Disentangling the socio-ecological drivers behind illegal fishing in a small-scale fishery managed by a TURF system

Silvia de Juan1*, Maria Dulce Subida2, Andres Ospina-Alvarez3, Ainara Aguilar2, Miriam Fernandez2

1 Spanish Scientific Research Council, Institute of Marine Sciences (ICM-CSIC), Passeig Maritim de la Barceloneta 37-49, Barcelona, Spain.
2 Estacion Costera de Investigaciones Marinas, Pontificia Universidad Catoolica de Chile, Alameda 340, C.P. 6513677, Casilla 193, Correo 22, Santiago, Chile.
3 Spanish Scientific Research Council, Mediterranean Institute for Advanced Studies (IMEDEA-CSIC/UB), C/ Miquel Marques 21, CP 07190 Esporles, Balearic Islands, Spain.

*corresponding author: sdejuan@icm.csic.es

Highlights:
- This study describes the development of a Bayesian network adapted to complex SSF.
- A Bayesian network was designed to identify drivers of illegal fishing.
- The network was based on the link between socio-economic drivers and resource state.
- Scenario analysis explored effects of variables that are susceptible to be managed.

Abstract: A substantial increase in illegal extraction of the benthic resources in central Chile is likely driven by an interplay of numerous socio-economic local factors that threatens the success of the fisheries’ management areas (MA) system. To assess this problem, the exploitation state of a commercially important benthic resource (i.e., keyhole limpet) in the MAs was related with socio-economic drivers of the small-scale fisheries. The potential drivers of illegal extraction included rebound effect of fishing effort displacement by MAs, level of enforcement, distance to surveillance authorities, wave exposure and land-based access to the MA, and alternative economic activities in the fishing village. The exploitation state of limpets was assessed by the proportion of the catch that is below the minimum legal size, with high proportions indicating a poor state, and by the relative median size of limpets fished within the MAs in comparison with neighbouring OA areas, with larger relative sizes in the MA indicating a good state. A Bayesian-Belief Network approach was adopted to assess the effects of potential drivers of illegal fishing on the status of the benthic resource in the MAs. Results evidenced the absence of a direct link between the level of enforcement and the status of the resource, with other socio-economic (e.g.,

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alternative economic activities in the village) and context variables (e.g., fishing effort or distance to surveillance authorities) playing important roles. Scenario analysis explored variables that are susceptible to be managed, evidencing that BBN is a powerful approach to explore the role of multiple external drivers, and their impact on marine resources, in complex small-scale fisheries.

Keywords: IUU, poaching, enforcement, fisheries management areas, artisanal fisheries, benthic resources.

INTRODUCTION

Small-scale, artisanal, fisheries (SSF) are the pillar of wellbeing for many coastal communities, as it is estimated that they contribute to half of the global catch [1], while employing 90% of the world’s fisheries [2]. However, these fisheries are largely unassessed [3] and often data poor [4]. SSF are becoming a priority for FAO, and efforts are on improving data gathering to guide monitoring and management protocols. Innovative approaches to maximize the available information from SSF are critical, e.g., the incorporation of Traditional Ecological Knowledge [5] or the use of fishers’ perception surveys [6]. While data gathering for the assessment of SSF is improving, there are several caveats driving fish stocks to overexploitation that need urgent assessment. These factors may be classified into two interacting types: those related with failure of management and conservation rules [7] and those related with the socio-economic context as the loss of the culture of care and responsibility for marine resources prompted by strongly market oriented fishery policies [8].

Scientific evidence suggests that non-compliance with fishing regulations is a widespread phenomenon in global fisheries [3,9,10], and emerges among the most important factors contributing to the overexploitation of marine resources [11,12]. However, information on illegal fishing practices in SSF is still scarce. SSF are potentially more prone to violations to catch limits or minimum sizes due to the nature of the operation [13]. Their usual spatially scattered nature impose serious challenges to monitoring, surveillance and enforcement to detect any non-compliance activities, facilitating illegal fishing [3,9,10]. 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 local context characteristics [8,14].

