Ocean and Coastal Management 227 (2022) 106290

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Multidimensional data analysis to guide the sustainability of a small-scale fishery affected by poaching

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ARTICLE INFO

Keywords:
Poaching
Enforcement
Fisheries' management areas
Artisanal fisheries
Benthic resources

ABSTRACT

The substantial increase in poaching within the fisheries' management areas (MA) system in central Chile is likely driven by an interplay of socio-economic factors. To assess this problem, the exploitation state of an important benthic resource in the MAs (i.e., keyhole limpet) was related to socio-economic drivers of the fishery. The potential drivers of poaching included the level of formal and informal enforcement and distance to surveillance authorities, a rebound effect of fishing effort displacement by MAs, wave exposure and land-based access to the MA, and alternative economic activities in the fishing village. A Bayesian-Belief Network approach was adopted to assess the effects of potential drivers of poaching on the exploitation state of limpets, assessed by the proportion of the catch that is below the minimum legal size and by the relative median size of limpets fished within the MAs in comparison with neighboring open access areas. Results showed the important role of socio-economic (e.g., alternative economic activities in the village) and context variables (e.g., fishing effort displacement or distance to surveillance authorities) as drivers of poaching in the study area. Scenario analysis explored variables that are susceptible to be managed, evidencing that an integrative ecological and socio-economic approach can offer solutions to the unsustainable exploitation of marine resources.

1. Introduction

Scientific evidence suggests that non-compliance with fishing regulations emerges among the most important factors contributing to the overexploitation of marine resources (Agnew et al., 2009; Donlan et al., 2020). However, small-scale fisheries (SSF) are largely unassessed (Costello et al., 2012) and information on illegal fishing practices in SSF is still scarce (Pita et al., 2019). The usual spatially scattered nature of SSF imposes serious challenges to monitoring, surveillance, and enforcement to detect any non-compliance activities (Costello et al., 2012; Mora et al., 2009). It is a complex problem to solve, as numerous socio-economic factors are probably playing a key role, and it is likely to be highly conditioned by the local context (Nahuelhual et al., 2020; Oyanedel et al., 2020). The absence of incentives to comply with fisheries norms has been pointed out as a significant problem for SSFs, particularly in scenarios where neoliberal fishing policies fostered severe extractivism to the detriment of traditional and more sustainable fisheries (Nahuelhual et al., 2020 and references therein).

There are many useful tools and legal frameworks which reduce overfishing, allow the rebuild of fish stocks, and protect the biodiversity of the oceans. Effective fisheries management has stopped overfishing in a large number of fisheries in Australia, Canada, Europe, New Zealand, Norway, USA (Hilborn, 2016). Areas protected from fishery activities are also effective conservation measures (Sala and Giakoumi, 2018). However strong compliance with the rules is at the heart of the successful conservation of natural resources (Keane et al., 2008). The Territorial User Right in Fisheries (TURF) in SSF has been proposed as an alternative to encourage trust, rule compliance, and fishers' involvement in the enforcement (Battista et al., 2018). They are also likely to allow fishers to sell fish at higher prices, reduce resource waste and increase fishers' incomes (Nguyen Thi Quynh et al., 2017, and references therein). Chile was a pioneer in the implementation of a TURF system to the SSF at a national scale in 2003, known as Management and Exploitation Areas for Benthic Resources (Fernández and Castilla, 2005). The TURF system in Chile has contributed to increasing the abundance of commercial species (Aburto et al., 2013) and has shown

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https://doi.org/10.1016/j.ocecoaman.2022.106290
Received 25 November 2021; Received in revised form 29 June 2022; Accepted 12 July 2022
Available online 18 July 2022

positive effects on biodiversity, reproductive output, population connectivity, and trophic web structure (Blanco et al., 2017, 2019; Gelcich et al., 2012; Pérez-Matus et al., 2017). However, recent studies suggest that poaching in the Management and Exploitation Areas (hereafter MAs) can be as high as 68% of the annual income obtained from this system in some regions of Chile (Bandin Llanos, 2013), and recent biological surveys provided evidence of poaching in several MAs (Fernández et al., 2020).

Research on fisheries working on a TURF basis identified a series of incentives promoting illegal activities. For instance, the usually limited human resources available for surveillance activities (both from the authorities and fishers) make it difficult to identify and punish poachers, and also the existence of a well-established black market in demand of fisheries products (Ballesteros and Rodríguez-Rodríguez, 2018; Oyanedel et al., 2018). Intense poaching in a given area has been related to the target species' attractiveness, accessibility to the area, area control by patrols, and perceived likelihood and consequences of being caught (Thiault et al., 2020). On the other hand, compliance with fishery regulations is tightly linked to the local context, where poachers might consider regulations weak, outdated, or unfair (Oyanedel et al., 2021). Therefore, fishers' compliance might be influenced by social or individuals context, including perceptions of regulation fairness and trust, and by external factors including surveillance and punishment (Iacarella et al., 2021). The complex interplay of factors driving poaching triggers the need for integrative approaches that can be accommodated to local context characteristics, including scarcity of data, to identify which are the main drivers of poaching in TURFs systems.

This work introduces a novel quantitative assessment of the effects of socio-ecological drivers on the extraction of the culturally important resource keyhole limpet in the central coast of Chile with the use of a Bayesian Belief Network (BBN) model. BBN's have been previously applied to consider management systems governing artisanal fisheries where the effects of qualitative and quantitative factors are of concern (Little et al., 2004; Pollino et al., 2007; Rambo et al., 2022; van Putten et al., 2013), or when considering social, environmental and economic factors leading to multi-objective management of coastal resources (Hoshino et al., 2016; Slater et al., 2013). Combining MA surveillance effort, fishers' perception of the number of poaching events, MA context factors, and the exploitation status of the resource in reference to the adjacent areas open to fishery activities, we modeled the occurrence probability of poaching over the resource. The size structure of the catch provides a reliable basis to assess the occurrence of poaching on keyhole limpets. Fishing regulations for this resource are limited to minimum legal size (6.5 cm of shell length) and, only in MAs, also fishing quotas. Therefore, the fraction of the catch below the minimum legal size is directly linked to poaching (Fernández et al., 2020).

