORAL REEFS FROM HUMAN POPULATIONS

Potential travel time as a new measure of accessibility – more than linear distance

Linear distance between fisheries and human settlements can fail to capture differences in accessibility incurred by road networks, landscape heterogeneity and coastline tortuosity. The existence of a road along the coast, for instance could facilitate faster access to a given coral reef than the direct travel by boat (Fig. 1a). To account for all these drivers of differential accessibility, we adapted the geographical concept of 'friction of distance' to develop a metric we refer to as 'potential travel time'. We first assigned speeds required to cross 24 different types of land cover for each cell of our global 1 km-resolution grid (e.g. 60 km h^{-1} on a road, 30 km h^{-1} on a track, 20 km h^{-1} on the ocean; see details in Supplemental methodological procedures and Table S1). These estimates were adapted from a global assessment of travel time between major cities (Nelson 2008) and represent the minimum travel time required to cross each type of surface, assuming that road and maritime travels are made by motorised vehicles. Road speed depends on road type while off road travel is foot based. Since these values can vary depending on available technology, infrastructures and vehicles we called our metric 'potential travel time'. We then used the Dijkstra's algorithm through the *accCost* function (R Development Core Team 2014) to determine the minimum cumulative cost in time between every coral reef in the world (27,212 coral reef cells) and (1) the nearest human settlement of any size (any populated pixel given by the finest resolution global human distribution grid, see Fig. S1), and (2) the nearest major market (considered as a national capital, a provincial capital, a major population centre, or landmark city; see Supplemental methodological procedures) since both have been shown to impact reef resources and functioning (Cinner *et al.* 2013; Advani *et al.* 2015).

We related the linear geographical distance and potential travel time from the nearest major market (Fig. 1b). Not surprisingly, linear distance and travel time are correlated globally ($R^2 = 0.9$); a reef far from people cannot be reached with limited travel time while a reef close to people (< 10 km) is always accessible with < 4 h travel time. However, a given linear distance value may correspond to a wide range of potential travel times (Fig. 1c). For any 10km-window along a whole linear distance gradient from 0 to 500 kilometres between a given reef and the nearest market, the range of travel time is highly variable. For example a range of linear distance to market between 105 and 115 kilometres (represented as red bar in Fig. 1c) corresponds to potential travel time ranging from 2 to 13 h. This result highlights the importance of integrating the landscape heterogeneity in accessibility assessments since considering travel on a unique surface may produce a coarse and unrealistic estimation of time required to reach reefs. Travelling only off-road, i.e. through the vegetation, only on road or only on the ocean provide over-simplified scenarios that are almost never met (Fig. 1b). Most of the pathways to reach the reefs combine road and maritime travel, preventing any simplification. Even if linear distance may appear to be a good surrogate for estimating potential travel time to reach the reefs globally (Fig. 1b), a map of residuals from predicted values shows that, relative to potential travel time, linear distance tends to underestimate accessibility in populated areas where roads are present and overestimates accessibility in more remote places (Fig. S2). This likely has to do with the potential travel time metric's recognition of reduced travel time on roads.

High but variable accessibility of coral reefs around the world

Our global assessment of coral reefs accessibility shows that 58% of coral reefs (15,609 out of 27,212 coral reef cells) are located at < 30 min travelling time from the nearest human settlement (Fig. 2). On average, each reef can be reached within 1 h 50 (SD = 4 h 15). The bulk of reefs are highly accessible in the Caribbean, the Coral Triangle, the Western Indian Ocean and the Pacific Islands. However, some areas like the Chagos Archipelago, the Spratly Islands, the Chesterfield Islands, the northwest Hawaiian Islands and the Coral Sea have reefs at more than 12 h travel time from the nearest human settlement. None of Caribbean coral reefs are more than 13 h from people (Fig. 2 a1 & b1).

Accessibility of coral reefs from major markets is high relative to the nearest human settlement (mean = 10 h), but is highly variable around the world (SD = 9 h). Our analysis shows that 25% (6,790 pixels) of reefs are located at < 4 h from the nearest major market, whereas 31% (8,428 pixels) of reefs are more than 12 h from the nearest market. Caribbean coral reefs appear much more accessible from markets than their Indo-Pacific counterparts (Fig. 2 a2 & b2).