The absence of incentives to comply with fisheries normative has been pointed out as a significant problem for SSF, particularly in scenarios where neoliberal fishing policies fostered severe extractivism in detriment of traditional and more sustainable fisheries ([8] and references therein). The common pool resources dilemma [15] has been in part solved using Territorial User Right in Fisheries (TURF). While these co-management systems aim to encourage trust, rule compliance and fishers’ involvement in enforcement [16], they are also likely to allow fishers to sell fish at higher prices, reduce resource waste and increase fishers’ incomes ([17] and references therein). Chile was pioneer on the implementation of a TURF system to the SSF at a national scale in 2003, known as Management
and Exploitation Areas for Benthic Resources (AMERB, hereafter MA) [18]. The TURF system in Chile has contributed in increasing abundance of commercial species [19] and has shown positive effects on biodiversity and trophic web structure [20,21]. However, the fishing pressure outside these management areas [22] and a negative perception of fishers on the TURF system in aspects related with economical revenues and government support [23,24] urge an upgrade in this management paradigm. Recent studies suggest that illegal extraction in the TURFs can be as high as 68% of the annual income obtained from this system in some regions of Chile [25], and recent biological surveys provided evidences of poaching in several management areas [26]. Research on fisheries working on a TURF basis, including some studies in central Chile, identified a series of incentives promoting illegal fishing. 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 that there is a well-established black market in demand of fisheries products [27,28]. These findings trigger the need of an integrative approach to identify which are the main drivers of illegal extraction in Chile TURF system.

Usually, TURFs’ efficiency is assessed through the ecological state of biological components or through the socio-economic benefits of the management [17]; the interaction between these two aspects has seldom been addressed. Here, we provide a quantitative assessment of the effects of socio-ecological drivers on the illegal fishing of the traditional and culturally important keyhole limpet fishery in the central coast of Chile. A Bayesian Belief Network (BBN) model was developed linking key biological and socio-economic components of the SSF. BBNs have been applied to consider management systems governing artisanal fisheries where the effects of qualitative and quantitative factors are of concern [29–33], or when considering social, environmental and economic factors leading to multi-objective management of coastal resources [34,35]. In the present work, we used a BBN model that integrates data from fisheries stakeholders and scientists to identify the key drivers that influence the proportion of illegal fishing in the TURF system, as well as the relationship between factors that have generally been regarded as determining the state of the resource (e.g., level of enforcement) and contextual factors (e.g., rebound effect of fishing effort displacement or distance to surveillance authorities). The BBN approach can help building a socio-ecological model of fisheries in an environment that is partly data-poor. Moreover, the graphical outputs also facilitate communicating the results to stakeholders. The present paper addresses relevant issues driving illegal extraction in the TURF system, including the identification of a) factors that determine the level of effective enforcement needed to reduce illegal fishing, and b) variables that can assist rapid assessment of effective enforcement and success of the SSF system.