An integrative model of multiple interacting factors affecting the conservation of natural resources is essential to address crucial issues such as the identification of factors that determine the level of effective enforcement needed to reduce poaching and spotting variables that can assist a rapid assessment of effective enforcement and success of SSF. The BBN model allows exploring in an integrative way the link between biological, socio-economic and context factors in a complex and partly data-poor SSF managed through a TURF system. It allows to integration of data from fisheries stakeholders and scientists to identify drivers of non-compliance with the MA regulations that are dependent on the socio-economic conditions of the local fishers and the MA. The BBN model also allows to explore a set of management scenarios to assess the influence of the external drivers on poaching in the MA. Moreover, the graphical outputs facilitate communicating the results to stakeholders. Understanding and communicating to stakeholders the drivers of non-compliance can contribute to more effective management of fisheries areas and guide the best practices for SSF management.

2. Methods

2.1. Description of the case study: small-scale fisheries in central Chile

Small-scale benthic fisheries in Chile are mostly organized around fishing coves known locally as *"Caletas"*, which serve as operational bases for the local fleet. At the time of the study, with data collected between 2015 and 2016, the harvesting fishing grounds showed two contrasting management regimes: (i) exclusive harvest rights assigned to fishers' organizations (TURFs), locally known as Management and Exploitation Areas for Benthic Resources (hereafter MAs) or (ii) historical fishing grounds without spatial entry restrictions, hereafter referred as open access areas (OAs). In these coves, fishers can be organized in associations that co-manage a MA, but there are also un-associated fishers. The most common fishery resources that can be extracted in the MAs are the Chilean abalone, locally known as *"loco", (Concholepas concholepas)*, keyhole limpets (a set of species of the genus *Fissurella*), the red sea urchin (*Loxechinus albus*) and subtidal kelp (mainly *Lessonia* spp.) that are exclusively exploited by fishers of the fishers' association. Outside the MAs, both fishers belonging to the association and officially registered un-associated fishers can extract fish and benthic resources (except Chilean abalone) (Fernández et al., 2020).

Some species-specific regulations operate both for MA and OA (e.g., temporal reproductive bans or minimum legal size), however, others apply exclusively to MAs (annual quotas) or OA (total ban of Chilean abalone). Due to differences in the administration of the MAs, not all these areas exhibit a similar enforcement level (Gelcich et al., 2013). The control of catch quotas and species' sizes and compliance with regulations is usually performed by the National Fisheries Service. Surveillance of the MAs, which is not mandatory, is conducted by fishers' associations, who must cover surveillance costs. In the present work, the term "poaching" refers to the illegal extraction of the resource, either due to non-compliance with the annual quotas by the associated fishers, or to illegally extracting the resource from MAs by un-associated fishers.

For the present study, data was gathered from 13 fishers' associations that manage 24 MAs on the central coast of Chile, i.e., each fishers' association presented between 1 and 3 operational MAs at the time of the study. These areas were selected as both fishers' survey and benthic resource (i.e., key-hole limpet) data were available (Fig. 1). Keyhole limpets were selected to assess poaching intensity as it is targeted as the primary resource in the management plans of most MAs in the area of study.

2.2. Interviews with Fishers

Interviews with the leaders of the fishers' associations were carried out from 2015 to 2016 to obtain information and perceptions on MA surveillance (i.e., surveillance effort and frequency), perceived poaching intensity (i.e., estimated poaching events per year), and the organization of the fishers' association (i.e., number of fishers, leadership, etc.). The study included two sets of interviews: face-to-face extended interviews focused on the 13 fishers' organizations included in the analysis, which covered ca. 250 km of the coast in central Chile. These interviews targeted the leader of the fishers' organization, however, in each association, additional questionnaires to ca. 10 fishers were gathered to contrast the leader's perception (see below). b, Remote (telephonic) interviews focused on 26 additional associations covering the entire study area (ca. 700 km) that allowed defining a surveillance effort (based on surveillance protocol and frequency) (Fig. 2). The two approaches had a set of common questions that aimed to explore the MA surveillance protocol, or lack of it, the evenness in surveillance across MAs, and the fishers' perception of the enforcement effectiveness and the number of poaching events per year. The full questionnaire is provided in the supplementary material.

The information gathered from the questions common across the 39 fishers' associations allowed defining a surveillance effort ranking in the