To take into account the variability of available boat technology, we re-assessed global accessibility using slow (10 km h^{-1}) and fast (40 km h^{-1}) boat speeds. Accessibility of coral reefs from the nearest population ranges between 3 h 40 (SD = 8 h 30) and 1 h 10 (SD = 3 h), and from the nearest market between 17 h (SD = 17 h 30) and 6 h 10 (SD = 4 h 40) using slow vs. fast boats respectively (Fig. S3 and S4). Future applications should consider variable travel speeds according to per capita Gross Domestic Product to reflect different levels of infrastructure and technology in developed vs. developing countries. Yet this country-scale assessment was beyond the scope of our initial exploration of travel time.

TRAVEL TIME FROM MARKET AS A KEY DRIVER OF CORAL REEF CONDITIONS

There is considerable effort to better understand the multi-scale drivers of change in coral reef ecosystems through

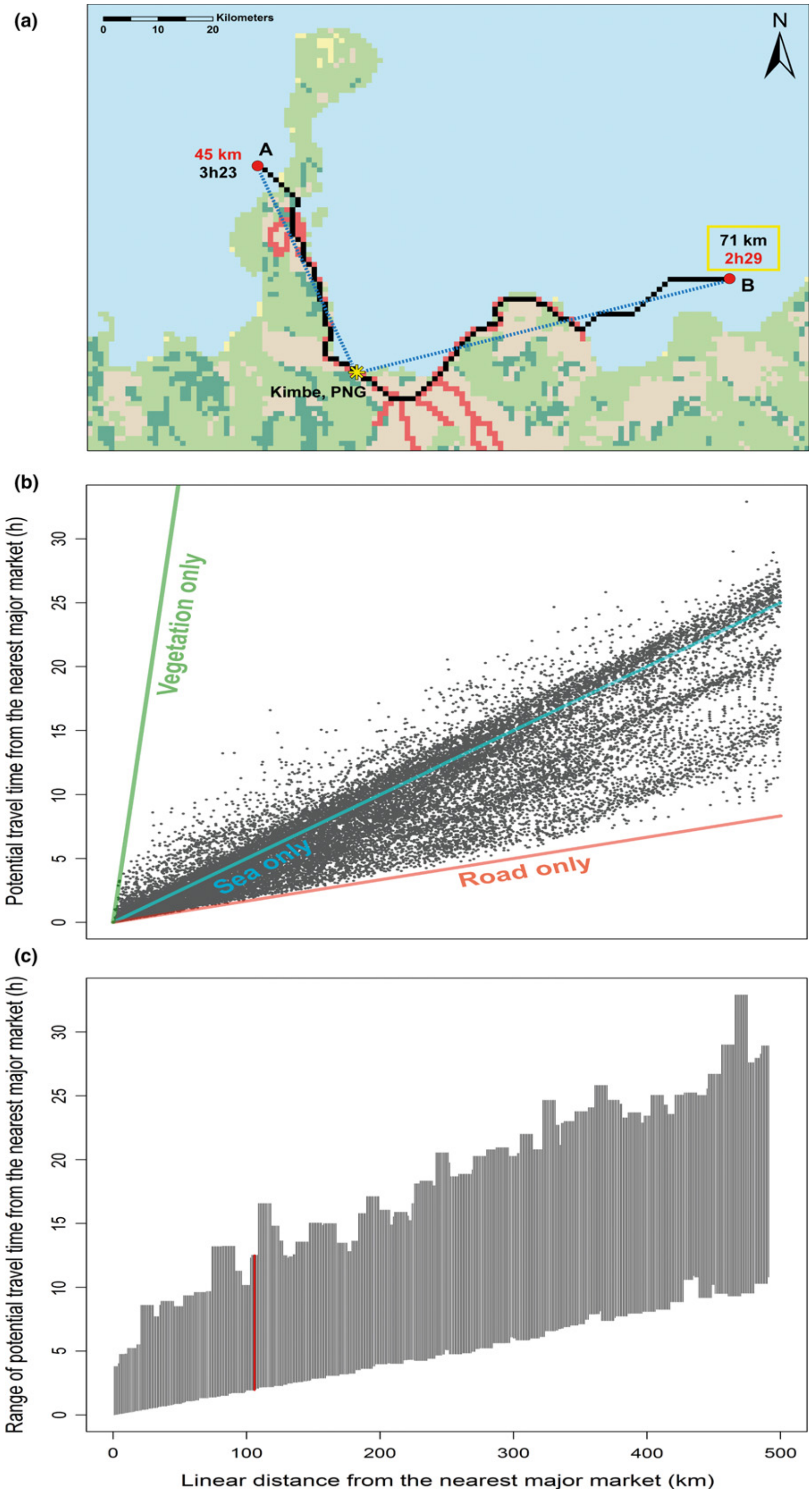

Figure 1 Potential travel time as a measure of accessibility. Accessibility is defined as the travel time to a location using land (road and land cover) or water (navigable river, lake and ocean) based travels and represents the 'cost' of travelling in time across a specific surface (e.g. land, sea, forest, etc.). As an illustration, the major market in Papua New Guinea, Kimbe (yellow asterisk), and two reef sites (red points) were considered (a). We calculated the linear distance and the travel time from the nearest market for 23,940 cells of coral reefs globally (b). Linear distance and travel time are highly correlated ($R^2 = 0.9$) but a small range of linear distance values (10 kilometres) may correspond to a wide range of potential travel time values (c). Travel time is a combination of road (red line), off road (green line) and maritime (blue line) travels.

