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Effects of assets and weather on small-scale coastal fishers' access to space, catches and profits

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ABSTRACT

Fishers' spatial behavior affects their incomes, livelihoods and ecological sustainability and is affected by establishment of protected areas, and the impacts of changing climate and weather patterns. An understanding of fishers' spatial behavior is essential for evaluating catch trends or estimating per-area yeilds. Location choice by fishers has largely been understood through foraging models and empirical studies in large scale, developed country fisheries. This paper uses participatory mapping, logbooks and remotely sensed weather (wind speed) data to explore the influence of weather and capital on the spatial behavior and success of coastal Kenyan small-scale fishers. We test generalized foraging models of fisher behavior. A reef crest separates available fishing grounds in the study area between two distinct areas of dissimilar fish catches. Over half of the fishing trips accessed grounds outside the reef, particularly in the calmer northeast monsoon season. Trips across the reef were more successful both in terms of catch and value per fisher and price per kg. Access across the reef was determined primarily by season but was also affected by métier and daily wind speeds. Amongst a sample of non-motorised trips, crossing the reef was the most important variable for predicting Value Per Unit Effort (VPUE). Other things equal, more productive grounds ought to attract more effort, but access to the fishing grounds beyond the reef is constrained by fishers' access to capital, fluctuations in weather and the interaction between these variables. Fishers with low levels of capital are more affected by daily weather that limits access to the more profitable fishing grounds. Fishers with more capital are able to access more productive grounds more freely, but at the expense of extra compensation for the capital needed. Thus while gross returns to offshore trips exceed similar returns for nearshore trips, net returns are likely to be more equal. In our study a stark exception to the pattern of higher returns from more capitalised gear is the relatively high VPUE achieved by spear fishers, making the assumption of free movement of labour between gears not valid. The study also adds a temporal complexity to this picture by showing the likelihood of accessing grounds beyond the reef crest varies temporally by season.

1. Introduction

Simple models of fishing depict harvest success as dependent upon the amount of effort deployed and the abundance of target species that comes into contact with effort (Ricker, 1954). However, these simple depictions fail to capture the importance of the underlying mechanisms that determine exactly how fishing gear is brought into contact with fish stock abundance. In fact, fishing is a searching activity, in which over time fishers learn, form and revise expectations about where accessible fish abundance is located, and then deploy effort in pursuit of those anticipated agglomerations of their prey. Success therefore is determined by the fisher's decisions pertaining to space and time across the seascape. This applies to the different scales of fishery from small scale artisanal fisheries in developing coastal countries to large industrial scale fisheries in developed country settings. Fishers' spatial behavior is important for understanding fisheries and interpreting catch data for per-area estimates of yield and sustainability (McClanahan, 2018). Marine protected areas represent a manipulation of spatial behavior, are increasingly applied as management tools, and require understanding of fishers' spatial behavior in their planning and evaluation.

The spatial-temporal behavior of fishers has been the subject of numerous conceptual and empirical studies, each bringing respective disciplinary perspectives to the question. Biological theories have

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examined spatial searching behavior by fishers with a framework borrowed from the foraging theory (Hilborn and Ledbetter, 1979; Hilborn and Kennedy, 1992). Under the foraging framework (MacArthur and Pianka, 1966; Emlen, 1966), fishers are assumed to be seeking out patches with the highest expected harvest. As competition for resource abundance unfolds, fishers are hypothesized to distribute fishing effort over space until the average harvest per individual is equal, so that areas with high fish abundance accommodate more fishers. A distribution of effort called the ideal free distribution, where the equilibrium allocation of fishing effort is assumed to approximate the distribution of abundance over space (Fretwell and Lucas, 1969).

Economists and other social scientists have also examined fishing location choice with conceptual frameworks that are analogous to and/or extensions of the foraging theory. For example, Gordon (1954) hypothesized that effort is distributed over space to equalize the value per unit fishing effort across patches. This author further stipulated that effort continues to expand until the common values of average fishing effort in each patch equalize with the cost of deploying effort. This generalization allows a rich description of the attractiveness of various patches by accounting for different species mixes with different prices, as well as a rich description of effort including heterogeneous fishing effectiveness and differences in effort deployment costs.

In addition to spatial variations in stock abundance and fishing effort, fishers' spatial behavior is crucially affected by short term and seasonal weather patterns. Weather affects navigation, fishing activities and the costs and risks of accessing different fishing grounds. A better understanding of how weather interacts with small scale fishing activities is important for predicting weather-related impacts of climate change on the behavior and livelihoods of fishers. The impact of climate change on storminess is highly uncertain and likely to vary between regions and seasons. Observed and projected changes in storminess along the East African coast due to climate change remain uncertain. Re-analysis of observations in the Arabian sea show an increase in the probability of the most extreme post-monsoon storms but projections for the southern Indian Ocean indicate decreased storminess (Sainsbury et al., 2018)

Empirical studies of fishers' behavior have largely supported the notions underlying what might be termed rational spatial choice behavior (Bockstael and Opaluch, 1983; Eales and Wilen, 1986; Bertrand et al., 2007; Abernethy et al., 2007). Typical empirical studies begin by hypothesizing a choice set consisting of potential discrete locations that fishers might visit, and then examine repeated choices by random samples or panels of fishers (Smith and Wilen, 2003; Abbott and Wilen, 2011). Statistical approaches typically use a multinomial discrete choice econometric framework, which essentially hypothesizes that fishers choose the option with the highest expected profits at each choice opportunity. Important challenges to using this method include how to: define the choice set (how to carve continuous space up into discrete locations), specify the process of expected payoff formulation, deal with interaction (information sharing) and interference (gear congestion), deal with various forms of spatial and temporal correlation and unobservable variables that influence behavior (Smith, 2000).