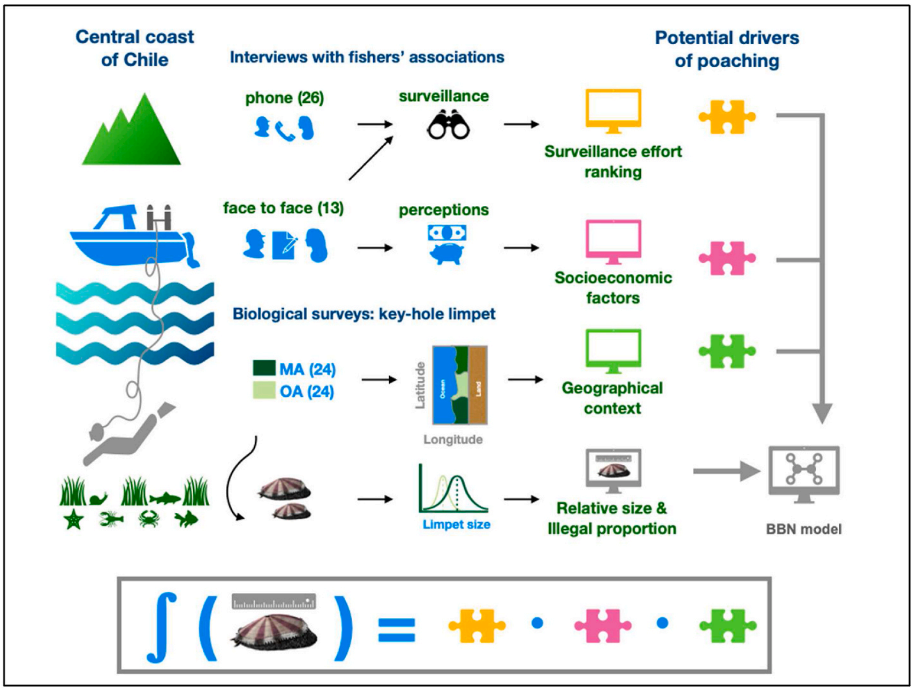

Fig. 1. Diagram illustrating data collection to assess the drivers of poaching within the TURF system in central Chile. Data were obtained from (a) interviews with fish fishermen (26 telephonic and 13 face-to-face) to assess surveillance efforts, perceptions on surveillance effectiveness and poaching intensity, and socio-economic characteristics of the associated fishermen and, (b) biological surveys to obtain size-structure data of the catch of key-hole limpet to assess relative size and illegal proportion in the Management Areas (MA) and adjacent Open Access (OA) areas as a proxy for poaching intensity in the MA. The interaction between ecological and socio-economic data is explored in a Bayesian Belief Network (BBN) model to identify relevant drivers of poaching in the study area.

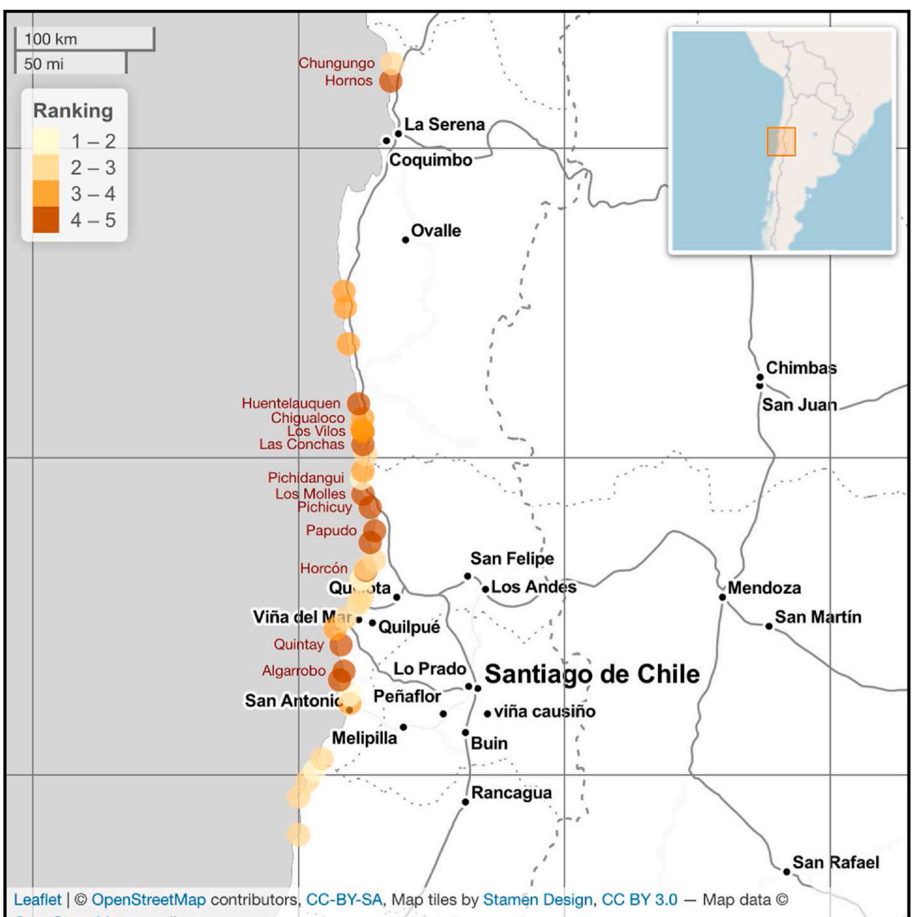

Fig. 2. Map of the study area including the names of the coves included in the study (local names in red), where operate the 13 fishers 'associations where biological surveys were conducted. The ranking corresponds to the surveillance effort (5 being the highest effort), which was performed with a wider set of 39 fishers' associations (dots included in the map; see Section 2.2 for methodological details).

study area. It was based on a dichotomy tree that represented all the options that a fishers' association exhibited in the study area at the time of the study (Fig. 3). Due to the limited information provided by the fishers, variability in surveillance effort over time could not be encompassed by the ranking; however, the extended interviews with the fishers' leaders in the subset of 13 associations suggest that the surveillance scheme had prevailed in the MAs for at least several years. As a result, an area could have a very high level of surveillance effort (rank 5), when the fisher association hires a ranger to perform 24 h Surveillance; on the other end, the lower rank (rank 1) is assigned when there is no surveillance in the area. Differences between high (rank 4) and very high effort (rank 5), with 24 h surveillance performed by either the members of the fishers' association (4) or by a hired person (5), are justified by an expected higher compromise by the paid person (Davis et al., 2017). In the case study, other combinations, e.g., hired ranger patrolling with fishers or only patrolling during the daytime, were not observed; however, this simple ranking could be adjusted with new scenarios emerging.

Fishers' perception of surveillance effectiveness among the MAs controlled by each fishers' association allowed the inclusion of a correction factor: the "effectiveness" of surveillance. The surveillance effort rank assigned to a MA was reduced by one score if the fishers' association dedicated less time to surveying a particular MA (relative to other MAs controlled by the same association), and by an additional score if the fishers perceived that surveillance in their MAs was not effective. As a result, 20 out of the 24 MAs included in the data analysis had an "effective surveillance" lower than the formal "surveillance effort". Despite this correction factor being inherently subjective, relying solely on fishers' perception, it allowed incorporating potential variability in the fishers' care of their MA and the effectiveness of their surveillance efforts. This information was extracted from the questionnaires extended to fishers' association members (approximate 10 fishers per association) and allowed to consider the fishers' opinion on the effectiveness of the surveillance protocol described by the fishers' leader. In the BBN model, both variables, "surveillance effort" and "effective surveillance" were included to explore the predictive power of the two factors.

