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Illegal fishing and compliance management in marine protected areas: a situational approach

Damian Weekers[1*], Gohar Petrossian[2] and Lauric Thiault[3,4]

Abstract
Protected Areas (PAs) are spatially representative management tools that impose various levels of protection for conservation purposes. As spatially regulated places, ensuring compliance with the rules represents a key element of effective management and positive conservation outcomes. Wildlife crime, and in particular poaching, is a serious global problem that undermines the success of PAs. This study applies a socio-ecological approach to understanding the opportunity structure of illegal recreational fishing (poaching) in no-take zones in Australia's Great Barrier Reef Marine Park. We use Boosted Regression Trees to predict the spatio-temporal distribution of poaching risk within no-take Marine National Park zones. The results show that five risk factors account for nearly three quarters (73.6%) of the relative importance for poaching in no-take zones and that temporally varying conditions influence risk across space. We discuss these findings through the theoretical lens of Environmental Criminology and suggest that law enforcement strategies focus on reducing the negative outcomes associated with poaching by limiting the opportunity of would-be offenders to undertake illegal activity.

Keywords: Illegal fishing, Poaching, Environmental criminology, Situational crime prevention, Great Barrier Reef Marine Park, Marine protected areas

Introduction
Wildlife crime represents a significant social and ecological problem that threatens vulnerable species, negatively impacts on natural habitats and undermines the global conservation agenda (Moreto, 2018; Nellemann et al., 2018). Poaching, a form of wildlife crime describing the illegal take of wild flora and fauna, is an activity commonly observed within both marine and terrestrial protected areas (PA). Due to the negative impacts that poaching can have on biodiversity, effective monitoring and enforcement of non-compliance within PAs is a critical element for ensuring successful natural resource management outcomes (Linkie et al., 2015; Plumptre et al., 2014). Capacity constraints such as limited resources and the large scale and difficult terrain found in many PAs means that to be effective, conservation managers must develop enforcement strategies that optimize the use of patrol assets (Hilborn et al., 2006; Nyirenda & Chomba, 2012). To prevent the illegal take of target species, these strategies should ensure that limited enforcement resources are allocated to the right places at the right times (Critchlow et al., 2015). Inherent in this approach is an understanding of the spatial and temporal risk patterns associated with specific poaching activities (Kyando et al., 2017; Weekers et al., 2020).

Wildlife crime research has consistently demonstrated that a wide variety of poaching types concentrate in space and time (Cowan et al., 2020; Kurland et al., 2018; Maingai et al., 2012; Nyirenda & Chomba, 2012; Petrossian, 2018;

*Correspondence: damian.weekers@gbrmpa.gov.au
[1] Great Barrier Reef Marine Park Authority, 28 Flinders St, Townsville, QLD 4810, Australia
Full list of author information is available at the end of the article

Weekers & Zahnow, 2019; Weekers, Mazerolle & Zahnow, 2020). While much of this literature has successfully described the spatial and temporal risk factors associated with poaching, environmental criminologists analyzing wildlife crime problems have sought to explain these patterns through human-ecological theory (Moreto & Pires, 2018; Peterossian, 2019). From this perspective, poaching hot spots emerge from the complex social-ecological system that influences how, when and where individuals engage with their environment (Hill, 2015). They argue that an understanding of the social dynamics of poaching hot spots provides conservation managers with an increased capacity to engage in proactive and prevention focused compliance management practices (Cowan et al., 2020; Moreto & Lemieux, 2015).

Guiding theory: environmental criminology

Environmental criminology represents a family of theories that explore the situational characteristics of crime to explain why crime tends to be concentrated in time and space, and the implications that this knowledge has on prevention management and crime control (see Wortley & Townsley, 2017). These theories, the *routine activity approach* (Cohen & Felson, 1979), the *rational choice perspective* (Cornish & Clarke, 1987), and *crime pattern theory* (Brantingham & Brantingham, 1993), operate at three different levels to examine how patterns of crime are embedded within the broader patterns of routine socio-economic activities. The three levels include:

1. Macro-level. The *routine activity approach* seeks to explain how the spatial and temporal rhythms of society create opportunities for crime to occur (Cohen & Felson, 1979).
2. Meso-level. *Crime pattern theory* examines how networks of activity nodes (home, work and leisure) connected by offender and target/victim awareness spaces create opportunities for crime to occur (Brantingham & Brantingham, 1993).
3. Micro-level. The rational choice perspective focuses on the choices that would-be offenders make when presented with a potential crime opportunity (Cornish & Clarke, 1987).

It is the emphasis on the setting of crime, or the 'crime event', rather than an individual's desire/disposition to commit a crime that separates environmental criminology from traditional criminological perspectives (Felson & Clarke, 1998). In the same way, there is a clear distinction between environmental criminologists who study wildlife crime from the perspective of crime settings, and *green* criminologists (Lynch, 1990) who follow a more traditional criminological approach by examining criminality (Moreto & Pires, 2018). As such, environmental criminologists analysing wildlife crime problems use their family of theories to show that specific types of wildlife crime are, (a) integrated within the broader routine structures of a society (*routine activity approach*), (b) that would-be offenders make choices within the context of immediate crime opportunities (*rational choice approach*) and, (c) the routine nature of a society limits the availability of opportunities for crime resulting in the formation of crime patterns (*crime pattern theory*). From this point of view, analyzing the opportunity structures of specific types of wildlife crime can provide an informative evidence base for developing proactive and prevention focused compliance management strategies.