For the most part, studies of spatial behavior by fishers have been confined to developed country fisheries. This is largely because data are more readily available as a regularly collected component of developed country fisheries regulation. In contrast, there are fewer studies of fisheries in developing countries, particularly in complex, small scale multi-species artisanal fisheries (Salas and Gaertner, 2004). The pertinent questions with regards to fisher behavior concern the relative behavior across fishery scale, and whether all users of marine resources, regardless of level of development, are likely to be equally motivated by rational analysis of trade-offs and costs and benefits of choices.

This study examines fishers' spatial-temporal practices in a particular geomorphic setting in a developing country, Kenya. A number of physical and economic features of this case study are favorable to testing hypotheses about spatial behavior of fishers. One important feature of the study site is that available fishing grounds are separated by a reef that serves as a barrier to easy access to the open seas. The study capitalizes on this physical feature of our study site by using it to frame a "natural experiment" where on a given day some fishers will fish outside the reef crest whereas others will not. This provided a convenient way to generate discrete fishing locations across marine space. Here assets as represented by the vessel type is a proxy for access to productive financial capital. The study provides a direct-test to hypotheses that revolve around the connection between capital, costs of servicing that capital, and the role of capital in providing access to richer and more profitable fishing grounds beyond the reef.

We test the bio-economic theory that biological and economic factors, and variations in weather jointly determine the distribution of fishing activity and yield over space and time (Sanchirico and Wilen, 1999). In the Kenyan study area, artisanal fishing is largely confined to the lagoon and reef slope along a continuous fringing reef, which creates a natural barrier and an inside and outside region. The locations outside the reef have higher fish catches than inside. But they are harder to access and involve risks to capital, equipment and even life (Daw et al., 2011) especially during rough weather conditions. Fishers with access to more capital are able to invest in and utilize vessel types that can more readily breach the reef barrier. Hence we would expect to see a foraging behavior equilibrium in which highly capitalized fishers realize higher valued returns per fishing trip, returns necessary to compensate for the investments required to access offshore grounds. The reef serves to separate choices into inside and outside areas, and thus we circumvent some of the difficult methodological questions, such as defining the choice set, that arise when spatial opportunities are considered continuous over space.

2. Hypotheses

In this study we examine four hypotheses (illustrated in Fig. 1) about this case based on a simple foraging model of how fishers distribute fishing effort across discrete space and across different métiers (combinations of vessels and gears) representing varied levels of capital investment, and the resultant patterns in fishing success (catch quantity and value per unit effort). If fishers are free to choose their fishing locations and between the available vessel and gear types, their distribution across locations and métiers would be predicted to reach an equilibrium in which higher costs of crossing the reef, and higher investments in certain métiers are compensated for by higher catch values.

Thus, firstly, the study hypothesizes that stock abundance, and subsequently catches and catch values will be higher from trips that cross the reef crest and access fishing grounds beyond (Fig.1a). Regardless of ecological productivity, the higher costs (in terms of capital

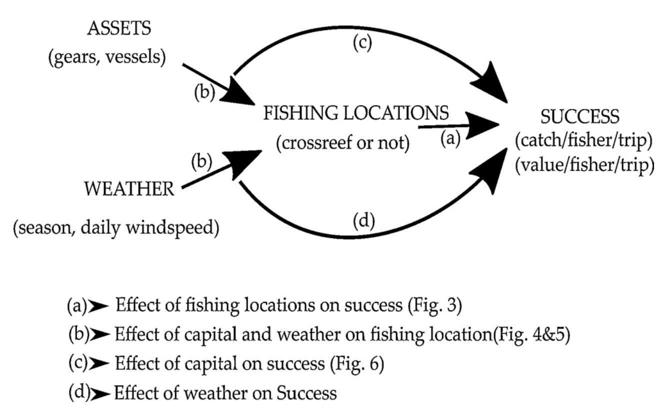

Fig. 1. Framework for analysis showing hypothesized relationships between assets, weather, fishing location and fishing success. Arrows show the hypothesized causal relationships between the variables.

requirements, time, labour or higher risks to capital or life) of fishing in grounds beyond the reef crest would be predicted to lead to an equilibrium situation in which higher yields over the reef roughly compensate for the additional costs of fishing there.

Secondly, the study hypothesizes that access to fishing grounds beyond the reef crest is affected by capital (as represented by métier) and weather (Fig.1b), which varies seasonally and also daily. Fishers are expected to be more likely to cross the reef when they a) have more capitalized fishing vessels and modes of propulsion, b) during the calmer (Northeast Monsoon) season, and c) on less windy days.