During the interviews, fishers also provided information on the number of poaching events that had been reported in their MAs over the past year: from low, with less than 20 events reported in the last year, to very high, with more than 100 events reported in the year. This information was contrasted with the surveillance effort rank in the area to test for a correlation between the two variables (where correlation could go in either direction, i.e., continuous surveillance discourages poachers or it is more effective in detecting poaching events); a lack of direct correlation is expected to be influenced by both bias in fishers' perception and also potentially by other factors driving poaching intensity. The supplementary material includes all the variables per MA (Table S1).

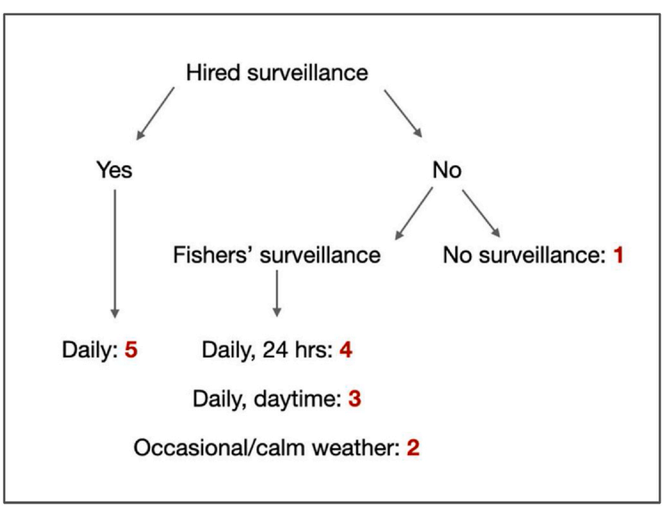

Fig. 3. Ranking of surveillance effort based on the fishers' organization: payment of external personnel for the continuous surveillance (hired surveillance), the organization of the fishers to conduct the surveillance of their areas or no surveillance of the areas. The duration of the surveillance could vary from every day, 24 h, to occasional. The highest surveillance effort is 5 (very high), and the lowest is 1 (very low).

2.3. *Attributes of management areas*

Expert scientists reviewed potential factors that could increase the probability of poaching, both based on previous studies (e.g., Davis et al., 2017; Fernández et al., 2020; Gelcich et al., 2013) and on the interviews with fishers. The additional context variables that were considered of relevance were: 1, availability of OA area per registered fisher concerning the total area assigned to MA (index IAOA, index of Open Access Area Availability; Fernández et al., 2020). 2, Surface of the MA, as larger surfaces are expected to be more difficult to guard (Wilen et al., 2012). 3, The distance between the MAs and the official surveillance base, the more distant, the less effective is enforcement as poachers must be caught in the act to be sanctioned; during the interviews, fishers claimed that lack of punishment prompted non-compliance in the MA. 4, Access to the MA from the land through main paved routes from the nearby location, also considering difficulty of sea access from land (e.g., a cliff implies difficult to access), as difficult access might function as natural protection against poachers. 5, Wave exposure of the fishing grounds; higher exposure acts as natural protection, as MAs with high wave exposure are less likely to be accessed by poachers (a high exposed area on the central coast of Chile is an area facing south, while a protected area is facing north). Points 4 and 5 were suggested by fishers' leaders as factors usually protecting their MA against poaching. This natural protection can further reduce the transaction costs of the surveillance (Wilen et al., 2012). 6, The existence of alternative economic activities in the cove (e.g., tourism, construction, recreation), according to fishers' leaders, results in less poaching pressure, as fishers find alternative sources of income.

The IAOA index is used as a context variable on the basis that the low availability of OA per fisher due to a high spatial density of MAs is related to an increase in poaching in OAs due to an effort displacement (Fernández et al., 2020). Such an increase in poaching in OAs may yield, under certain circumstances (like low enforcement, low compliance, and/or lack of economic alternatives), a rebound effect of increased poaching in MAs. For each fishers' association, the IAOA is a proxy of the proportion of OAs that corresponds to each officially registered diver who fishes around that cove. It considers fishing effort density and proportion of OA areas concerning MA, in the accessible fishing grounds of the cove. The lower the estimate of IAOA, the lower the proportion of OAs concerning MAs (fewer areas open to fisheries available near a cove) and, therefore, higher poaching pressure over OAs and MAs as a rebound effect. Details of the methodological approach are provided by (Fernández et al., 2020).

The geographical variables distance to surveillance, wave exposure, and access from the land were estimated using Google Earth software (Gorelick et al., 2017). The presence of alternative activities was depicted in the fishers' interviews. The supplementary material includes all the variables per MA (Table S1).

2.4. *Biological surveys*

Benthic resource catch data were collected between October 2017 and July 2018 in 24 MAs controlled by the 13 fishers' associations to assess the size structure of keyhole limpet catches (i.e., harvested fraction of key-hole limpet population), as described in (Fernández et al., 2020). Paired MA and OA sites were sampled in each area by the local fishers with an observer onboard. In each area, at least two sites were sampled since a minimum of one MA and one OA were required. The sampling procedure was identical for the two management regimes (MA and OA). Samples were directly obtained from the catch of a benthic fisher and measured onboard the fishing boat or at the landing beach or small-scale port. The sample size is different among sites because all individuals in the fishing bags were measured, until reaching the minimum sample size of 200 individuals, following the protocol established by (Andreu-Cazenave et al., 2017). The size of keyhole limpets was measured as the total length of the shell to the nearest mm. Non-parametric Wilcoxon signed-rank tests were used to compare medians of the size distributions of the catch between MA and OA within each fishers' association (W will be used to indicate the Wilcoxon test statistic).