The opportunity structure of wildlife crimes

Environmental criminologists have consistently demonstrated that crime concentrates in both space (Andresen et al., 2017; Sherman et al., 1989; Steenbeek & Weisburd, 2015) and time (Ratcliffe & Rengert, 2008; Townsley et al., 2000). Indeed, the persistent observation that most crime tends to occur in a small number of places, prompted Weisburd (2015: 133) to formulate a law of crime concentration which states that, *for a defined measure of crime at a specific microgeographic unit, the concentration of crime will fall within a narrow bandwidth of percentages for a defined cumulative percentage of crime.* Similarly, there is a growing body of research undertaken by conservationists and criminologists alike, demonstrating that the law of crime concentration observed in traditional forms of crime is also evident across a wide variety of wildlife crimes. For example, analyzing patterns for elephant poaching in the KNP in Kenya, Maingi and colleagues (2012) found that most killings were spatially concentrated near roads and waterholes and were more common during the dry season. Similar patterns have also been observed in the examination of illegal fishing. For example, examining illegal fishing in the Cocos Island Marine Protected Area (MPA), Arias and colleagues (2016) identified spatial clustering of poaching activity on a seamount within the MPA and the illegal activity occurring most often during the third quarter of the year. These conservation studies reflect similar spatial and temporal patterns for poaching widely observed within the conservation literature (see for example, Davis & Harasti, 2020; Kyando et al., 2017). While these findings are critical to the examination of wildlife crime problems, the social explanations for why these patterns exist within this literature remains largely unexamined (Moreto & Lemieux, 2015).

In recent years, environmental criminologists with an interest in wildlife crime have advanced these important observations through the application of the sociological theories that underpin their discipline (Moreto & Pires, 2018). In an effort to operationalize the generalized findings that poaching tends to be concentrated in time and space, these researchers apply empirical models to unpack the opportunity structures found in a wide variety of wildlife crimes (Moreto & Pires, 2018). Critical to the goal of increasing the relevance of social science in conservation management, many of these studies also provide guidance on applying opportunity-based prevention management strategies (Lemieux, 2014; Moreto & Pires, 2018; Petrossian, 2019; Weekers, et al., 2020). For example, studying the opportunity structure of illegal, unreported and unregulated (IUU) fishing in West African waters, Petrossian (2018) identified proximity to landing ports and the availability of target fish species, as key micro-spatial risk factors, where motivated offenders converge with desirable targets in the absence of capable guardians. These findings reflect the central premise of the crime setting perspective, *that easy or tempting opportunities entice people into criminal action* (Felson & Clarke, 1998: 2). In this case, the author identifies a number of situational crime prevention techniques aimed at interfering with the opportunity structure for IUU fishing including enhancing fishery licensing and offload regulations, and targeting enforcement efforts in hot spot locations (Petrossian, 2018). In so doing, Petrossian clearly articulates a direct association between the theoretical explanation of opportunity in poaching, the formulation of risk through empirical analysis and the application of a set of structured prevention strategies aimed at improving the management of the fishery resource.

Situational crime prevention and wildlife crime

Situational crime prevention (SCP) provides a framework for applying a wide range of prevention management strategies to underlying analysis of the opportunity structure of specific types of wildlife crime. At the core of this framework lies the assumption that successful prevention measures are those that are aimed at altering the situations in order to reduce the likelihood of crime. These can be achieved either by reducing the physical opportunities needed to commit a crime, such as, for example, through target hardening, access control, and concealing targets; or by increasing the perceived risk of apprehension by, for example, extending the guardianship of places or people through place managers, strengthened formal surveillance, and rule setting. If it is the opportunity that leads to crime, the situational crime prevention strategies are then to be geared toward the reduction of such opportunities, which are to be (a) directed at highly specific forms of crime; (b) involve the manipulation of the immediate environment in a systematic and preferably permanent way, and (c) increasing the risks and reducing the opportunities for crime (Clarke, 2017). Situational crime prevention puts forward five different mechanisms designed to alter a motivated offender's perceived risk of apprehension. These include *increasing the perceived effort* needed to commit the crime; *increasing the perceived risk* of getting caught if carrying out the crime; *reducing the perceived rewards* of the crime (i.e. the cost–benefit analysis shifts more toward cost); *reducing the provocations* and *removing excuses* for engaging in criminal behavior. Each of these mechanisms comprise five distinct strategies that can be used to achieve crime reduction.

SCP argues that preventive measures should be designed around changing the *near* situational rather than focusing on the *distant* dispositional causes of crime. Such an approach is based on the expectation that focusing on the direct link between cause and effect will not only lead to successful crime reduction, but that such an approach will also likely lead to a more immediate effect on crime (Clarke, 2017). Moreover, this framework calls for a focus on very specific categories of crime and the understanding of their specific situational dynamics and mechanisms, so that the most appropriate response strategies, drawn from the 25 techniques, are selected to address it.

The current study

Recreational fishing is one of the most popular leisure activities in the Great Barrier Reef Marine Park (GBRMP) (GBRMPA, 2019). Illegal recreational fishing (poaching[1]), in zones where such activity is restricted, is recognised by the Great Barrier Reef Marine Park Authority (GBRMPA) as a significant compliance management problem (GBRMPA, 2019). During 2019–20, the Reef Joint Field Management Program (RJFMP) Compliance Unit reported 702 offences for illegal recreational fishing from a total 1349 reported offences for the year (GBRMPA, 2021). The actual level of non-compliance is, however, not well understood, with the true 'dark figure' of this type of poaching likely to be much higher than observed (Bergseth er al., 2017; Williamson et al., 2014). This study examines illegal recreational poaching in no-take Marine National Parks (MNPs) in the GBRMP (see Fig. 1) between January 2015 to December 2019. The aim of this research is to build on previous studies examining the opportunity structures of wildlife crime problems, by testing the relative importance and relationship between the social and ecological features of poaching

[1] We define poaching as the illegal take of flora or fauna for a specific purpose (commercial, recreational, traditional or subsistence) (see Moreto & Pires, 2018).