METHODS

Small-scale fisheries in central Chile

Small-scale benthic fisheries in Chile are mostly organized around fishing coves
locally known as *caletas*, which serve as operational bases for the local fleet and fisher organizations. The benthic fisheries operate around 17 km away from the coves [22] to a depth of approximately 20 m (official diving depth), and the harvesting fishing grounds show two contrasting management regimes: (i) exclusive harvest rights assigned to fishers’ organizations (TURFs), locally known as management areas (hereafter MAs) or (ii) historical fishing grounds without spatial entry restrictions, hereafter referred as open access areas (OAs). The most common fishery resources that can be extracted in the MAs are the Chilean abalone or loco (*C. conholepas*), keyhole limpets (a set of species of the genus *Fissurella*), the red sea urchin (*Loxechinus albus*) and kelp (mainly *Lessonia* spp.) that are exclusively exploited by fishermen pertaining to the fisheries association. Outside the MAs, both fishers belonging to the association and officially registered un-associated fishers can extract fish and benthic resources (except loco). While some species-specific regulations operate for both management regimes (e.g. temporal reproductive bans or minimum legal size) others apply exclusively to MAs (annual quotas) or OA (total ban of locos). However, due to differences in the administration of the MAs, not all these areas exhibit a similar enforcement level [36]. A well-enforced MA implies that the maximum quotas are respected, and the area is surveyed to avoid illegal fishing. The control of catches and enforcement of regulations is usually performed by the National Fisheries Service, with about 25,000 enforcement actions during 2018 focusing on MLS regulations in both artisanal and industrial fleet [24]. However, fishers’ associations must cover surveillance costs, although it is not mandatory. In the present work, the term poaching refers to the illegal extraction of the resource, either due to noncompliance with the annual quotas by the associated fishermen, or to illegally extracting the resource from MAs by un-associated fishermen.

For the present study, data was gathered from 13 fishers’ associations that manage 24 areas in the central coast of Chile (Fig. 1). Each fishers’ association presented between 1 and 3 operational MAs at the time of the study. Different sources of data were gathered for the study. In 2016-2020, face-to-face interviews and telephonic questionnaires were carried out to the leaders of the fishers’ associations to obtain information and perceptions on MA enforcement, poaching intensity and the organization of the fishers association. In 2017-2018, biological surveys were conducted in MAs and neighbouring OAs to assess keyhole limpet size structure.

*Interviews with fishers*

Interviews with the leaders of the fishers’ associations were carried out from 2016 to 2020 in 40 associations along the central coast of Chile. Two sets of interviews were carried out: (a) face-to-face extended interviews focused on 16 coves that covered ca. 250 km of the coast in central Chile; and (b) remote (telephonic) interviews focused on 24 coves covering the entire study area (ca. 700 km). The two approaches used the same questionnaire that aimed to explore the enforcement protocol, or lack of it, the evenness in enforcement across MAs and the fishers’ perception on the enforcement effectiveness and poaching records.
Figure 1: Map of the study area including the names of the 13 coves included in the study (local names in red). Note that each association might have between 1 and 2 management areas, resulting in 24 areas included in the analysis. The ranking corresponds to the enforcement level (5 being the highest enforcement). The ranking was performed with a wider set of 39 fishers’ associations (included in the map).
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per year. The full questionnaire is provided in supplementary material.

The information gathered during these interviews allowed defining the level of enforcement endured by each fishers’ association. The enforcement ranking was based on a dichotomy tree that represented all the options that a fishers’ association could exhibit. As a result, an area could have a very high level of enforcement (rank 5), when the fisher association hires an external person to perform 24h surveillance; on the other end, a very low enforcement (rank 1) occurs when there is no surveillance in the area (Fig. 2). Differences between high and very high enforcement, with 24 hours surveillance performed by either the members of the fishermen association or by a payed person respectively, is justified by an expected higher compromise by the paid person [23]. Fishers perception on enforcement effectiveness (i.e., fishermen perceived the enforcement in their MAs was either effective or non-effective) and surveillance differences among the MAs controlled by each fishers’ association (i.e., an association survey all MA equally vs. surveillance efforts focus on a single MA) allowed the inclusion of an additional variable that considered the “effectiveness” of enforcement. To compute this variable, the enforcement level of a MA (ranked in 1 to 5) was reduced by one score if the fishers’ association dedicated less time to survey this MA (relative to other MAs controlled by the same association), and by an additional score if the fishers perceived that enforcement in their MAs was not effective. As a result, 20 out of the 24 MAs had an “effective enforcement” lower than the formal “enforcement level”. During the interviews, fishers also provided information on number of poaching events that had been reported in their MAs on 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. All the variables per MA are included in the supplementary information (Table S1).