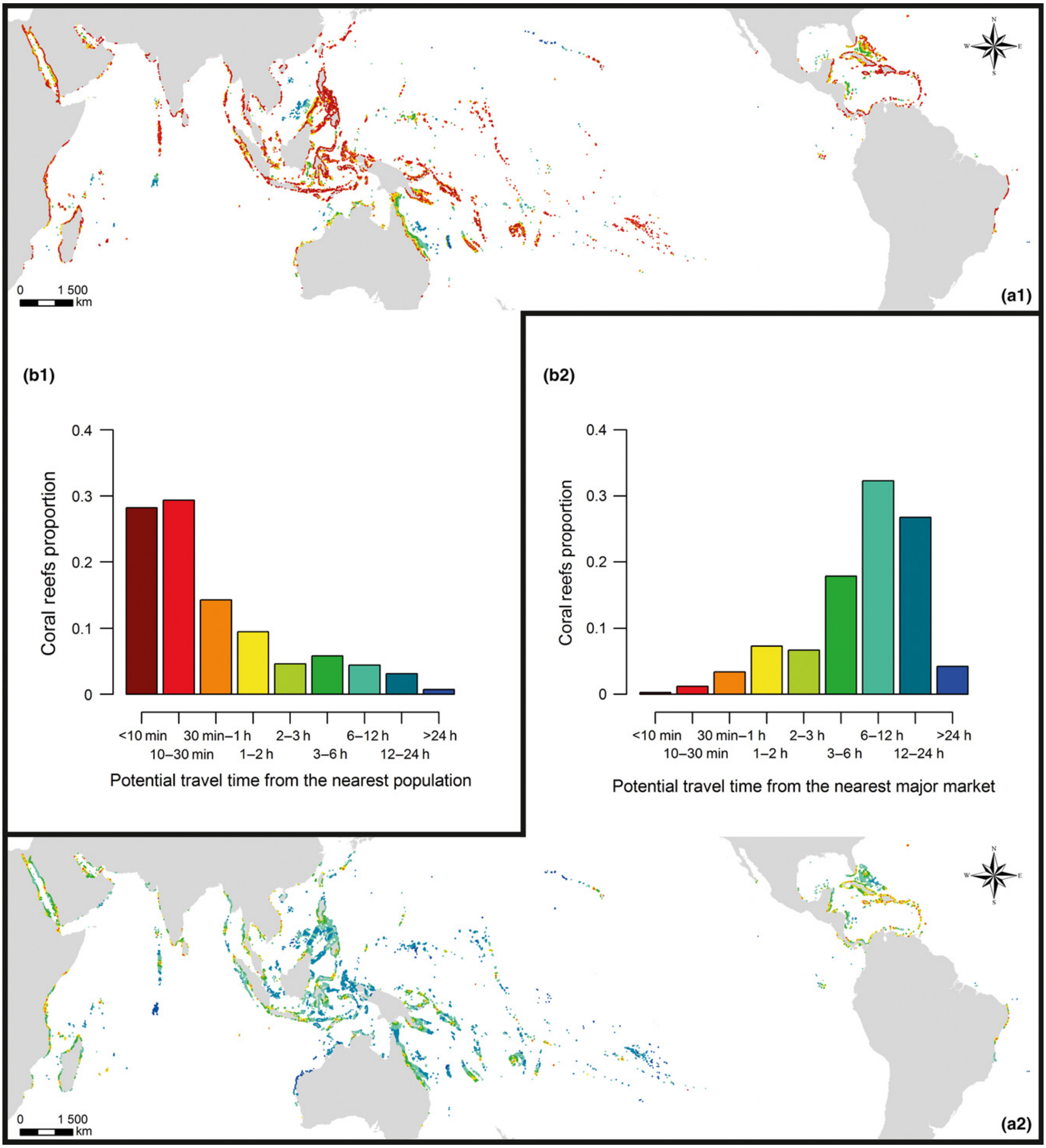

Figure 2 Accessibility of any coral reef from people (nearest market and nearest human settlement) around the world. Global coral reefs are extremely close to people (a1 & b1); 58% of reefs located at < 30 min travelling from the nearest human settlement while 25% of reefs are located at < 4 h from the nearest major market (a2 & b2). Only few areas appear as remote reefs (further away than 12 h travelling from human settlements) like the Chagos Archipelago, the Spratly Islands, the Chesterfield Islands and the Hawaiian Islands.

predictive modelling from local to global scales. For instance patterns of biomass and biodiversity across coral reef assemblages have been explained by several non-mutually exclusive processes that involve the roles of energy (Tittensor *et al.* 2010), climate (Pellissier *et al.* 2014), habitat (Rogers *et al.* 2014), biogeography (Parravicini *et al.* 2013), humans (Mora *et al.* 2011) and environmental stochasticity (Dornelas *et al.* 2006). A key goal of this body of research is to identify drivers of change that can be used as policy levers to positively influence the future conditions of coral reefs (Cinner & Kittinger 2015). We suggest that the availability of travel time estimation to reach the reefs from markets or populations may help to decipher the many dimensions of human influence on ecosystem conditions when integrated to models in combination with other commonly used predictors (e.g., environment and habitat). Coral reef conditions (biomass or biodiversity) and functioning (e.g. herbivory) are classically related to the density of local human populations (Bellwood *et al.* 2012; Williams *et al.* 2015) and more recently to the linear distance to humans (Advani *et al.* 2015) or markets (Brewer *et al.* 2012; Cinner *et al.* 2013). Here, we test whether potential travel time from market is a better predictor of reef fish biomass than local human density and linear distance to market in a case study from New Caledonia.