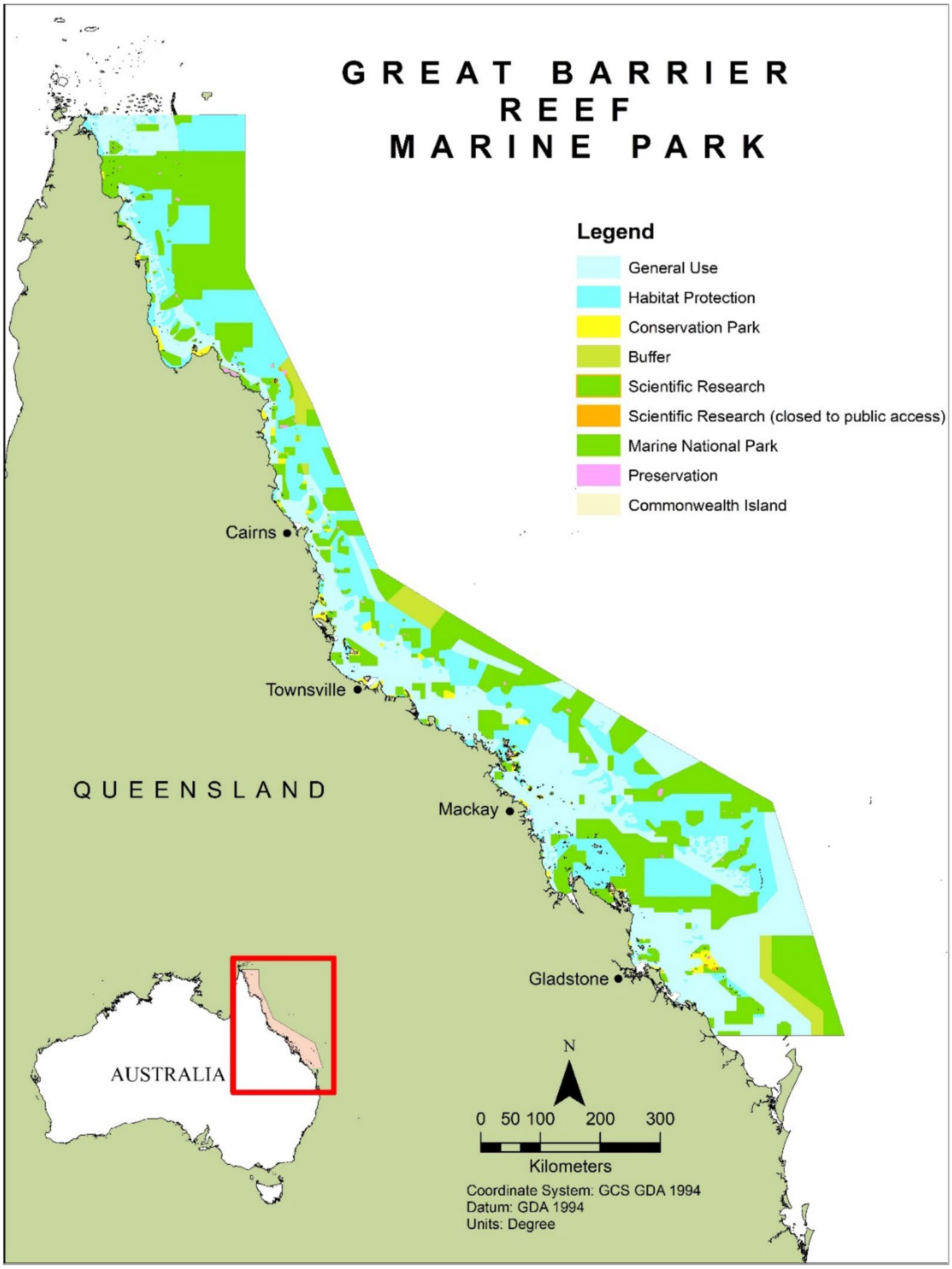

Fig. 1 The Great Barrier Reef Marine Park, Queensland, Australia

opportunity. Consistent with the theories of environmental criminology, we would expect our results to show that poaching is concentrated in both space and time. Furthermore, we would expect to observe significantly important interactions between offenders, targets and places underpinning the opportunity structure of poaching. We discuss the policy implications of our findings through the framework of SCP.

Methods

Study area

The GBRMP is a large marine protected area (MPA) covering 344,400km^2 and running 2300 km along the coast of Queensland in Australia. Created in 1975, the GBRMP was rezoned in 2004, increasing the designated area for no-take MNPs from 3 to 33% of the MPA (Fig. 1). Enforcement operations in the GBRMP are undertaken by the RJFMP with support from partner agencies. In 2020, the RJFMP reported 1052 days of dedicated compliance patrols, including 98 days of helicopter patrols in addition to fixed-wing surveillance flights by Maritime Border Command (GBRMPA, 2021). Compliance patrols are highly targeted, with 78% of patrol days undertaken during high use periods (GBRMPA, 2021).

Data and methods

Predictors of poaching risk

We considered 16 variables related to the biophysical, fishing, management, weather, and temporal dimensions expected to influence poaching by recreational fishers (Table 1). The selection of these predictors expanded on previous work that identified the primary factors mediating the spatial distribution of poaching incidents in the Cairns Management Region (Thiault et al., 2019). The biophysical measures include slope, depth, distance to reefs, latitude, aspect, and distance to islands; fishing is measured in terms of fishing capacity and distance to boat ramps; and management measures include distance to facilities and distance to boundaries. The weather dimension was characterized by swell (height and direction) and wind (speed and direction), and day of the week and month of the year were included to account for the temporal dimension.

Data sources Distance related predictors (i.e. accessibility, facilities, islands, reefs, and boundary) were derived from the most up-to-date data available on each of the elements' locations. Bathymetry data (depth) was obtained from the DeepReef database (https://www.deepreef.org/bathymetry/65-3dgbr-bathy.html), and slope and aspect were derived from this model. Fishing capacity, defined as the overall ability of the recreational fishery to extract resources in a 50 km radius, was modeled by summing the number of motorized recreational boats registered within a 50 km radius around each cell. All data covered the entire GBRMP and were represented by 250 × 250 m cells, which represented the best compromise between higher spatial resolution and lower computing time. Weather variables (wind speed and direction, and swell height and direction) were derived from ECMWF's atmospheric reanalysis of the global climate (ERA5 hourly data). We used pairwise relationship correlation coefficients (no coefficient greater than |0.65|) and variance inflation factor estimates (scores lower than 3.5) to assess collinearity among predictors.