Attributes of Management Areas

Additional context variables considered relevant to assess poaching intensity over key-hole limpet were: 1) Availability of OA area per registered fisher in relation to the total area assigned to MA, in each cove (index IAOA); low availability of OA per fisher due to a high spatial density of MAs has been related with an increase of illegal fishing in OAs due to an effort displacement [26]. Here we suggest that such an increase in illegal fishing 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 cove, the IAOA is a proxy of the proportion of OAs that corresponds to each diver officially registered who may exert fishing effort around that cove. It considers fishing effort density and proportion of OA areas in relation to MA, in the accessible fishing grounds of the cove. The lower the estimate of IAOA, the lower the proportion of OAs in relation to MAs (less areas open to fisheries available near a cove) and, therefore, higher poaching pressure over OAs and over MAs as a rebound effect. Details of the methodological approach are provided by Fernandez et al. [26]. 2) Surface of the MA, as larger surfaces are expected to be more difficult to guard. 3) Distance between the MAs and the official
Figure 2: Ranking of enforcement level based on the fishermen’s organization: payment of external personnel for the continuous enforcement (hired enforcement), the organization of the fishers to conduct the enforcement of their areas, or no enforcement of the areas. The duration of the enforcement (guard) could vary from every day, 24hrs, to only occasional. The highest enforcement is 5 (very high), lowest 1 (very low)
surveillance base, as this official body is responsible for sanctioning the poachers, so fishermen contact them when a poacher is spotted in the area; the more distant, the less effective is enforcement as poachers must be caught in act in order to be sanctioned. 4) Access to the MA from land through main paved routes from the nearby location, considering also difficulty of sea access from land, e.g., a cliff implies a difficult access; difficult access might act as a natural protection against poachers that often reach MAs from land. 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 in the central coast of Chile is an area facing south, while a protected area is facing north). 6) Existence of alternative economic activities in the cove (e.g., tourism, construction, recreation); this, according to fishers' leaders, results in less poaching pressure, as fishers find alternative sources of income. The geographical variables distance to surveillance, wave exposure and access from land were estimated using Google Earth software. The presence of alternative activities was depicted from the fishers' interviews. All the variables per MA are included in the supplementary information (Table S1).

**Biological surveys**

Keyhole limpets (*Fissurella* spp.) are targeted as primary resources in the management plans of the vast majority of MAs. This resource is currently classified as fully exploited, with minimum landing size set at 6.5 cm for shell length in the study area, which correspond to an age of 2 years of benthic life. In order to assess the influence of the management regime on the proportion of undersize limpets in the catch, a field study was conducted between October 2017 and July 2018 in MAs associated to the 13 fishers' associations (Fig. 1), as described in Fernández et al. [26]. 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, i.e., a semi-autonomous diver (hookah), and measured onboard the fishing boat or at the landing beach or small-scale port. 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. [37]. 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 cove (W will be used to indicate the Wilcoxon test statistic). For further detail on the analysis of the data see Fernández et al. [26].

**Bayesian Belief Network Development**

Developed as essentially qualitative graphical models, BBNs are especially powerful explaining the causal relationships between variables (nodes) via conditional probability distributions. In BBNs, the processes are not necessarily explicitly captured, on the contrary, the expected probabilities of the outcomes are based
on particular combinations of events. Moreover, the probabilities coming from the combination of qualitative and quantitative data can be assigned to the BBN nodes and could come from combinations of expert opinions, empirical field data or previous experiences cited in the literature. Since BBNs provide a probability of an outcome rather than a discrete (deterministic) one, a mean (expected) outcome and a confidence interval can be determined. The way in which each input is combined to report the probability of an outcome is determined by a weighting combination rather than by a numerical estimation process. In other words, it is not necessary to develop formal structural relationships linking the different components of the model, allowing for non-linear or discontinuous results if deemed appropriately.