2.5. Bayesian Belief Network development

To identify the key drivers of poaching on limpets in the MAs, we built a Bayesian Belief Network (BBN) model integrating data from fisheries stakeholders and scientists (see Supplementary material for more details on this method). In our study, the conceptual model (directed acyclic graph: DAG) was developed iteratively based on the system understanding by the research team. The first DAG was created by 12 initial nodes (Fig. 1), which include 10 drivers: 1, MA surface; 2, number of MA per fishers' association; 3, distance to surveillance authority; 4, access to MA from the land; 5, wave exposure of the MA; 6, availability of OA (IAOA); 7, alternative activities in the cove; 8, surveillance effort; 9, surveillance effectiveness; 10, perceived poaching level; and 2 response variables: 1, the proportion of the catch corresponding to keyhole limpet below the minimum landing size (i.e., illegal proportion), as a high proportion is an indication of higher predisposition for poaching and, 2, the difference in median size between the MA and adjacent OA (ê, as the normalized median MA/median OA). Values close to 1 indicate a good state of the resource with the highest median sizes in MA compared to the paired OA area. All relationships between the 12 initial nodes were considered and quantified.

Data scoping and data analysis furthered the development of the model to select the final set of parsimonious nodes to populate the conditional probability tables (CPTs) and the conditional probability distributions (CPDs), which determine the strength of the links in the DAG. Then, Bayesian structure learning via score maximization was performed using the tabu search (Scutari et al., 2019) in the space of the DAG. The aim was to obtain an alternative number of possible DAGs in which all possible combinations of the input data were compared. As a general-purpose optimization technique and greedy search strategy, the tabu search employs local moves designed to affect only a few local distributions, therefore, the new DAG candidate can be scored without recomputing the full marginal likelihood (Scutari et al., 2019). The team of experts inspected the post-parameterization model, and the structure of the DAG was accepted as plausible according to the nature and robustness of the available data. All analyses were carried out using R language and environment for statistical computing version 3.6.2, released 2019-12-12 (R Core Team, 2021; http://www.r-project.org/) and the packages *bnlearn* v.4.6.1 (Scutari, 2010); *tidyverse* (Wickham et al., 2019); *ggplot2* (Wickham, 2016) and *leaflet* (Cheng et al., 2021).

2.6. Conditional probability queries or "what would happen if ..." scenarios

A query returns the probability of a specific event given some evidence. For example, a query could be of the type "If A occurs and B does not occur and C is greater than X and less than Y, what is the probability that D is greater than Z?". Based on this approach, a set of scenarios was explored to assess the influence of the external drivers on the state of the benthic resource. The scenarios considered that the management target is to improve the state of keyhole limpet stock and to reduce the proportion of limpets below minimum landing size. In our study, the variables that are susceptible to being managed are those linked to the fishers' association and management bodies. The conditional queries first consider the probabilities of the response variable under conditional drivers based on 2000 permutations. The conditional drivers were selected from the BBN outcome and included surveillance effort, distance to surveillance, availability of OA area, and alternative economic activities in the cove.

3. Results

3.1. Size structure of keyhole limpet in management areas

Significant differences in median keyhole limpet sizes were found in 22 out of 24 OA-MA paired comparisons (11 out of 13 fishers' associations). Although in 19 out of 22 paired comparisons the median size was larger in MAs than in OAs, as expected for a well-enforced MA, in three cases the reverse pattern was observed, suggesting non-compliance with the management regulations. Furthermore, we found two cases with poaching levels in MAs equal to or higher than OAs: MAs showing a proportion of undersize individuals in the catch similar to the OA (13 and 11%, respectively); and MAs showing significantly higher proportions of undersize individuals (71%) concerning the 41% recorded in the OA (plots for median sizes in OA and MA and statistical test are included in supplementary material; Fig. S1 and Table S2).

3.2. Enforcement level and effectiveness

Of the 39 fishers' associations where surveillance effort was assessed (Figs. 2), 13% had no surveillance, 33% only occasional surveillance, and 23% a daily daytime (8-h) surveillance. The rest of the MAs had daily surveillance (24 h), which is performed either by fishers (8%) or hired personnel (23%). The subset of 13 associations included in the study (where biological assessments were conducted) exhibited variable surveillance effort, from low to very high, with no example of no surveillance (very low); therefore, the variable included in the BBN has 4 levels. By considering the correction factor (effectiveness) on the surveillance effort endured by the fishers' association, in 20 MAs the effort rank was reduced by 1 or 2 scores (supplementary material; Table S2).

There was no linear relationship between the level of surveillance effort and the number of poaching events per year reported by the fishers' leaders during the interviews. In most sites, high surveillance effort is linked to moderate-low perceived poaching; and low effort is related to high or very high perceived poaching. However, in some cases, high surveillance effort is related to very high perceived poaching (15% of cases), or low surveillance effort is related to low perceived poaching (8% of cases) (Fig. 4).

Similarly, there is no consistent relationship between the state of the resource, measured either as the illegal proportion of keyhole limpets or as the relative size of individuals in the catch in MAs, and the surveillance effort level and surveillance effectiveness in each MA (Fig. 5). The absence of a direct link suggests other variables are playing a role in the state of the benthic resource (as a proxy for poaching in the MA).