Presence and pseudo-absences of poaching incidents

Building a reliable poaching risk distribution model requires geolocalized data on both confirmed presence and absence of poaching incidents in the area. Presence records (i.e. occurrence of poaching incidents) were obtained from the RJFMP at the GBRMPA. The data represents all reported incidents of illegal recreational fishing in no-take zones for the period January 2015 to December 2019 ($n = 947$). The presence data used in this study represents reliable records at GPS resolution. Confirmed absences of incidents (i.e. locations where poaching *never* occurred) are more difficult to obtain due to the diffuse nature of offenders and the impracticability to monitor the entire GBRMP constantly. To address this gap, we created artificial absence data (herein pseudo-absence) using geographically stratified random selection (i.e. based on density estimate of presence records) (Barbet-Massin et al., 2012).

Building a poaching risk distribution model

All analyses were performed using the R statistical software version 3.4.0. We used Boosted Regression Trees [BRT; Elith et al. (2008)] to examine the presence-absence of poaching incidents in relation to biophysical, fishing, management, weather, and temporal predictors, and model the spatial distribution of poaching risk within the GBRMP's Marine National Parks (MNPs). Gradient boosted regression tree approaches, such as BRT, are increasingly used over statistical approaches for prediction because they better handle interactions among predictor variables and non-linearity than regression-based approaches (Elith et al., 2008); both of which were expected to emerge in our case.

The occurrence and distribution of poaching incidents was modelled using a binomial distribution following the *gbm.step* routine in the {dismo} package v. 1.1–4. In order to account for such heterogeneous surveillance effort, we applied weights to each presence and pseudo-absence record based on patrol monitoring effort, defined here as the number of patrols' paths within a 5 km of each cell (visual and patrol vessel radar range), was rescaled 0 (no surveillance) and 1 (maximal value observed). Monitoring effort[2] was

[2] Monitoring effort includes VMS patrol data for all RJFMP activities including undertaking conservation actions, environmental monitoring, community engagement, incident response and compliance enforcement.

Table 1 Description of predictor variables applied in the modelling, the rationale for their use and link to Situational Crime Prevention techniques (shown in bold italics)

Dimension	Measure	Description	Construct	Range (unit)	SCP Rationale
Biophysical	Reef aspect	Compass direction that a slope faces (E:90°; S: 180°; W:260°; N:0° = 360°)	Influences the exposure of recreational vessels to particular wind and current conditions. We would expect recreational fishers to choose sheltered locations to fish	0–360 (°)	The identification of biophysical fishing attractors within no-take MNPs can be used by managers to develop strategies that ***Increase the Effort*** and ***Increase the Risk*** of poaching at these locations
	Depth	Distance from the surface to the sea bottom	Shapes fish composition and biomass and determines anchoring length. Target reef fish species are generally present in shallower waters and we expect the risk of poaching to decrease with increased depth	0- -3751 (m)	
	Islands	Distance to the nearest island	Islands represent important recreational boating attractors and are potential access nodes to surrounding MNPs. Increased general recreational activity may increase the risk of poaching	0–164.6 (km)	
	Reefs	Distance to the nearest reef	Specifically describes the reef habitats populated by reef fish species targeted by recreational fishers	0–136.3 (km)	
	Slope	Incline of the sea bottom	Topography influences fish composition and biomass. Sloping sea bottom provides habitat for fish species targeted by recreational fishers	0–50.6 (°)	
Fishing	Accessibility	Distance to the nearest boat ramp access point	Determines ease and cost to access a given area from access nodes. Also has safety implications. We expect the risk of poaching to decrease with increased distance from boat ramps (distance decay)	0–555.1(km)	If distance decay influences poaching risk, then the highest risk no-take zones are those nearest to access points. This information can be used to ***Increase the Effort*** and ***Increase the Risk*** of poaching at these locations
	Fishing capacity	Number of motorized recreational boats registered within a 50 km radius	Provides a proxy for the number of would-be offenders in a given area. We expect the risk of poaching to increase with the increased number of would-be offenders	0–495670 (n)	SCP techniques that ***Increase the Risk***, ***Reduce Provocations*** and ***Remove Excuses*** may be applied to maximise voluntary compliance within the pool of potential offenders
Management	Boundary	Distance from the nearest boundary	Poachers may fish in close proximity to MNP boundaries so as to be able to reduce their perceived risk of detection by patrols	0–45.1 (km)	Employ strategies that ***Increase the Effort*** and ***Increase the Risk*** of poaching along the boundary of MNPs
	Facilities	Distance to the nearest pontoon or mooring	Public infrastructures can provide safety and facilitate access to high use sites	0–482.4 (km)	Strategies that ***Reduce Provocations*** and ***Remove Excuses*** may be applied at these locations

Table 1 (continued)

Dimension	Measure	Description	Construct	Range (unit)	SCP Rationale
Weather	Wind speed	Wind speed 10 m above sea-level	Weather reports are widely used by recreational fishers to plan their activity in the GBRMP	0.2–18.6 (m/s)	Ensure that patrol effort is effectively applied during weather conditions suitable for recreational boating and during appropriate times to ***Increase the Effort*** and ***Increase the Risk*** to would-be offenders
	Wind direction	Direction from which the wind blows	Wind direction can influence sea conditions and recreational fishers' decisions on where to fish to maximize reward (?)	0–360 (°)	
	Swell height	Significant wave height of first swell partition	Swell height will influence both on water travel and stationary comfort levels for recreational fishing activity	0.1–4.7 (m)	
	Swell direction	Mean direction of waves in the first swell partition	Swell direction can influence sea conditions and recreational fishers' decisions on where to fish	0–360 (°)	
Temporal	Day	Day of the week	Previous research shows that poaching risk increases over weekends	1–7	
	Month	Month of the year	Previous research shows that poaching is seasonal	1–12	

derived from Vessel Monitoring System (VMS) data provided by the RJFMP, which consisted of five-minute poll information for every patrol vessel operating in the GBRMP, and comprised all activities undertaken by the patrol vessel for the same time period. Presence records were weighted as the inverse of their corresponding cell's monitoring effort value (i.e. 1–rescaled monitoring effort), on the basis that incidents detected in highly monitored areas should have less influence on the model than those detected in rarely monitored ones. Conversely, pseudo-absences were weighted proportionally to patrol effort, on the basis that pseudo-absences located in highly monitored areas were more likely to be true absences than those located in rarely monitored areas. We generated pseudo-absences so that the sum of the weights on the pseudo-absences equals the sum of those on the presence records. This process yielded a total of 1514 pseudo-absence points.