BBNs consist of two structural models: 1) a conceptual model (directed acyclic graph, DAG) that represents the best available knowledge about the functioning of the system and representing the links between the model variables (called nodes); and 2) conditional probability tables (CPTs) and conditional probability distributions (CPDs), which determine the strength of the links in the DAG. Directed arrows representing cause-effect relationships between system variables indicate the statistical dependence between different nodes. Each arrow starts in a parent node and ends in a child node. Feedback arrows from child nodes to parent nodes are allowed. The DAG can be developed by experts based on an understanding of the system and/or based on empirical observations. This initial structure of the DAG is the basis for an operational BBN. The probabilistic relationships between the model nodes are specified in the CPTs and CPDs. The CPTs and CPDs can be parameterised based on expert opinion, derived from mathematical or logical equations, or learned from the relevant empirical data structure. The nodes are restricted to a limited number of states that describe the probability distribution of system variables (e.g., a node can be discrete, with incremental or decremental states or levels, or be continuous type). The probability distribution of each node is contained in its CPT or CPD, and each given state of one variable is associated with a probability between 0 and 1, so that the sum of the state values adds up to 1 (100%).

In our study the DAG was developed iteratively based on the system understanding of the research team (see section 2.3 for the expected links between variables). The first DAG was created by 12 initial nodes: 10 drivers, 1) MA surface, 2) number of MA per fishermen association, 3) distance to surveillance authority, 4) access to MA from land, 5) wave exposure of the MA, 6) availability of OA (IAOA), 7) alternative activities in the cove, 8) enforcement level, 9) enforcement effectiveness, 10) perceived poaching level; and 2 response variables, 1) the proportion of 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 (è, as the normalized median MA/median OA). Values close to 1 indicate a good state of the resource with highest median sizes in MA compared to the paired OA area. All possible relationships between the 12 initial nodes were considered and quantified. The draft DAG structure included the main components relevant
to the limpet fishery (Fig. 3).

Data scoping and data analysis furthered the development of the model to select the final set of parsimonious nodes to populate the CPTs and CPDs. Then, Bayesian structure learning via score maximisation was performed using the tabu search [38] 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 optimisation technique and greedy search strategy, the tabu search employs local moves designed to affect only few local distributions, therefore, the new DAG candidate can be scored without recomputing the full marginal likelihood [38]. 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 (http://www.r-project.org/) and the “bnlearn” package v.4.6.1 [39].

**Figure 3:** Possible links between variables based on expert knowledge. In red, MA attributes; in blue, variables obtained from the fishers’ interviews; response (biological) variables in green.

*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 were 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 case study, the variables that are susceptible to be 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 enforcement level, distance to surveillance, availability of OA area and alternative economic activities in the
cove. The management scenarios were also explored the other way around: what would be the probabilities of different values of the selected drivers for a specific biological response? We considered as an optimal biological response a relative median size in the MA above 0.59 and an illegal proportion of limpet bellow 0.31. These responses occurred in ca. 15% of the MAs included in the study.

**RESULTS**

*Size structure of keyhole limpet in Management Areas*

Significant differences in median keyhole limpet sizes were found in 22 out 24 OA-MA paired comparisons (11 out of 13 coves). Although in 19 of 22 paired comparisons 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 unwanted management outcomes (Algarrobo MA1, Chungungo MA1 and Chungungo MA2). Furthermore, we found two coves with illegality levels in MAs equal to or higher than OAs: Chigualoco, where the MA 3 showed a proportion of undersize individuals in the catch similar to the OA (13 and 11%, respectively) and Chungungo, where the MAs 1 and 2 showed significantly higher proportions of undersize individuals (62 and 71%, respectively, see Fig. 6) in relation to the 41% recorded in the OA (plots for median sizes in OA and MA and statistical test are included in supplementary information; Table S2).