3.3. Bayesian-belief network

The size structure reveals the effects of poaching on limpets since a minimum legal-size regulation applies to this resource. The level of poaching was also assessed relying on fishers' perceptions (supplementary material; Table S1); however, the perceived poaching exhibited an unexpected link with the condition of the resource, as lower reported poaching events were linked with lower average sizes in MA and higher proportions of illegal size, suggesting a potential lack of temporal correlation between the poaching events currently identified by fishermen and the state of the benthic resource that is a result of cumulative poaching over time. Alternatively, the poaching events declared by

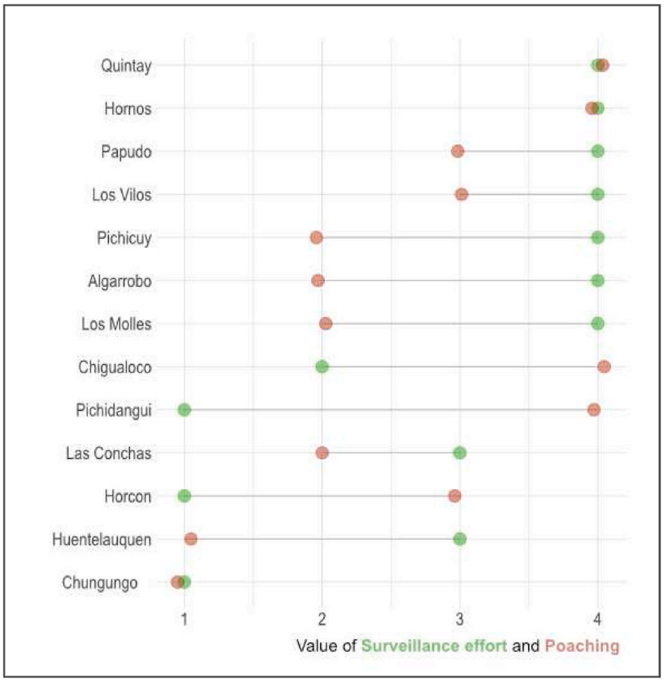

Fig. 4. Cleveland dot plot showing the overlap between the ranking of surveillance efforts endured by the fishers' association (green dots, 1, low, to 4, high) and the level of poaching perceived by the fishers (red dots, 1, low, to 4, high).

fishers might correspond to extractions beyond the quota (which is set in the management plan of each MA). Therefore, the variable poaching events were excluded from the final BBN to minimize bias in the interaction response direction between variables. Access and number of MAs were also excluded from the optimal network, as these variables had no link with the biological variables in our case study.

The most parsimonious BBN included most links that were predicted by expert knowledge in the draft DAG. However, some links were rather unexpected (Fig. 6). For example, the existence of alternative activities plays a major role in the network, influencing both the magnitude of the effects of availability of OA area (with less fishing pressure rebounding on the MAs) and surveillance effort, as alternative activities might reduce the time dedicated to survey the MAs. On the other hand, the availability of OA areas is linked to the illegal proportion of limpet through the distance to the surveillance authority and, therefore, poaching reports are not effective. Surveillance effort has effects on the relative size of the MA (ê) through the effectiveness of surveillance; therefore, it highlights the relevance of uneven surveillance efforts across several MAs controlled by a single association. Some of the links were probably casual, considering the limited number of fishers' associations and MAs included in the study (Fig. 6): availability of OAs and distance to surveillance are linked to the surface of the MA and to wave exposure. Whereas the availability of OAs is controlled by both the number and extension of the MA available per fisher, probably the

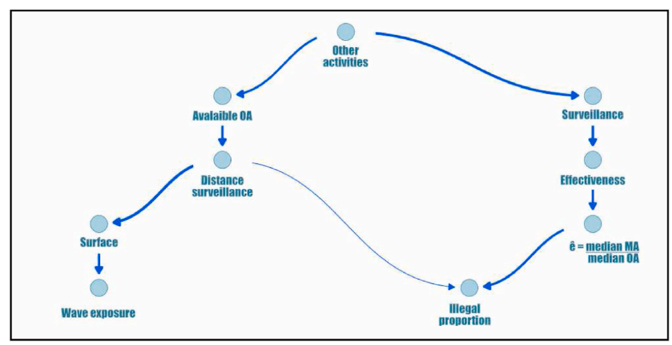

Fig. 6. Bayesian-belief Network obtained for the case study. The thickness of the arrow represents the strength of the link.

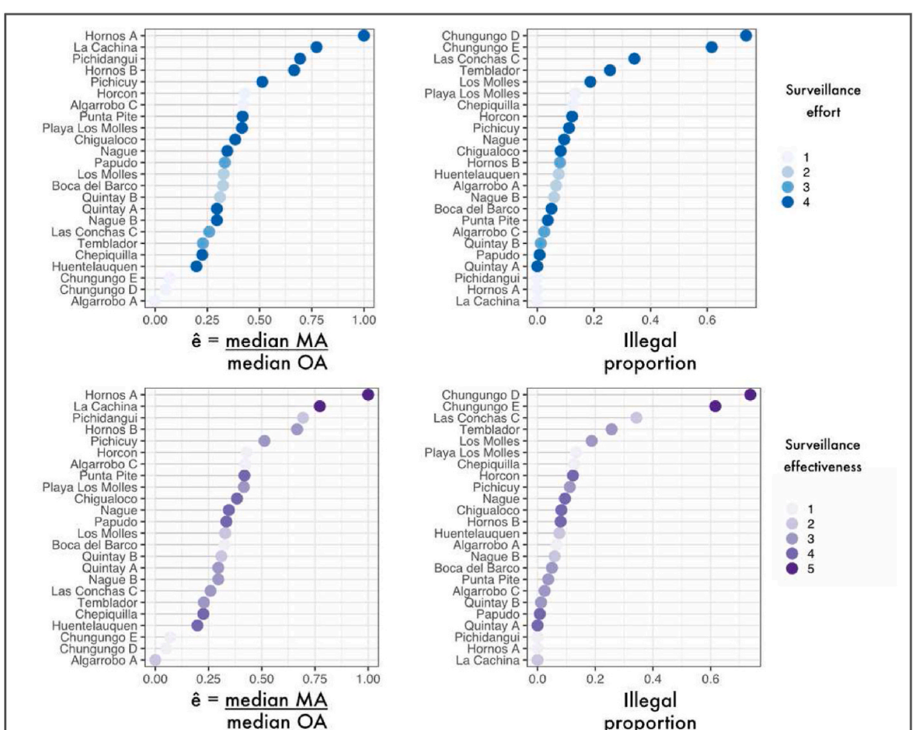

Fig. 5. Relationship between the relative median size of individual limpets fished in the MA (ê), left panels, and the proportion of illegal limpets in the catch, right panels, and the surveillance effort level (upper panels) and surveillance effectiveness (bottom panels) in the case studies (24 MAs, indicated by their local names).

sections of the coast most exposed to waves, and/or less accessible from the coves, tend to concentrate less MAs.