BRTs require the specification of three main hyperparameters (hereafter referred to as 'parameters' for consistency with the BRT literature): tree complexity (tc), which controls how many levels of interactions are fitted, learning rate (lr) which determines the contribution of each new tree, and the bag fraction (*bf*). In order to identify the best set of parameters, we first explored all combinations of the parameters (tc = [3; 5; 7; 9]; lr = [0.01;0.005;0.001]; bf = [0.6; 0.7; 0.8]) using tenfold cross-validation, and retained the set of parameters maximizing cross-validated Area Under the Curve (AUC). Optimal parameters were as follows: $tc = 7$, $lr = 0.005$, $bg = 0.6$. Other parameters were kept at their default values. The final BRT model performed well, with deviance explained of 56.6%, high predictive performance (AUC score of 0.98) and minimal spatial autocorrelation (maximum Moran's I of 0.08 in the model residuals (Fig. 2)).

The median relative importance of the 16 predictor variables calculated on 1,000 bootstrap replicates of the original dataset was combined to assess the relative contribution of each dimension (temporal (month of the year and day of the week), weather (wind speed, wind direction, swell height, and swell direction), biophysical, management and fishing-related variables. Similarly, we visualized the effect of each predictor by means of partial dependence plots with 95% confidence intervals, obtained by plotting the bootstrapped fitted function in relation to individual predictors, while keeping all others at their mean. We also quantified relative interaction size between predictors by measuring residual variation between pairwise model predictions with and without interactions. We used 250 bootstrap resampling to test the significance of the strongest interactions. For each bootstrap, we randomly resampled incidents occurrence before re-fitting the BRT model and then recorded the size of the interactions to generate a distribution under the null hypothesis of no interaction among predictors (Elith et al., 2008).

Finally, we generated a set of 250 model predictions across the GBRMP and calculated the median estimate of predicted probability of incident occurrence to represent the poaching risk at each 250 m * 250 m pixel (i.e., the spatial resolution of predictor variables) with a continuous scale (0–1).

Results

Figure 3 illustrates the relative importance of the 16 predictor variables from the results of the bootstrap fitted function modelling. The results show that five factors represent nearly three quarters (73.6%) of the relative importance for poaching in no-take MNPs in the GBRMP. Variables associated with *Management* and *Fishing* accounted for 59.1% of predictive poaching risk. As a result, the highest risk MNPs tend to be inshore and mid-shelf zones adjacent to large population centres (see Fig. 3).

The model also demonstrated the relative importance of prevailing weather conditions (17.5%) on poaching risk. In particular, wind speed (8.4%) and swell height (6.1%) were shown to be more important than both biophysical and temporal predictor categories. The results of these two variables reveal that the risk of poaching is highest in sea conditions with less than 10 knots of wind and under 1 m of sea swell. The model also showed that both the direction of the wind (1.4%) and the direction of the swell (1.6%) while statistically significant, were less important risk factors for poaching.

Figure 3 also reveals that while overall the relative importance of biophysical factors (16.8%) was important, the two most important poaching risk variables were slope (5.2%) depth (3.2%), which related directly to the bathymetry and the locations of suitable fish habitats.

Finally, the model results show that temporal factors, day of the week (1.5%) and month of the year (1.3%) held the lowest relative importance for poaching in no-take MNPs when compared with all other predictor categories.

Testing the relative strenght of interactions between the predictor variables (Table 2) revealed that the six strongest interactions all included weather related predictors (*wind speed* and *swell height*). These results indicate that regardless of the spatial risk associated with specific locations in the GBRMP, the risk of poaching decreases dramatically in sea conditions of greater than 10 knots of wind and more than 1 m of swell. The results of this analysis also showed a significant interaction between the predictor varable with the highest

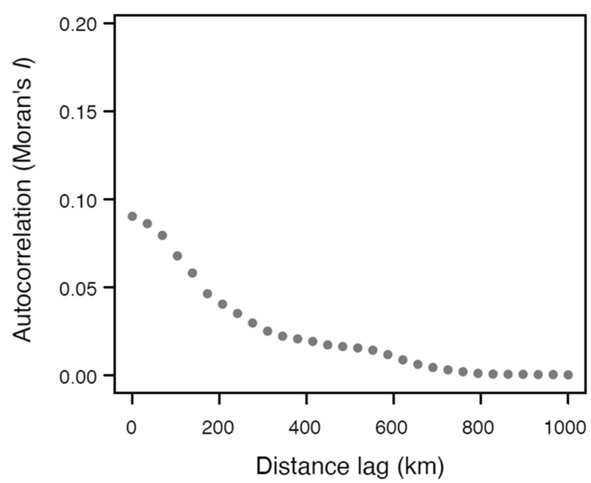

Fig. 2 Moran's I correlogram of the residuals from the Boosted Regression Trees (BRT) model. The figure illustrates that error terms were independent, thereby validating the model

importance (*fishing capacity*, 38.4%) and the third lowest predictor (*day*, 1.5%). The identification of this interaction reveals that the overall opportunity structure for poaching in the GBRMP is comprised of three important situational elements associated with spatial, environmental and temporal risk factors.

Discussion

Summary of findings

Drawing from three environmental criminology theories, namely the rational choice perspective, the routine activities approach, and the crime pattern theory, this research set out to examine the relative importance of the various biophysical, weather, temporal, as well as fishing and management predictors of illegal recreational fishing in Australia's Great Barrier Reef Marine Park. In so doing, it sought to identify the most relevant and useful predictors of illegal fishing that can inform management and compliance efforts, as well as to assist in the decisions on where limited enforcement efforts should be placed. A total of 16 predictors were examined, and their levels of importance were identified, both separately (Fig. 3), and through pairwise interactions with other predictor variables (Table 2). Critically, the results show that poaching risk in MNPs is not constant, and that temporally varying conditions influence risk across space.