Thirdly, the study hypothesizes that fishing trips based on higher capital investments in vessels and gears will reap more catch value per fisher per day than lower capital fishing métiers (Fig. 1c), for two reasons. First, more mobile and capitalized vessels can access the outside reef grounds that are more productive and less heavily exploited. Second, to be economically sustainable, a métier with more capital and manpower must catch enough per trip to compensate both labour and capital, on average. Motorized vessels involve significant cash investments and sail powered vessels also represent more outlay than simple paddled vessels. The compensation needed to pay capital is out of pocket in some cases, such as when a third party owns a vessel and leases its services for a share of catch. But even on owner-operated vessels, the investment has an opportunity cost that must be compensated to keep that capital in fisheries rather than an alternative.

Fourthly, beyond the effect of crossing the reef crest, we hypothesize that capital, season and weather have an additional influence on fishing success (Fig. 1 c and d)

3. Materials and methods

3.1. Study area

The study was undertaken over a period of two years from eight distinct landing sites along the Kenya coast (Takaungu, Kuruwitu, Kinuni, Vipingo, Bureni, Bamburi, Tiwi and Tradewinds; Fig. 2). The respective fishing grounds along these landing sites display characteristics of most previously reported fishing in coastal Kenya, whereby fishing is generally assumed to be concentrated in areas between the shore to the outer reef (McClanahan and Mangi, 2000). The majority of the fishers did not own or utilize any vessel for fishing, while some used simple non-motorized crafts like canoes (dau, hori) and small sail outrigger boats (ngalawa). A small number of fishers also utilized motorized fishing boats.

Common fishing gears include spear guns, gill nets, and handlines used by single fishers or in multi-membered crews for a single trip. Weather and currents affect fisher decisions on effort allocation in this area (Daw et al., 2011). As a result, there is typically more fishing activity in the calmer Northeast monsoon season (October and March) than in the stormier South East monsoon season (April to September; (McClanahan, 1988). Important fish species targeted by Kenyan coastal fishers include parrotfishes (Scaridae) and rabbitfishes (Siganidae) (McClanahan and Mangi, 2000) and sometimes fishers target schooling pelagic species like sardines and needlefishes (Belonidae) or kingfishes (Scombridae) in certain periods of the year.

Most of the fish caught by Kenyan artisanal fishers is sold to local fish dealers who are sometimes also owners of the fishing vessels and gear. Some of the fish is later sold in large cities like Mombasa at a higher prices. Lower quality and smaller fish are often sold to female fish-fryers who process the fish for sale to local populations (Matsue et al., 2014; Wamukota, 2009) Two locally managed no take zones exist near Kinuni and Tiwi landing sites and a government-run no take marine national park is located near Bamburi.

3.2. Sampling and data collection

Data were collected between November 2009 and May 2011 covering both the calmer Northeast monsoon and the generally rougher Southeast monsoon seasons. A systematic sampling approach was employed in selecting fishers from representative gear types to participate in the study. Because of the potential sensitivity of the data gathered and the level of collaboration required (including most frequently fished sites), we worked with a group of 33 fishers who volunteered to take part in data collection. To collect information on fisher movement, we conducted participatory mapping using GIS where fishers were trained to use track functionality of handheld GPS units and map out the fishing trips. After each trip, fishers also logged the trip attributes on a logbook including: boat type (vessel), gear type, number of fishers per trip, catch and value of the fish sold divided where possible by species group. GPS data were checked and cleaned and tracks which were incomplete or spurious due to inconsistent usage or operation of GPS units were deleted (Patel, 2015).

3.3. Environmental data

Seasonal wind patterns have been reported to affect fishing activities along the Kenyan coast (McClanahan, 1988). We obtained estimates of daily wind speed for the study area from the Blended and Gridded High Resolution Global Sea Surface Winds (Zhang et al., 2006). The Blended Sea Winds dataset contains high-resolution ocean surface vector winds and wind stresses, on a global 0.25° grid and time resolution of every 6 h, (http://nomads.ncep.noaa.gov/). We could not match wind speed to the exact time of fishing because of the 6-hr temporal resolution of the wind speed data and some missing data. Thus we averaged all the wind speed data for each day to obtain an indicator of daily wind speed.

3.4. Data analysis

We combined trip observations from the landing sites of Kuruwitu, Vipingo, Kinuni and Bureni into a single site (labelled Kuruwitu) due to the close proximity of these landing sites and the sharing of fishing grounds. We combined the GPS data, wind data and logbook data (Fig. 1) in order to address the different hypotheses formulated. Information from 1708 fishing trips was assembled from the logbook data. For each trip the recorded information were: fisher ID, vessel type used, gear used, weight and value of fish by species grouping, and average wind speed for the day. For a subset of the trips (441) we also had complete GPS tracking data which allowed us to identify whether the trip crossed the reef crest or not.

We ranked the value of fisher assets on an ordinal scale from low to high, based on vessel type, means of propulsion, gear used and estimated costs of these. Fishers without boats waded in nearshore areas (foot fishers), or swam along the reefs, using either spearguns or small nets or lines. Fishers with small dugout canoes paddled inside and outside the reef, using gear including nets and lines, as did fishers with small dugouts with sails. At the most capitalized end of the spectrum we sampled a small number of vessels with outboard gasoline that deploy nets and lines. Engine-powered vessels often used crews of several men, whereas small sailboats and paddleboats used one or two fishers.