3.4. Scenarios to achieve a good state of the fishery resource

To observe a low proportion of illegal limpets in the catch, the ideal scenario includes a high availability of OA areas per fisher and a short distance to a surveillance authority base (scenario 2 in Table 1). The combination of any of these variables with alternative economic activities for the fishers and high surveillance efforts increases the probability of a lower proportion of limpets of illegal size in the catch (scenarios 1, 3, and 6 in Table 1). In particular, the combination of the high availability of OA areas with any of the other three variables yielded a high probability (>0.88) of an illegal proportion below 30% of the catch. On the other hand, the external drivers had a weak effect on the relative median size of limpets fished in MAs, with values closer to 1 indicating larger median sizes in the MA compared to neighboring OA. Either high surveillance effort or high surveillance effectiveness combined with the presence of other activities did not yield probabilities higher than 39% (Table 1).

4. Discussion

Bayesian-belief networks are useful for SSF research due to flexibility in incorporating data of different nature, where both fishers' and experts' knowledge plays a key role (Fig. 1), and by exploring scenarios to identify key drivers of poaching as a focus for management. The BBN exercise on a TURF system in central Chile allowed identifying the role of multiple external socio-economic and geographical context drivers in poaching an important fishery resource. The BBN applied to the SSF on the central coast of Chile suggested an absence of a direct link between the level of MA surveillance effort and the state of the benthic resource, with other socio-economic (e.g., alternative economic activities) and context variables (e.g., availability of OA in relation with MA or distance to surveillance authorities) playing important roles. The fishers' knowledge and scientific expertise are essential in a data-poor situation (as is the case of the illegal catch of resources) and BBN is an integrative method able to incorporate different data structures. However, the models are as good as the data input, and scientific recommendations for decision-makers to eradicate non-compliance actions should be underpinned by good data that provides a solid basis (Keane et al., 2008). An inherent problem associated with data-poor case studies that rely on end-user input is the bias of the individual's perceptions. In these cases, models should be revisited as additional knowledge is acquired, and outputs should be contrasted with similar publications. On the topic of our study, Thiault et al. (2020), also evidenced the importance of context factors, like fishing capacity or accessibility, as predictors of poaching risk. In our case study, BBN model outputs can be improved in the future by gathering surveillance effort data with new approaches such as the use of technology for the MA surveillance (Appleby et al., 2021). In addition, poaching reports should be systematically registered in public databases.

The interviews with fishers showed high variability in surveillance protocols and that a concern frequently shared by the fishers' leaders was the high cost of allocating human resources to survey the area, as these costs must be covered by the fishers' association. Often, one association oversees more than one MA, which prompts the allocation of the limited resources only to one area, either the most accessible or the most productive one. This variability was considered in the conception of the variable "effective surveillance", which takes account of different efforts invested in surveillance of the MAs under the same fishers' association; the model revealed the importance of "effective surveillance" in the state of the resource within the MAs. These observations are aligned with previous results in the same study area where fishers reported that their organizations often decide not to monitor the MAs that are furthest away (less accessible) from the cove (Davis et al., 2017).

On the other hand, the relationship between the surveillance effort level and the number of poaching events per year reported by the fishers was not consistent, and an opposite relationship was observed in several fishers' associations. The observed lack of consistency in these results might be showing a bias due to the negative fishers' perception of the effectiveness of the poaching sanctioning system and the importance of poaching for the viability of their MA (Davis et al., 2017). Lab-in-field experiments focusing on the effect of co-enforcement on limiting the access to common-pool resources in the study area showed that the existence of external poaching sanctions (like those imposed by government authority) improved the willingness of resource users to invest in surveillance, ending up with a reduction in poaching (Chávez et al., 2018). Compliance-monitoring agencies in Chile concentrate on access control with less emphasis on compliance with quotas, bans, or minimum legal size. According to the national fisheries law, the National Fisheries Service SERNAPESCA must publicly deliver an annual report of enforcement actions, which, in its last edition reveals low enforcement in the central coast of Chile, when compared with other regions of the country. Despite being one of the most populated coastal areas in the country and home to the national fisheries enforcement agency, the central coast of Chile only concentrates 8.8% of the total field enforcement actions in the country (SERNAPESCA, 2019). This might be in part related to the distance between the coves and the enforcement agencies base in an area with a high density of coves and MAs that might imply a focus on the most accessible areas. The implementation of local enforcement tools must be necessarily considered to address this difficulty.

An added administrative issue is the closure of the delivery of artisanal fishing permits for more than 10 years, which has left young generations of fishers with no choice but to fish illegally (Nahuelhual et al., 2018). Fishery leaders' perceptions gathered during this study support this statement, as leaders often pointed out that there is an increasingly large proportion of young, un-associated, fishers that are discouraged by the current co-management system that does not fulfill the cost-benefit balance. The recurrent idea among different stakeholders (i.e., fishers, government, and intermediaries of the resource value chain) is that poaching is a consequence of the lack of opportunities and economic needs (AU-IBAR, 2016; Nahuelhual et al., 2018), reflected by the variable "alternative economic activities" in our model. Thus, managers must ensure fishers do not have "a reason to poach", by putting efforts into the socio-economic well-being of the cove. But,

Table 1
Queries were performed over the BBN (Fig. 6). Probabilities of the response variable under conditional drivers based on 2000 permutations.