A total of five predictors designed to measure the fishing, management, and weather dimensions, collectively predicted 73.6% of the variation in illegal fishing

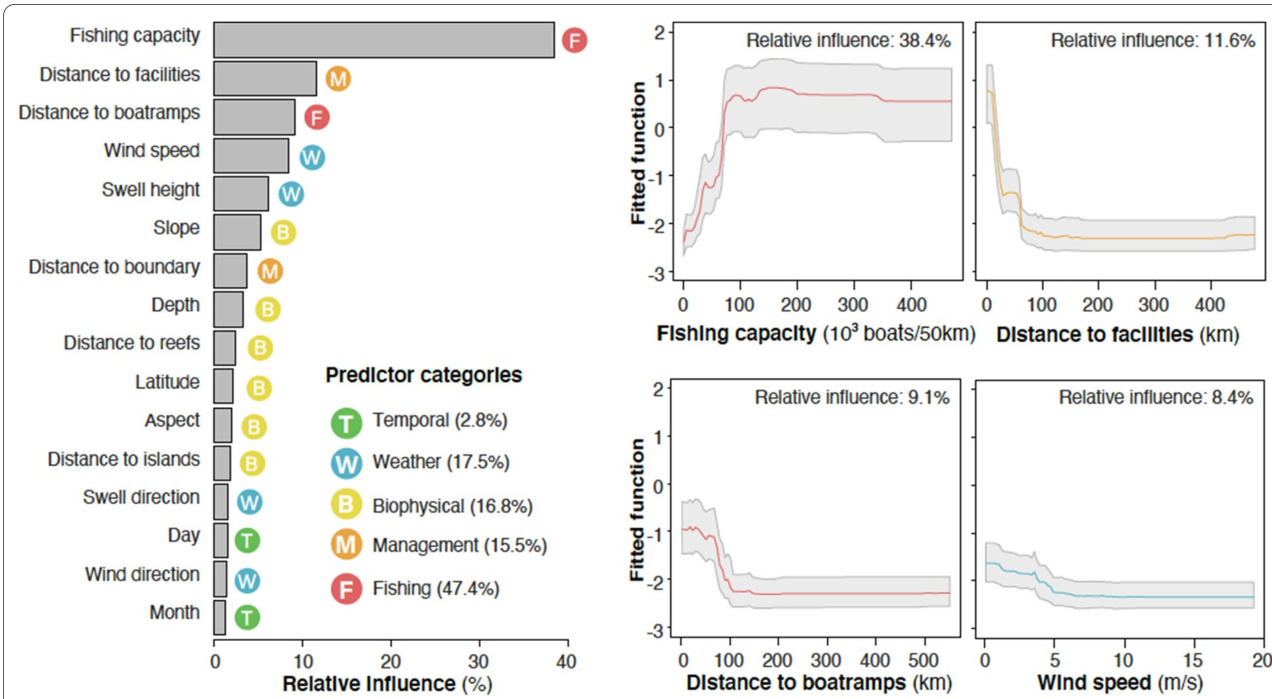

Fig. 3 Predictors of poaching incidents by recreational fishers in the GBRMP. The bar plot shows the relative importance of the predictor variables. The other graphs are partial dependency plots with 95% confidence intervals for the four most important variables predicting the occurrence of poaching incidents by recreational fishers in the GBRMP. They show the effect of a given predictor on the probability of occurrence of poaching incidents while keeping all other variables at their mean

Table 2 Pairwise interactions between predictor variables. A summary description is given for the trend associated to a peak in incidents occurrence probability. Smaller values indicate weaker interactions. All interactions were significant ($p<0.01$)

Predictor 1	Predictor 2	Relative strength	Summary
Wind speed	Distance to boat ramps	10.66	Lower wind and nearer distance to boat ramps
Wind speed	Distance to facilities	7.75	Lower wind and nearer distance to facilities
Wind speed	Fishing capacity	5.38	Lower wind speed and higher recreational boat density
Swell height	Distance to facilities	3.39	Lower swell and nearer distance to facilities
Swell height	Distance to boundaries	3.13	Lower swell and nearer distance to MNPs' boundaries
Swell height	Fishing capacity	2.62	Lower swell speed and higher recreational boat density
Fishing capacity	Distance to facilities	2.42	Higher recreational boat density and lower distance to facilities
Fishing capacity	Day	2.20	Higher recreational boat density and during the weekends

in no-take MNPs. Fishing capacity and accessibility (two measures of 'fishing'), accounting for 47.5%, and distance to facilities (one of the two 'management' measures) accounting for 11.6%, together predicted almost 60% of the variation in poaching risk. Subsequently, illegal recreational fishing activities occurred most frequently in areas with the highest concentration of motivated offenders where the distributions of the desired targets overlapped with their activity spaces the most (Fig. 4). These results are consistent with the findings of prior literature that examined the role of fishing capacity and its effect on poaching (Thiault et al. 2019), thus emphasizing the importance of incorporating response strategies that are specifically targeted at areas that exhibit such qualities. Additionally, the distance to the nearest pontoon or mooring and the distance to the nearest boat ramp access point, both of which are locations that facilitate access to high-use sites, emerged as the second and third most important predictors. This finding is consistent with the general conclusions of the 'distance decay' criminological literature that examined conventional criminal activities (e.g. Bernasco & Block, 2009; Rengert et al., 1999), wildlife crime, and illegal fishing specifically (e.g. Advani et al., 2015; Weekers, Zahnow & Mazerolle, 2019; Davis & Harasti, 2020). For example, in their study of robberies in Chicago, Bernasco and Block (2009) showed that distance matters: robbers tended to target locations in census tracts where they lived, as well as the areas (within their home tracts) that seemingly offered a greater supply of suitable targets for robbery. Kurland et al's (2018) study of redwood burl poaching in the Redwood National and State Parks in Northern California, USA, found that these incidents were significantly more frequent in areas accessible to roads. Weekers and colleagues' (2019) examination of illegal recreational fishing in the GBRMP also revealed that accessibility, which they measured in terms of the distance to the nearest boat ramp from the MNP boundary, was a significant factor explaining the frequency of poaching incidents in the area.