A summary of methodological approach is shown in (Fig. 1). Data were plotted to evaluate relationships between wind speed, season, assets, whether trips crossed the reef and Catch Per Unit Effort (CPUE) (kg/fisher/trip), Value Per Unit Effort (VPUE)(USD/fisher/trip) and mean catch price (USD/kg) (Fig.1). CPUE, VPUE and price were log-transformed to normalize the data that had a roughly lognormal distribution. For each hypothesis the maximum available sample size was used (i.e. hypotheses that did not involve fishing location used all available logbooks regardless of whether matching GPS data existed). T-tests were used to compare VPUE, CPUE and mean catch value/kg for trips that did and did not cross the reef. The influence of season, weather and assets on likelihood of crossing the reef crest was evaluated initially by visual plots and then, due to multiple unknown

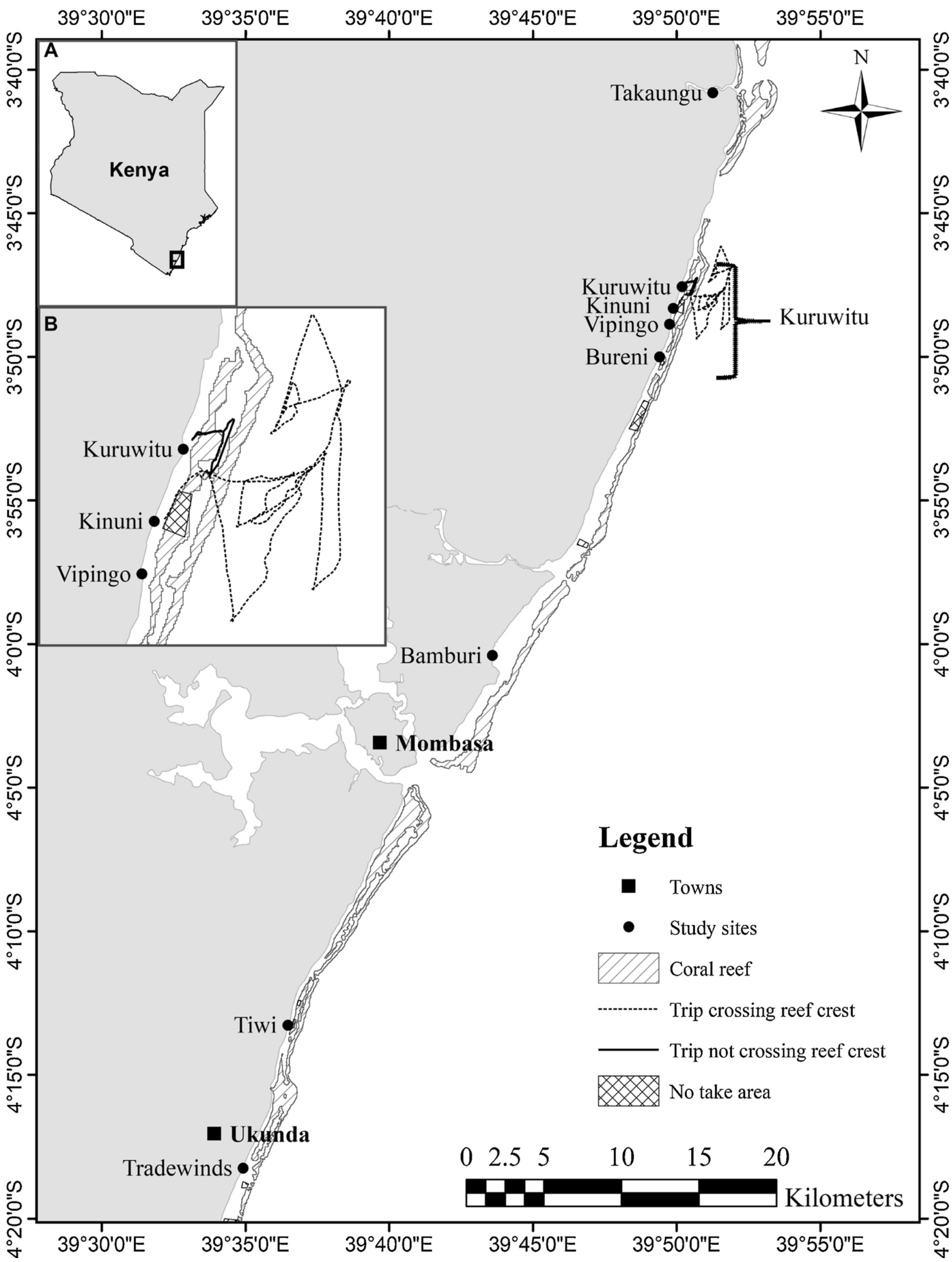

Fig. 2. Map of the Kenyan coastline around Mombasa, showing the major towns and the landing sites where data were collected. Inset B shows examples of two fishing trips, one crossing the reef and one where fishing is within the lagoon.

potential interactions, through a classification tree to identify combinations of factors which led to higher proportions of trips that crossed the reef.