We used 1,357 Distance Sampling Underwater Visual Census (UVC) surveys of fish communities (Fig. 3a) to quantify the relative influences of environment, habitat and human impact on fish biomass (Supplemental methodological procedures, Table S2, Fig. S5). Human impact is assessed through three potential proxies: (1) the density of people within a buffer of 20 km around each UVC survey, (2) the linear distance between each UVC survey and the major market located in the regional capital of Noumea and (3) the travel time to reach each UVC survey from the market. We use generalised linear models (GLM) and boosted regression tree (BRT) models to predict fish biomass and rank the different explanatory variables according to their Akaike weight (AIC_w) and their relative contribution respectively (see Supplemental methodological procedures). We demonstrate that humans shape the level of reef fish biomass since each proxy of human impact has a significant effect beyond that of habitat and environment (Table 1). Then we show that potential travel time from the market is the strongest predictor of fish biomass since its AIC_w is 1 (essential variable in all best GLM sub-models) and its relative contribution to the BRT model is 28% surpassing that of all other competing variables (Fig. 3b). In contrast, human density and linear distance to market have lower AIC_w values (0.33 and 0.44 respectively) and contribute to BRT models at, respectively, the fourth (11%) and third rank (13%) suggesting their marginal influence on fish biomass compared to travel time. Finally the most parsimonious model ('best' in Table 1), based on variable selection using the AIC criterion, only retains potential travel time from the market as the sole human driver of fish biomass on New Caledonian reefs. This GLM model explains 45% of variation in fish biomass across reefs. However, the BRT model, which takes into account variable interactions and thresholds effects, explains up to 70% of this variation highlighting potential interplay between human, environmental and habitat drivers. When extracting the 'pure' effect of travel time from the market on fish biomass using a partial plot from the GLM we observe a saturating relationship (Fig. 3c). Low biomass values (< 100 kg ha^{-1}) are mostly found when travel time is lower than 10 h (Fig. 3c). All remote reefs (Fig. 3a) have a fish biomass higher than 500 kg ha^{-1}, which has been suggested as a potential threshold to maintain healthy and functioning coral reefs (McClanahan *et al.* 2011; MacNeil *et al.* 2015).