Our findings also indicate that the risk of poaching was highest in sea conditions that had less than 10 knots of wind and with sea swells that were under one meter high, explaining 8.4% and 6.1% of the variation in poaching, respectively. Collectively, the weather variables, which also included wind and swell directions, accounted for 17.5% of the variation in poaching risk. Further, when interactions were considered, the two main weather variables remained highly relevant, with the strongest interactions emerging from the combination of 'weather' and 'fishing', as well as 'weather' and 'management' variables (Table 2). The emergence of this pattern should not be ignored, as they point to a decision-making process that is unique to committing a type of crime that is conditional of the weather. Consistent with past research (Davis & Harasti, 2020; Widmer & Underwood, 2004), wind and sea conditions are essential conditions for the increased levels of recreational activities, including illegal ones.

The findings on the lack of a strong temporal effect in terms of the day of the week and month of the year represent a unique and important contribution to the wildllife crime literature. Most studies examining the temporal variations of illegal recreational fishing have consistently found strong temporal patterns associated with these activities. For example, Weekers et al (2020), in their analysis of spatio-temporal concentrations of poaching in the GBRMPA found that the risk of this activity peaks on weekends (and, to some, extent Fridays). Similarly, Davis & Harasti (2020), in their analysis of illegal fishing in no-take areas in New South Wales, Australia, found a significantly higher number of vessels fishing in these areas on non-working days that included both weekends and public holidays. The results of the pairwise analysis (Table 2) show a significant interaction between the predictor variable with the highest importance (*fishing capacity*, 38.4%)

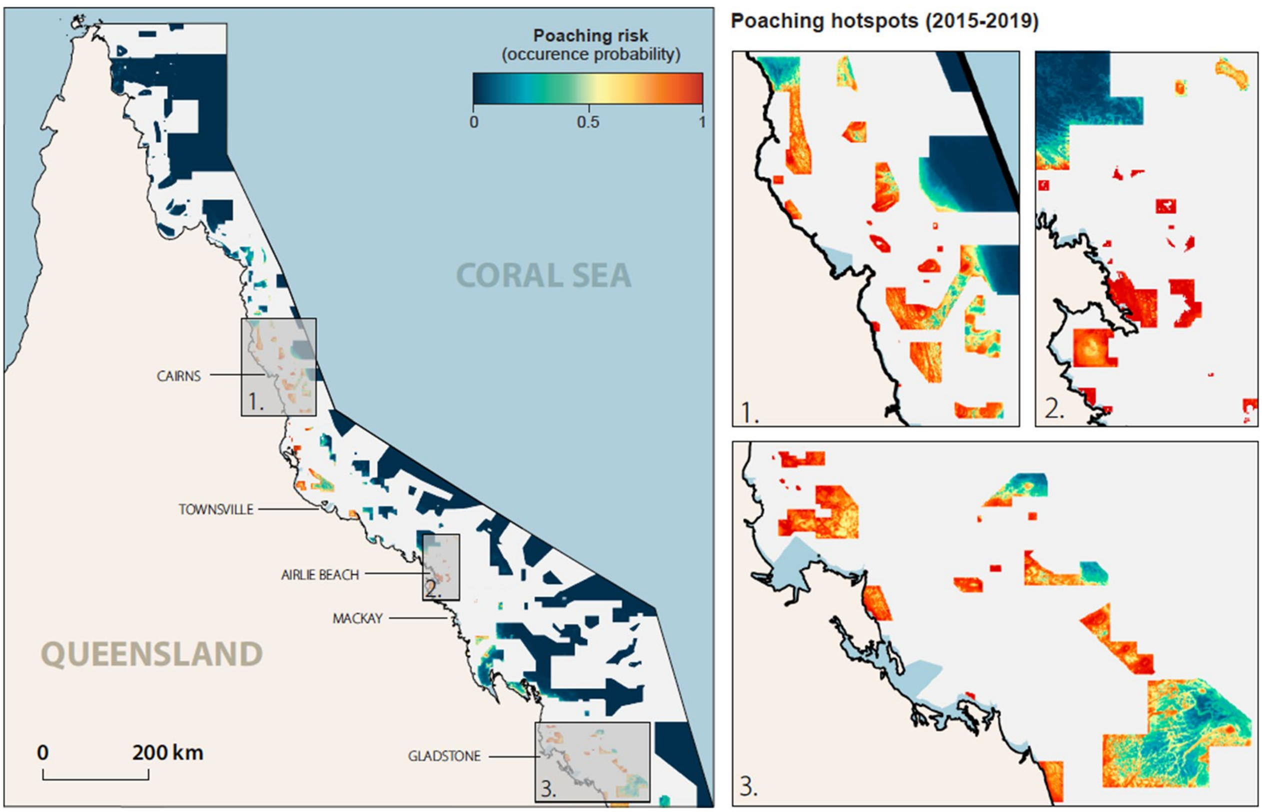

Fig. 4 The map illustrates the spatial risk for poaching in no-take MNPs in the GBRMP based on the relative importance of, and interactions among, the predictor variables identified in Table 1. The insert maps provide a detailed view of the three highest risk areas adjacent to population centers at Cairns, Airlie Beach and Gladstone

and the third least important predictor (*day*, 1.5%). This significant relationship confirms the findings of these previous studies identifying weekends as the highest risk periods for poaching, but critically to our understanding of opportunity, demonstrates that temporal factors are subordinate to weather (wind, swell). That is, while recreational activity and subsequent recreational poaching is concentrated near large population centres and on weekends, it remains limited to suitable boating conditions identified in our modelling as less than 10 knots of wind and one meter of sea swell. As such, we extend the understanding of the opportunity structure for recreational poaching in MPAs to include periods of good weather.