To attempt to disentangle the direct influence of capital and weather on VPUE (e.g. due to more efficient fishing), and the influence on VPUE due to access to grounds over the reef crest, we conducted a multi-model inference analysis (Burnham et al., 2011) based on a model of VPUE as predicted by métier, season, wind speed, whether a trip crossed the reef crest and landing site. Running all possible candidate models with different combinations of the predictor variables and examining the Akaike Information Criterion (AIC) and Akaike weight of each candidate model allowed us to assess the relative support in the data for the importance of each predictor variable. This is a more appropriate statistical approach than choosing a single 'best' model structure given the uncertainty of which variables are important (Burnham et al., 2011). To minimize the number of predictor variables and to take account of differences between the geography of the different sites, and because not all métiers were well represented at all sites, we created a nominal variable that combined landing site and métier with six levels representing site-métier combinations with a large sample of trips. Only trips included in these six site-métier combinations (n = 188, sail boat-handline, small paddle boat- net, small paddle boat handline, No boat-Net, No boat-Speargun) were used for this analysis. We ran the dredge function in R package MuMin to run and evaluate all possible candidate models.

The effect of level of capital investment on VPUE was not evaluated by statistical modelling because of the low sample of high-capital gears. Instead, we plotted trip value by métier ordered according to capital, and how this interacted with seasonality.

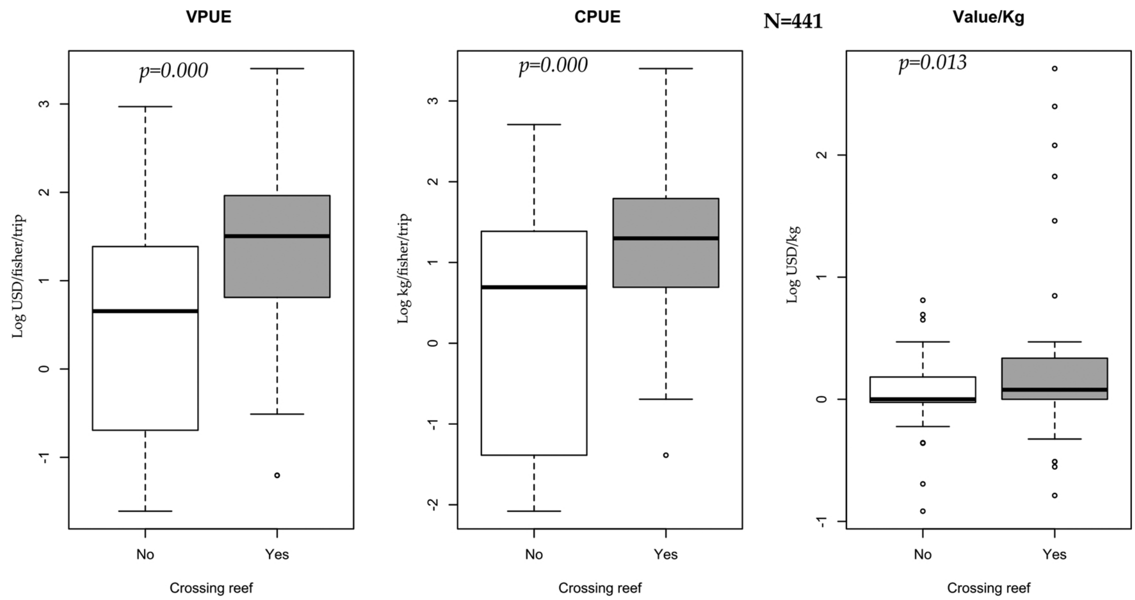

Fig. 3. Difference in CPUE, VPUE and catch price of fishing trips made inside and outside of the reef crest, with the associated *t*-test p values.

4. Results

4.1. Influence of access beyond the reef crest on CPUE, VPUE and fish price

Trips across the reef crest achieved significantly higher value per unit effort (4.54USD/fisher/trip) than those inside (2.58 USD/fisher/trip, p = 0.000). This was a result of both higher catches across the reef (4.3 kg/fisher/trip) than inside (2.4 kg/fisher/trip, p = 0.000) as well as a higher average value of fish caught on reef-crossing trips (p = 0.013, Fig.3).

4.2. Influence of assets and weather on fisher access beyond the reef crest

The majority of the trips (55%) were made across the reef, although this varied by season, with 65% trips in the calm (northeast monsoon) season crossing the reef compared to only 26% of trips in the windy season (southeast monsoon).

The seasonal pattern of higher proportions of trips crossing the reef crest in the calm season was similar across all métiers, although we only had a small number of observations from vessels with engines and sails during the rough season (Fig.4).

Reef crossing behavior by fishers with no vessel were apparently more influenced by daily wind speed than more capitalized métiers. Net and speargun fishers without a boat showed a clear trend in the calm season, with a majority of trips crossing the reef crest on calm days and vice versa on the windiest days. Small, paddled boats using handlines showed a strong seasonal difference with no cross reef trips in the windy season, but limited impact of daily wind speed. Most engine and sail-powered vessel trips crossed the reef with little evidence of any effect of daily wind, although we have fewer data from those métiers and almost no data from the windy season. This could be due either to the increased riskiness for undercapitalized métiers (storms and rough weather make access across the reefs too dangerous) or to selection of fishers and/or métiers that are less frequently used to cross the reef.

The classification tree analysis (Fig. 5) showed that season was the most important factor in predicting if a fishing trip would be made in or across the reef. Only about one quarter of trips during the windy season crossed the reef crest. The next most important factor for those trips in the calm season was métier. The likelihood of crossing the reef was divided into two separate groups. Fishers using engines, sailboats with hand line, and swimming with spear gun were more likely to cross the reef compared to those using small paddle boats with nets or with handlines, and those swimming with nets. For these métiers, the likelihood of crossing the reef was influenced by landing site, with those in Takaungu and Kuruwitu more likely to cross the reef to fish than those of Bamburi, Tiwi and Tradewinds.