Table 1 Comparison of candidate models predicting reef fish biomass as a function of environmental, habitat and human impact variables across the coral reefs of New Caledonia

Model	AIC	R^2	*F*
Null	2085	0	
Environment + Habitat	1544	0.37	LR-test
Environment + Habitat + Human density	1449	0.41	98.854*
Environment + Habitat + Linear distance	1413	0.43	138.3*
Environment + Habitat + Travel time	1352	0.45	206.2*
Best	1350	0.45	

**P*-value < 0.001. We calculated the Aikaike Information Criterion (*AIC*) and the total adjusted R-squared (R^2) for each model and sub-model (see Supplemental methodological procedures and Table S2). A likelihood ratio test (LR-test and *F*-value) between the 'Environment+Habitat' model and each enriched model with one aspect of human influence (population, linear distance or travel time) shows the significance of adding human impact variables. The 'Best' model is the most parsimonious according to the *AIC* criterion containing only travel time and some selected environmental variables (mean depth, surface cover of live coral, surface cover of macroalgae, the reef type and island type).

DISPROPORTIONNAL ISOLATION OF MARINE PROTECTED AREAS FROM PEOPLE

While numerous approaches can be used to sustain marine resources (Costello *et al.* 2008; Gelcich *et al.* 2008; Worm *et al.* 2009; Cinner *et al.* 2012), Marine Protected Areas (MPAs) are widely recognised as a key management tool (Gaines *et al.* 2010; Veitch *et al.* 2012; MacNeil *et al.* 2015). As in terrestrial systems, scientists have voiced concerns that protected areas are being disproportionally placed in remote areas, away from human impacts, and consequently are 'residual reserves' with limited benefits for biodiversity since not adverting direct exploitation (Mora & Sale 2011; Devillers *et al.* 2014; Watson *et al.* 2014). However, remote MPAs offer reference conditions to evaluate management measures or time to recovery (MacNeil *et al.* 2015), and can be emblematic so making publicity for marine protection worldwide (Singleton & Roberts 2014). Our goal is not to discuss the value of remote MPAs but to assess the degree to which remote areas receive disproportional protection, or whether the 1,140 coral reef MPAs we reported (Fig. S6) are unevenly distributed along gradients of accessibility based on travel time.

Intersecting the 1,140 MPAs globally with our 10 × 10 km coral reef grid, we first identify which coral reef cells are protected (6,935 among the 27,212 cells) and to which MPA they belong (Supplemental methodological procedures). For each protected coral reef cell, we then calculate the potential travel time from the nearest human settlement and major market. To examine whether protected coral reefs around the world are disproportionally farther from people, we estimate the deviance between the accessibility of protected reefs and the global distribution of coral reef accessibility for five categories of potential travel time: ≤ 10, 10–30 min, 30 min–2 h, 2–12 h, > 12 h. We then compare the proportion of reefs protected relative to the global distribution of reefs in each travel time category (Fig. 4). Relative to the global distribution of reefs, the proportion of reefs receiving protection is lower near people. We find an average 'deficit' of −19% lower protection on reefs that have a potential travel time lower than 2 h. However, reefs further from people (potential travel time higher than 2 h) are disproportionally protected. This relative 'sur-