Poaching hotspots do not emerge independent of the environment. Reasoning offenders always look for cues for where crime opportunity in the physical and social environments will converge with their daily routines and 'activity spaces' (Brantingham & Brantingham, 1993), and the perceived effort, risk, and reward will play a significant role in their decision about the areas in which they choose to carry out their illegal activities. These offenders have been described as foragers, who "must find a good hunting ground before starting to chase prey" (Bernasco & Block, 2009, p. 96), and illegal recreational fishers are not any different, as demonstrated by the findings of this study. These conclusions lead to important policy implications discussed in the following section.

Policy implications

Limited enforcement resources relative to the vast size of the GBRMP constrain any efforts to effectively patrol these areas if focused data-driven interventions are not implemented. This is why we call for targeted interventions that take into account the concentrations of these activities as revealed by this study findings, as well as derive from the techniques of situational crime prevention.

Considering the number of recreational boats, used as a measure of fishing capacity, was a strong predictor of illegal recreational fishing, the most reliable option to deal with the problem would be to increase the risk of apprehension by *strengthening formal patrol surveillance* around these particular areas. Compliance officers can also encourage *informal surveillance* and *reduce provocations* by establishing and maintaining a strong relationship with communities adjacent to these areas and by seeking their assistance in establishing a culture of compliance. Management strategies that balance enforcement and community engagement will produce better conservation outcomes. For example, Martin and colleagues (2013) found that a combination of targeted patrols, support for local communities through increased national park entrance fees, and community guardianship led to a significant reduction in rhino poaching in Nepal despite increasing prices for rhino horn during the study period. Conversely, Ogogo and colleagues (2014) found that poorly equipped rangers and an absence of alternative community livelihood options were the primary factors that limited the success of anti-poaching programs in Nigeria. To improve conservation management outcomes, the authors suggested increasing enforcement resources, involving surrounding communities in the management of the national park, and creating alternative income streams (Ogogo et al., 2014). Other considerations could include improving the capacity of the wildlife authorities by enhancing their work conditions through leadership training, bolstering staff morale, and rewarding their work through increased salaries.

Distance to the nearest boat ramp and the nearest pontoon or mooring, measures of accessibility and management, emerged as significant predictors, suggesting that poachers sought entry sites that required minimal effort. Therefore, patrol surveillance efforts should be strengthened at these particular locations in order to *increase the effort* and *reduce the reward* of engaging in poaching. Increasing the patrol visibility in these particular locations will send a clear message to the would-be poachers that these areas are not viable access points to engage in illegal activity.

Compliance literature suggests that successful interventions should take advantage of both the normative approaches that incorporate community-based interventions and compliance mechanisms, as suggested earlier, and regulatory approaches that seek to strengthen the formal enforcement mechanisms that include focused patrols, regulations and laws, and fines and punishment (Kahler & Gore, 2012; Nielsen & Meilby, 2013; Oyanedel et al., 2020). Focused patrol efforts should take into consideration weather conditions, as the latter affect the planning activities of would-be offenders just like they would guide the activities of compliant recreational fishers. Therefore, targeted patrol efforts should be organized during weather conditions that are most conducive of recreational fishing.

Study limitations

We are aware of the inherent data limitations in this study, specifically that the data are only available for known illegal fishing activities, and that pseudo-presence of such activities had to be derived through statistical modeling (Cerasoli et al., 2017; Thiault et al., 2019). However, this limitation is not particular to this study and is a common limitation of studies that deal with both conventional and wildlife crime (as there is always a 'dark' figure of crime). We are, however, confident that the patterns revealed in this study are reliable indicators of the actual illegal recreational offending behavior, as the data used in this study were derived through the triangulated collection methods that involved not only air and sea patrol, but also a combination of multi-agency records.

This research uses multiple years of data, specifically an aggregate of illegal recreational fishing data from 2015 through 2019. As such, it may have inadvertently masked possible variations of incidents, such as, for example, illegal activities carried out by repeat offenders. However, given the focus of the research questions, which was understanding and explaining the incidences of the illegal recreational fishing activities (regardless of who committed them), this limitation is unlikely to change the outcomes of the analyses. Future research, more focused on the characteristics of the offenders, can potentially look into disaggregating the incidents by offender characteristics.

Conclusion

In their seminal work, *Opportunity Makes the Thief*, Felson and Clarke (1998) argued that crime was largely a product of opportunity. This was novel at the time when criminological thinking was dominated by theories that favored the explanations of dispositional causes of crime that were so deeply rooted in criminological thinking. Rather than focusing on the immediate environmental landspace and how this shapes the motives for crime, these dispositional theories relied on buidling an understanding about the (less tangible) motivations that gave rise to crime. Felson and Clarke's (1998) work, thus, addressed the limitations of the dispositional approach to crime by positing that opportunity, in fact, is a *necessary* condition for crime because regardless of one's motivations, crime is not possible to commit without "overcoming its physical requirements" (pg. 1). This was, in a sense, a paradigm shift that has since gained significant empirical support.

Research examining the opportunities of crime has grown exponentially, penetrating the wildlife crime realm in the last decade. Mounting empirical evidence suggests that in order to succeed in reducing illegal fishing, one should focus on addressing specific contextual factors that facilitate it with a particular emphasis on opportunity reduction. This is likely to lead to immediate and lasting outcomes. Environmental criminology not only offers a valuable perspective to understanding illegal fishing, but it also offers a plethora of tools that can be used to prevent it. After all, preventing poaching is undoubtedly a more desirable outcome than engaging in retroactive dialogue to understand offenders' motivations.

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Authors' contributions
DW and GP designed the study, analysed the data and authored the article. LT designed the statistical model, and co-authored the paper. All authors read and approved the final manuscript.

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Availability of data and materials
Data and materials for this project have not been made available.

Declarations

Competing interests
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Author details
[1]Great Barrier Reef Marine Park Authority, 28 Flinders St, Townsville, QLD 4810, Australia. [2]Department of Criminal Justice, John Jay College of Criminal Justice, Haaren Hall-63107, 524 West 59th Street, New York, NY 10019, USA. [3]National Center for Scientific Research, PSL Université Paris, CRIOBE, USR 3278, CNRS-EPHE-UPVD, Maison des Océans, 195 Rue Saint-Jacques, 75005 Paris, France. [4]Moana Ecologic, Rocbaron, France.

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