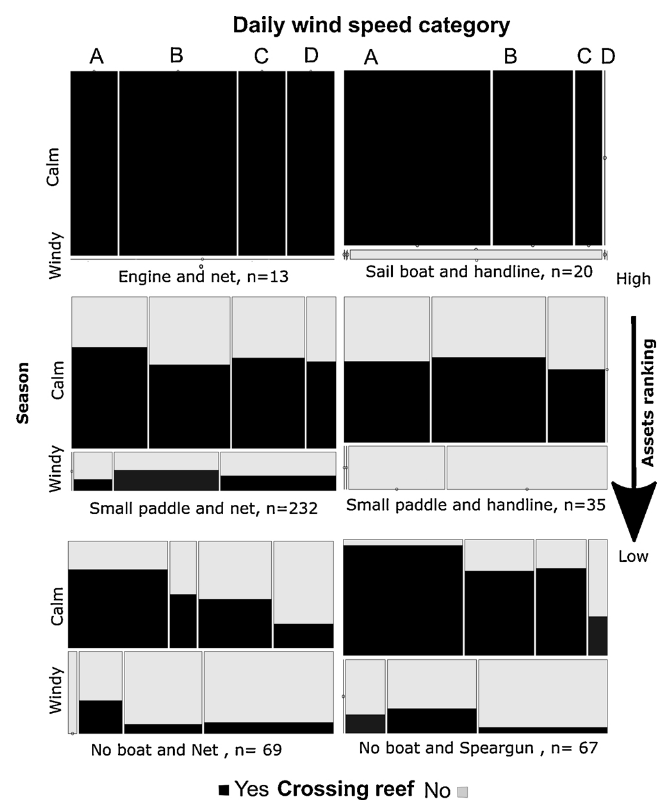

Fig. 4. Mosaic plot showing the proportion of trips crossing the reef for each métier and by season and daily wind speed category. The métiers have been ranked from high capital to low capital by boat type. Daily windspeed is shown as quartiles with A the lowest windspeed and D the highest.

4.3. Influence of assets and weather on fishing success

Of all candidate models in the multi-model analysis of factors

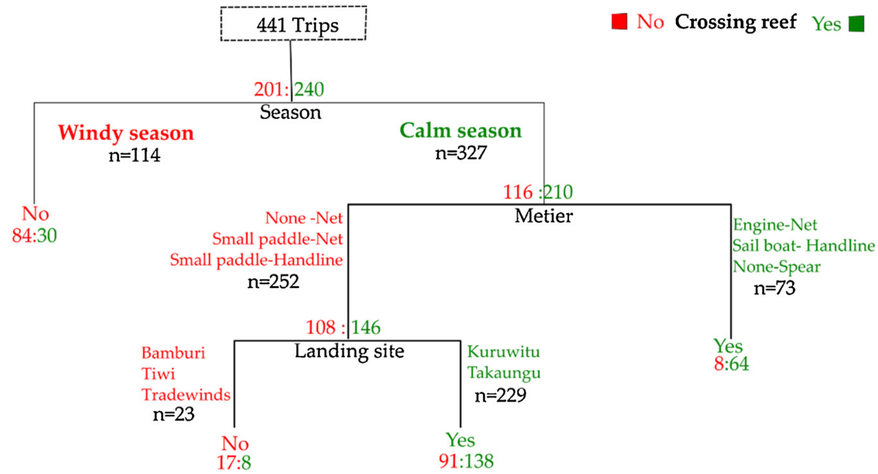

Fig. 5. Classification Tree for factors that predict trips that cross the reef. The ratio of trips that cross and do not cross the reef are given for each branch of the tree. (Factors included in the classification tree analysis included métier, season, daily wind speed and landing site.

Table 1
Multi-model analysis of factors affecting VPUE. Model Variable codes Crossing reef = 1, Landing site métier = 2, Season = 3, Wind speed = 4.

Variables	df	logLik	AICc	delta	Weight %
1,4	4	−1370.16	2748.5	0.0	28.5
1,3,4	5	−1369.3	2748.9	0.4	23.3
1,3	4	−1370.63	2749.5	0.9	17.8
1,2,3,4	8	−1366.81	2750.4	1.9	11.1
1,2,4	7	−1368.11	2750.8	2.3	9.0
1,2,3	7	−1368.46	2751.5	3.0	6.3
1,	3	−1373.42	2753.0	4.4	3.1

affecting VPUE, the data gave most support to models including the cross-reef variable (accounting for 99% of the Akaike weight). Daily wind speed was the second most important variable (in models accounting for 72% of Akaike weight) and the nominal variable including landing site and métier was the least important (Table 1). Models including this site and métier term accounted for only 27% of Akaike weight, and the model with only this explanatory variable had even less support than the null model. Possibly the high Akaike weights for crossing reef is due to some collinearity between reef crossing, métier and weather. Reef crossing then may be a convenient single binary variable which incorporates some indication of capitalization and favorable weather with limited costs in terms of degrees of freedom, leading to more favorable AICc values. However, the model with only site and métier has a very much lower probability of being the best model than the model with cross reef, wind and season which has the same degrees of freedom, indicating that the site and métier variable is much less informative for predicting VPUE than crossing reef, wind and season. The hypothesized decline in gross returns per trip per fisher with decreasing capitalization was not obvious across all métiers. While VPUE was high for the small sample of engine-boat trips, no-vessel fishers, got similar or higher gross returns compared to higher-capital metiers, especially in the windy season (Fig.6).