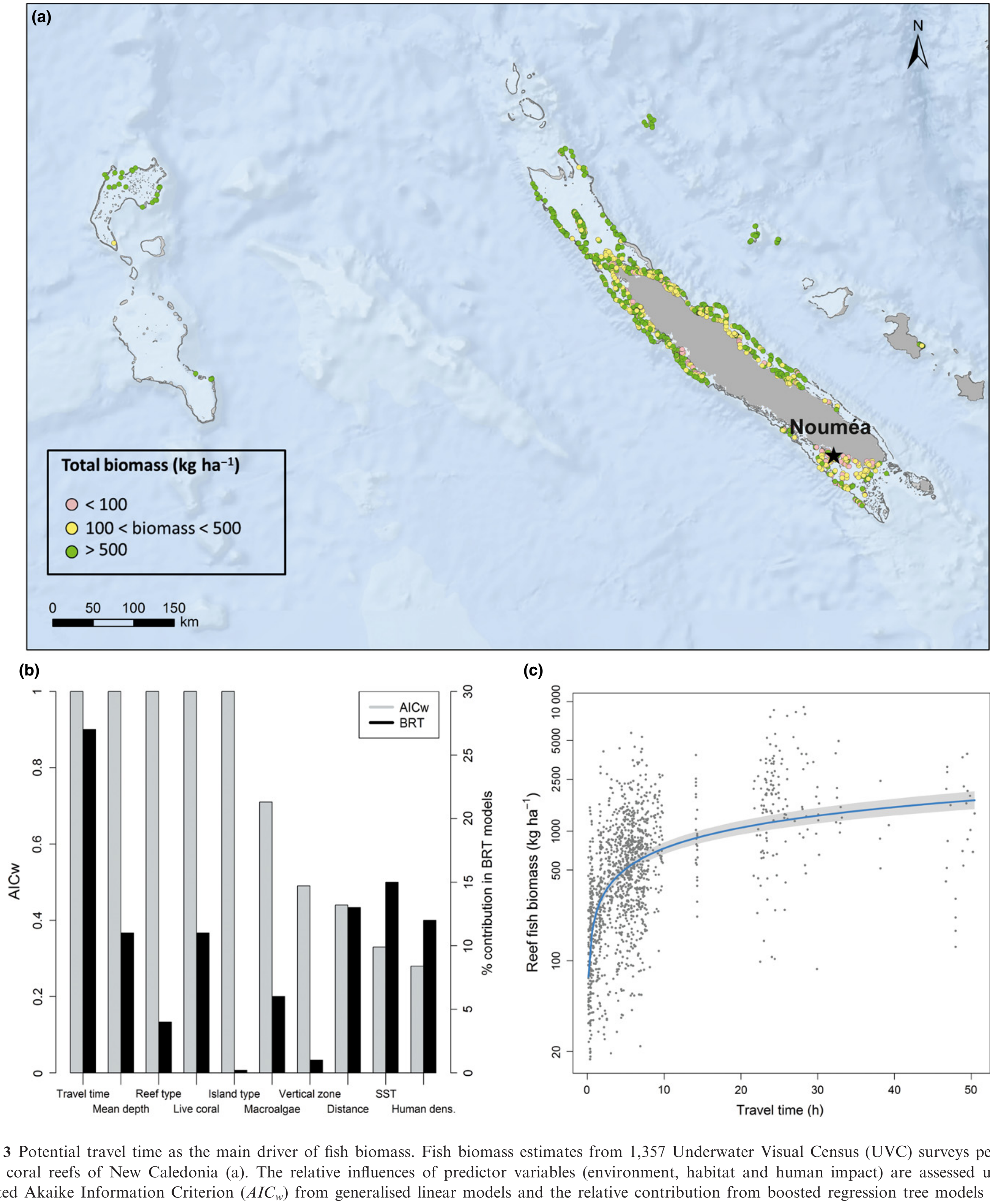

Figure 3 Potential travel time as the main driver of fish biomass. Fish biomass estimates from 1,357 Underwater Visual Census (UVC) surveys performed across coral reefs of New Caledonia (a). The relative influences of predictor variables (environment, habitat and human impact) are assessed using the weighted Akaike Information Criterion (AIC_w) from generalised linear models and the relative contribution from boosted regression tree models (b). The partial plot (c) shows the 'pure' relationship between potential travel time and reef fish biomass, i.e. while considering the other predictor variables.

plus' of protection is even more marked for isolated coral reefs (potential travel time > 12 h) with more than twice (127%) the proportion of protected coral reefs compared to the global distribution (Fig. 4a). Importantly, this disproportional protection of isolated reefs is much less pronounced when using travel time from markets (Fig. 4b).

This trend of protecting inaccessible reefs tends to emerge because of complex ecological, socioeconomic and political