Scenarios	Variable 1	Variable 2	Response	Probability
1	Available OA = very high or high	Other activities = TRUE	Illegal proportion ≤ 0.3	0.881
2	Available OA = very high or high	Distance to surveillance = close	Illegal proportion ≤ 0.3	0.935
3	Available OA = very high or high	Surveillance effort = very high or high	Illegal proportion ≤ 0.3	0.961
4	Surveillance effort = very high or high	Other activities = TRUE	Relative size at MA ≥ 0.4	0.378
5	Surveillance effectiveness = moderate to very high	Other activities = TRUE	Relative size at MA ≥ 0.6	0.394
6	Other activities = TRUE	Distance to surveillance = close	Illegal proportion ≤ 0.3	0.991
7	Surveillance effectiveness = very high or high	Distance to surveillance = close	Illegal proportion ≤ 0.3	0.987

bearing in mind the latter as a necessary long-term task, immediate actions on preventing poaching must be considered. Currently, fishers must cover the (increasingly high) cost of surveillance of their TURFs but rely on the administration to punish poachers (Gelcich et al., 2017). This suggests a vicious circle around the problem of poaching in TURFs: economic needs prompt poaching and deter fishers to invest in surveillance, in response the government administration strengthens formal sanctions but does not improve enforcement mechanisms, letting the SSF stuck in an illegality trap (Nahuelhual et al., 2020).

The sustainability of SSF is a complex socio-economic and ecological problem (Basurto et al., 2013), with many local variables playing a key role and no bullet-proof solution. The FAO guidelines for sustainable SSF highlight the need to adopt a more integrative approach considering the sustainability of the resources and the human development; in this context, property rights might lead to the exclusion of vulnerable fishers (Jentoft, 2014) that, as in our case, could lead to an increase of illegal activities. The illegal catch in Chilean SSF has been termed a wicked problem by (Nahuelhual et al., 2018), as it is characterized by its complexity, uncertainty, and interdependence of factors. Therefore, a multi-dimensional assessment, such as the one presented here, is necessary to address the problem of poaching on benthic resources in Chile. A Bayesian-belief network is a strong tool to address this multi-dimensional problem, as it nourishes from expert knowledge and is flexible to be used for scenario analysis by local actors. The scenario analysis explores variables that are susceptible to be managed, including distance to surveillance authorities and a spatial planning approach to fisheries restrictions. It is legitimate to state that, according to our model, lowering illegality in benthic artisanal fisheries in central Chile depends mostly on two government administrative matters: improving authority surveillance mechanisms and rules (to increase the effectiveness of anti-poaching controls and reduce the negative consequences of higher distances to surveillance authority bases); and specific actions in marine spatial planning of the TURF system (to increase the availability of OAs around each MAs).

In the current TURF system in Chile, fishers select a MA, and it is assigned under request, but there is no advice from decision-makers and scientists on where to allocate the area (only on quotas). There is an inherent problem with the planification of the system that might lead, for example, to high fishing pressure in adjacent open access areas (Beckensteiner et al., 2020; Fernández et al., 2020). Ospina-Alvarez et al. (2020) showed the benefits of a planned network of MAs on the central coast of Chile that would positively affect fisheries and biodiversity conservation. However, this spatial modeling exercise also revealed the importance of enforcement for the effective functioning of the network of the restricted area and the need to consider environmental and human dimensions. High fishing pressure on the OA areas, with overexploited benthic resources (Andreu-Cazenave et al., 2017), has a negative feedback on the MAs (de Juan et al., 2015). A systematic and science-based spatial planning of the fishery restricted areas would avoid high concentrations of MAs in sections of the coast, those more densely populated, while identifying the most productive areas for the placement of fishery restricted areas (Ospina-Alvarez et al., 2020). This spatial approach to the problem would alleviate fishing pressure on the restricted MAs; however, additional actions, like increasing surveillance efforts, are necessary for the effective performance of a network of well-enforced MAs.

While TURFs systems aim to incentive fishers' care of their fishing grounds, these need to be well planned and supported financially and logistically by the administration. Property rights schemes could benefit from a re-formulation that considers the social rights and benefits (beyond the individual rights, as highlighted in the FAO guidelines, Jentoft, 2014) and fishers' traditional ecological knowledge (Ruano-Chamorro et al., 2017), so the conservation of the ecosystem is a priority over the individual interests to exploit the resources (Moon et al., 2020). However, in the case study, the top-down component of the co-management system seems to fail as there is poor planning and financing. The decision-making power granted to fishers in the current co-management process is very much limited to a MA monitoring and surveillance, with insufficient resources and support to carry out this task. The balance of the fishers-administration role must be planned to ensure a fully democratized system that can cope with illegal fishing and overexploitation. Addressing these complex problems inherent to the functioning of SSF are central, as SSF can play a key role in the sustainable development of global fisheries.

5. Conclusions

The sustainability of SSF is a complex socio-economic and ecological problem, with many local variables playing a key role and no bullet-proof solution. Therefore, a multi-dimensional assessment is necessary to address the problem of poaching on benthic resources in SSF. A Bayesian-belief network is a strong tool to address multi-dimensional problems, as it can be based on expert knowledge while empirical data is gathered to increase the reliability of the outputs. In our study, the BBN showed that the existence of alternative economic activities is alleviating fishing pressure around the coves, and, in the case of areas with low availability of OAs, this translates into lower poaching in the MAs. From our results, we can suggest that poaching in the MAs arises from a complex network of drivers, from methodological to logistic problems, which appear to be linked to the monitoring of compliance, lack of support of government agencies in the co-management process, socio-economic context of fishers, and unsuitable spatial planning of the TURFs. A local perspective is needed to address poaching and illegal practices while strengthening the spatial planning of coastal fisheries. This change in perspective should be aided by a suitable diagnosis of local socio-economic contexts of fishers that contribute to tailoring successful fisheries management plans.

Author contribution

SdJ: conceptualization, investigation, methods, formal analysis, writing-original draft. DS: conceptualization, investigation, formal analysis, writing-original draft. AO-A: methods, software, formal analysis, writing-original draft. AA: data-collection and data treatment. MF: conceptualization, writing review, editing, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was partly funded by a Fondecyt Project 1171603 grant to MDS and MF and ANID-Millennium Science Initiative Program (Project RC 1300004 and NCN19_05) from Ministerio de Economía, Fomento y Turismo de Chile. The authors want to thank all participants of the surveys for their essential contribution to this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2022.106290.

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