5. Discussion

This study exploits special features of these Kenyan coastal fisheries in order to shed light on factors that determine fishing effort and success. The study examines access to distinct fishing grounds that are separated by a reef crest. The discrete nature of the reef allows binary classification of trips to support this kind of study. Fishers use a variety of métiers distinguished by motive power and gear type. These range from minimally capitalized métiers such as individual fishers with spear guns who swim near the reef, to more highly capitalized métiers with multiple crew using nets or lines and hooks deployed offshore in engine-powered boats. Thus the fishery in the present study site is characterized by the co-existence of low-intensity métiers involving minimal or smaller investments and high intensity métiers utilizing more capital.

Despite the small-scale nature of this fishery, a majority of trips were in fact made beyond the reef crest enclosing the lagoon, even for fishers operating without a vessel. This could affect calculations of area-based estimates of coral reef yields (e,g, McClanahan, 2018) and lead to an overestimate of productivity of lagoon habitats.

The second clear result is that crossing the reef does matter for fishing success, as hypothesised. Trips to fishing grounds beyond the reef crest yielded larger CPUE. Many studies are limited to analysis of CPUE, but the logbook data on values shows that the effect on VPUE is even more marked, with catches from beyond the reef crest also attracting higher per kg prices (Fig. 3). The implications are that studies only limited to CPUE may fail to explain fishers' motivations given that the majority of catches in this fishery are sold.

The comparison of Akaike weights of candidate models emphasized this result, finding that crossing the reef was the single most informative predictor of VPUE for a sub-set of data across six site-métier combinations. Under the simplest foraging theories, fishers would be predicted to forage over space until the average returns per site visit are equal (Gillis et al., 1993). In more general foraging theories, differences in gross returns per visit (such as found here) can be explained by the differential costs of access. In this fishery, crossing the reef bears a cost, in terms of time, risk, physical effort, and capital and operating costs of engine- and sail-powered boats that cross the reef more frequently. The costs or risks of crossing the reef is not constant but influenced by weather, so that in adverse conditions the reef may act as a hard barrier which interrupts the free choice of fishers to fish inshore or offshore. This would further allow the higher returns from cross reef trips to be maintained in a long-term equilibrium.

Fig. 3 is consistent with a foraging theory equilibrium whereby more distant and difficult to access offshore sites generate higher gross returns than more nearby sites. Hilborn and Ledbetter (1979); Millington (1984); Hilborn and Kennedy (1992) found similar results applying general foraging theories to fishers' behavior in developed country fisheries. They interpret their findings as consistent with a more general foraging model identified with the economist H.S. Gordon (1954). This study adds a temporal complexity to this picture by showing the likelihood of accessing grounds beyond the reef crest varies temporally by season (Fig. 5) and, for fishers without a boat, by weather on individual days (Fig.4).

The role of capital in accessing grounds beyond the reef was

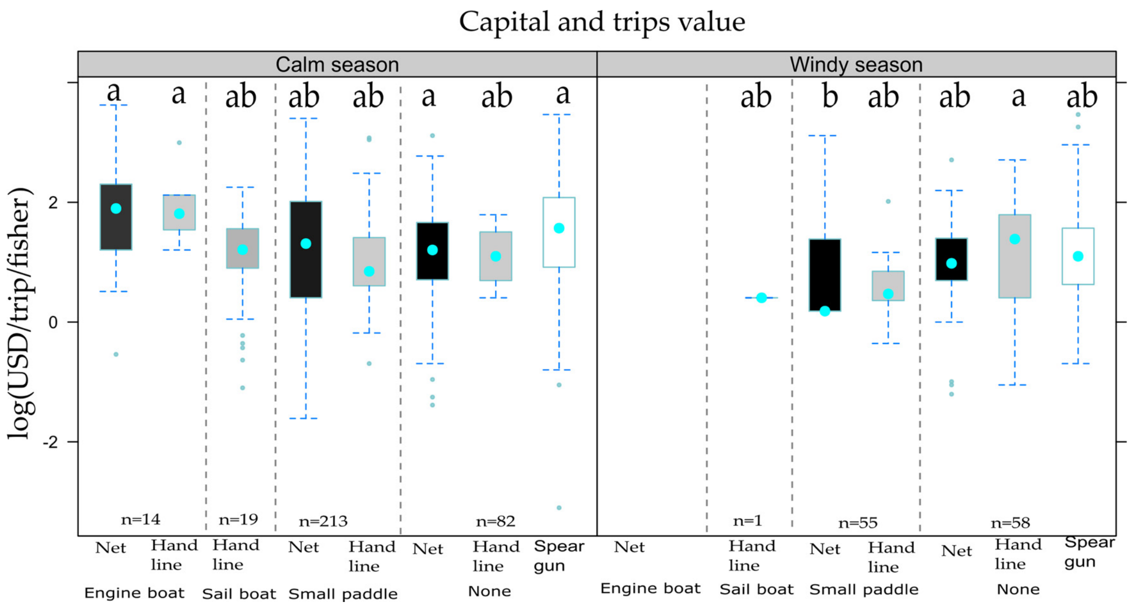

Fig. 6. Effect of capital on trip value per unit effort (VPUE). The métiers have been ranked left-to-right from high capital to low capital by boat and then gear type. Letters represent results of post hoc Tukey test. Métiers that share a letter are not statistically significantly different.

partially supported. Engine and sail boats did indeed consistently cross the reef crest more than other vessel types, but un-capitalised spear-fishers were also more likely than other métiers to cross the reef during calm season (Figs. 4 and 5). Sail and engine boats crossing the reef have access to more distant grounds and offshore patch reefs than spear-fishers who are confined to the reef slope just beyond the crest (Patel, 2015).