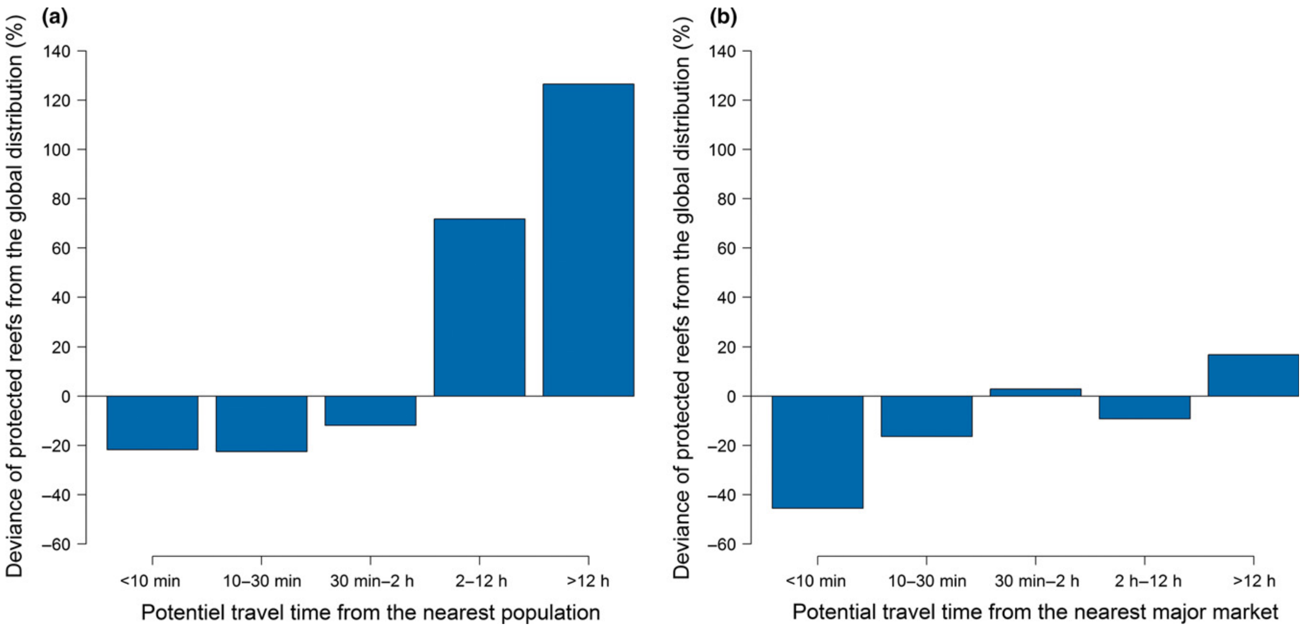

Figure 4 Deficit and surplus of protection for global coral reefs. The proportion of reefs receiving a deficit or a surplus of protection relative to the distribution of reefs globally is assessed along a gradient of isolation (≤ 10 min, 10–30 min, 30 min-2 h, 2–12 h, >12 h) using travel time from the nearest population (a) or the nearest market (b).

trade-offs that aim to maximise conservation benefits while minimising costs to the people engaged in natural resources exploitation (McNeill 1994; Pressey *et al*. 1993; Jones 1999; Stewart *et al*. 2003). Indeed, some fishers are very unlikely to support development of no-take MPAs, particularly in their primary fishing grounds (McClanahan *et al*. 2012), so locating MPAs further away from people can be a sensible strategy for reducing opposition from fishers but with questionable conservation benefits (Singleton & Roberts 2014; Wilhelm *et al*. 2014). The concern with the pattern of disproportionally protecting inaccessible areas that we quantified is that conservation targets (such as 10% protection of oceans by 2020) can be met without actually reducing human impacts on the seascape (i.e. because MPAs get placed in locations which are already *de facto* protected because of their inaccessibility; Devillers *et al*. 2014). Our results suggest that in situations where MPAs are located where they do little to actually reduce human impacts, complementary tools such as gear restrictions and user rights may help to sustain reef fisheries in accessible areas (Costello et al. 2008; Gelcich *et al*. 2008; McClanahan *et al*. 2011; Cinner *et al*. 2012; MacNeil *et al*. 2015) with less opposition from fishers (McClanahan *et al*. 2012).

FUTURE DIRECTIONS

To sustain coral reef ecosystems, we need to understand the complex interactions between people and reefs. Our development of a global measure of potential travel time is an important step towards this objective, and we suggest three areas where future applications could be beneficial: (1) using travel time as a proxy for fishing effort to identify refuges and analyse extinction risk, (2) assessing financial cost and profitability for artisanal reef fisheries and (3) assessing potential impacts of expanding road networks. To facilitate these and other applications, we provide our global potential travel time estimates for coral reefs as a spatial layer at 10 km-resolution upon request or for a set of coordinates.

Species accessibility and refuges on coral reefs

The extent to which a species is under fishing pressure is classically estimated through either its catch rates (Bejarano *et al*. 2013) or its geographical overlap with fishing effort (Comeros-Raynal *et al*. 2012). The former is a direct measure of extraction but is unavailable in many data-poor fisheries while the latter is an indirect estimate which is challenging to downscale (Teh *et al*. 2013). Alternatively, the potential travel time to reach the reefs from markets or people, certainly in interaction with other social–economic aspects, can provide a standardised way to approximate fishing pressure with a host of potential applications. These could include: (1) identifying refuges where the geographical ranges of threatened or endangered species may overlap with inaccessible areas; and (2) providing a standardised index of potential exposure to fishing threats to include in evaluations of vulnerability or extinction risk (Parravicini *et al*. 2014).

Assessing profitability and costs of fishing coral reefs

Travel time is a first step towards the assessment of travel cost in terms of energetic or monetary units. Beyond time and distance, travel cost also depends on the type of vessel (size, engine, etc.), labour costs, infrastructure (road, harbour, etc.), and the price of fuel (including government subsidies). Estimating travel costs would require detailed data currently unavailable for a global analysis but could be well suited to a downscaled analysis. Ultimately, based on expected yields and seafood prices, isoclines or contours of profitability could be drawn for artisanal fisheries on coral reefs. Such estimates and maps may also serve to define reefs where accessibility is too restricted to host profitable fisheries, show where short travel time and low travel cost from humans may promote over-exploitation, and even highlight potential consequences of fisheries fuel subsidies. The travel cost to reach any reef from a market or a village would make a valuable management tool to better map artisanal fisheries effort, yields and economic outcomes in what is generally a data-poor fisheries.

Future impacts of road building on coral reefs accessibility

The global network of roads is rapidly expanding under multiple needs of accessibility to resources, industries and infrastructures. Most of the 25 million kilometres of new roads anticipated by 2050 will be built in developing countries to sustain their social and economic development, but this could have profound impacts on biodiversity (Laurance *et al.* 2014). The spread of this road network in the last terrestrial wilderness areas (e.g. Amazon) and its ecological consequences have been widely documented particularly the accentuated depletion of natural resources (Barber *et al.* 2014). Comparatively the impact of road construction on marine ecosystems remains largely overlooked (Schmitt & Kramer 2009). Travel time provides a framework to assess scenarios of future road development on reef systems, highlighting potential ecological consequences and trade-offs associated with specific plans. Development of new and faster roads along the coasts will increase the accessibility of some reefs to humans (Fig. 1a), likely resulting in overfishing and potential impacts on corals (Mumby 2006; Hughes *et al.* 2007). Travel time calculations using future scenarios of road building may help to identify reefs that are particularly at risk and develop potential alternatives that could still meet socioeconomic goals with less environmental impact.

CONCLUSION

Better understanding the dynamics of coral reef social–ecological systems is one of the most critical challenges that scientists and managers are facing today (Cinner 2014). The severity of human impacts on reef systems has been widely acknowledged, though the causes of, and solutions to, these impacts are debated (Hughes *et al.* 2010; Rogers *et al.* 2015). It is clear that human population size and density are major drivers of change on reefs (Mora *et al.* 2006, 2011; Bellwood *et al.* 2012; Williams *et al.* 2015), but in addition to these demographic pressures, drivers such as market integration and poverty also shape the ways that people use and govern coral reefs (Cinner *et al.* 2009, 2013). However, these drivers of unsustainable exploitation are often poorly considered by both scientists and policy makers, leading to insufficient governance and diminished outcomes. A critical step is to better understand, and integrate into governance, the complex, multi-scale interrelationship between humans and coral reefs with accessibility being critical.

ACKNOWLEDGEMENTS

We thank the associate editor and three anonymous referees for their constructive comments and corrections. We thank the PRISTINE project funded by the TOTAL foundation for providing support and data in New Caledonia. We also thank the crew of the different oceanographic vessels used to collect these data: the IRD oceanographic vessel 'ALIS', the Government of New Caledonia oceanographic vessel 'Amborella' and the Waitt Institute oceanographic vessel 'PlanB' used during a Pristine Seas survey with the National Geographic Society. We also thank the Secretariat of the Pacific Community (SPC) for providing data collected in New Caledonia under the European Union funded PROCFish-C program. Sampling was also funded by the Initiative Française pour les Récifs Coralliens (IFRECOR, New Caledonia office) and supported by the Province and Government of New Caledonia.

AUTHORSHIP

J.C., C.M. and D.M. conceived the project; all authors designed the study; S.D., L.V., L.W. and M.K. collected the data. E.M., L.V. and C.H. performed the analyses; E.M., J.C. and D.M. wrote the first draft and all authors contributed substantially to revisions.

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Editor, Marcel Holyoak
Manuscript received 5 October 2015
First decision made 10 November 2015
Second decision made 8 December 2015
Manuscript accepted 24 December 2015