Offshore trips require financial and physical vessel capital and running costs to access distant grounds and trips must on average earn enough to pay those extra costs. Importantly this does not mean that the offshore fishers themselves take home the extra returns. Instead, fishers are likely to earn their opportunity costs associated with other uses of their time, and the surplus value per trip reflects amounts paid to owners of boat and gear capital. Under this theory, no input earns abnormal returns; instead labour and vessel and fishing gear capital are paid just enough so that, in equilibrium, they are compensated for participating. Also important under this theory are the ecological consequences. In the bio-economic model (Gordon,1954), fish stocks offshore would not be depleted to the same degree as nearshore fisheries under open access conditions because cost barriers prevent similarly high degrees of exploitation. In biological terms this could be critical for the long term sustainability of such a heavily exploited area, where opportunity costs of labour and underemployment make it challenging to limit total fishing effort (Cinner et al., 2009). The barriers to, and higher costs involved in, fishing beyond the reef crest may provide a partial refuge for stocks or breeding populations that could help to maintain productivity of the more intensively fished grounds within the reef crest.

A stark exception to the pattern of higher returns from more capitalised gear is relatively high VPUE achieved by spearfishers. This gear requires no vessel and very low capital costs. This suggests that the assumption of free movement of labour between gears is not valid. Access to particular fisheries is determined by economic, social, knowledge or physical barriers. In the case of spearfishing, these include physical costs of effort in deploying the gear, physical strength and skills of diving, breath holding, swimming long distances and tolerating long periods submerged in the water. Spearfishing, as a result tends to be done by younger fishers with specific skills and may not be accessible to fishers using other gears (Gillett and Moy, 2006). When the assumption of free movement, either across space or between métiers is relaxed, it becomes predictable that fishers in some métiers or fishing grounds can reap higher profits, which are not dissipated by additional labour flooding into that space.

The study focussed on a binary distinction between fishing inside versus outside the reef crest and the impact of capital and weather on this distinction. Weather can also affect the efficiency of fishing, performance of gears, time spent travelling relative to fishing and choice of fishing grounds (beyond a simple cross-reef dichotomy). Fisher interviews reported weather to be the most influential factor on Kenyan small-scale fishers' choices of where to fish (Daw et al., 2011). Likewise capital would be expected to directly influence VPUE in addition to the effect of supporting access across the reef crest, either by accessing more distant grounds once crossed, more scope for searching due to higher mobility, and more capacity to handle large catches. However, the multimodel inference using AIC surprisingly suggests that across six non-motorised métier-site combinations, crossing the reef is the most important variable for predicting VPUE (Table 1). Additional impacts of season, wind, métier and site are indicated by higher log likelihoods for models including these terms, but overall, métier and site was the least informative predictor of VPUE across this subset of data. VPUE, as per fisher per trip, incoporates labour but not operating or capital costs. Under assumptions of rent dissipation, returns on labour, after costs have been taken out should be similar across different métiers, thus predicting that VPUE should be higher for more capitalised métiers. We found a non-significant indication of higher VPUE from a small sample of motorised trips (Fig. 6), but no evidence for this trend between non-motorised metiers (Table 1, Fig. 6). Amongst the non-motorised fisheries in this system, gross returns are driven by access accross the reef (Fig. 3), while access across the reef is primarily driven by season and daily winds, and only secondarily by metier (Fig. 5). Thus capital is not the main determinant of gross returns, and less capitalised metiers can periodically access higher returns from fishing across the reef under favourable conditions.

The findings suggest some important points regarding policy options for fisheries in settings such as coastal Kenya. It is tempting, given the higher returns per trip offshore, to recommend policies that somehow give more access to those richer fishing grounds to more fishers. For example, development of interventions and strategies often involve subsidizing or donating fishing vessels, gears and or training in order to allow nearshore fishers to access offshore grounds. Such developments are also popular in the visions of fishing communities themselves (Daw et al., 2015). This may raise incomes in the short term as fishers re-deploy to the relatively less exploited more distant fishing grounds. But in the long run, more capital offshore and the resultant higher fishing mortalities will reduce stock biomass and catch per unit effort so that initial gains would be unlikely to be realised over time (Gillis et al., 1993). In addition, increased fishing pressure beyond the reef may deplete stocks that support inshore productivity through fish movement and reproduction (McClanahan, 2018). As long as the fishery operates under open access, a long-term equilibrium with subsidized offshore fishing capital could result in less sustainable catches that are likely to be even lower than catches before the subsidies. Policies that appear to generate gains in poverty reduction in the short run may thus wind up making the ecosystem less productive and less sustainable over the long run.

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