*Enforcement level and effectiveness*

From the 39 coves where enforcement was assessed (Fig. 1), 13% had no enforcement, 33% only occasional enforcement, 23% a daily 8-hours enforcement. The rest had daily enforcement (24 h), which is performed either by fishers (8%) or hired personnel (23%). The subset of 13 coves included in the study exhibited variable enforcement, from low to very high, with no example of no enforcement (very low); therefore, the enforcement variable included in the BBN has 4 levels. Three fishermen associations had low enforcement, 1 moderate, 2 high and 7 very high enforcement. However, by considering the effectiveness of the enforcement level endured by the fishermen association, in 20 MAs the enforcement level was reduced by 1 or 2 scores. In 11 MAs from associations with very high enforcement level, the effective enforcement was lower than the formal enforcement: 1 MA changed from very high to low; 5 from very high to moderate; 5 from very high to high (supplementary information; Table S2).

There was no linear relationship between the level of enforcement and the number of poaching events per year reported by the fishermen leaders during the interviews. Generally, sites with high enforcement have moderate-low perceived poaching; and low enforcement is related with high or very high perceived poaching. However, in some cases, high enforcement is related with very high perceived poaching (Quintay and Hornos) or low enforcement is related with low perceived poaching (Chungungo) (Fig. 4).

Similarly, there is no evident 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 enforcement level and enforcement 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.

Figure 4: Cleveland dot plot showing the overlap between the ranking of enforcement endured by the fishers’ association (green dots, 1, low, to 4, high) and the level of poaching perceived by the fishermen (red dots, 1, low, to 4, high)

Bayesian-belief network

A BBN approach was adopted to explore the influence of a set of external potential drivers of poaching intensity over keyhole limpet state within the MAs (Fig. 3). Keyhole limpet state was assessed through the relative size of limpets fished in MAs and the illegal proportion of limpets in the catch (see methods for further details). The limpet state is considered a proxy for the effects of poaching on benthic resources. The level of poaching was also assessed relying on fishermen perceptions (supplementary information; Table S1); however, the perceived poaching exhibited an unexpected link with the
Figure 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 enforcement level (upper panels) and enforcement effectiveness (bottom panels) in the case studies (24 MAs, indicated by their local names).
condition of the resource, as lower reported poaching events were linked with lower average sizes in MA and higher proportions of illegal size. Therefore, this variable was excluded from the final BBN. 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 (Fig. 3 vs. Fig. 6). 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 enforcement level, as alternative activities might reduce the time dedicated to survey the MAs. On the other hand, availability of OA area is linked to the illegal proportion of limpet through the distance to the surveillance authority and, therefore, poaching reports are not effective. Enforcement has effects over the relative size in the MA (ê) through the effectiveness of enforcement; 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 coves and MAs included in the study (Fig. 6): availability of OAs and distance to surveillance is 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 in an area of the coast, probably the sections of the coast most exposed to waves, and/or less accessible from the coves, tend to concentrate less MAs.

![Figure 6: Bayesian-belief Network obtained for the case study. The thickness of the arrow represents the strength of the link.](image)

Scenarios to achieve a good state of the fishery resource

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In order to observe a low proportion of illegal limpets in the catch, the ideal scenario includes a high availability of OA areas per fisher and 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 enforcement increases the probability of a lower proportion of limpets of illegal size in the catch (scenario 1, 3 and in Table 1). In particular, the combination of 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 neighbouring OA. Either high enforcement or high effectiveness combined with the presence of other activities did not yield probabilities higher than 39% (Table 1).

Table 1. Queries 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 |
|-----------|------------|------------|----------|-------------|
| Sce. 1    | Available OA = very high or high | Other activities = Y | Illegal proportion <= 0.3 | 0.881 |
| Sce. 2    | Available OA = very high or high | Distance to surveillance = close | Illegal proportion <= 0.3 | 0.935 |
| Sce. 3    | Available OA = very high or high | Enforcement = very high or high | Illegal proportion <= 0.3 | 0.961 |
| Sce. 4    | Enforcement = very high or high | Other activities = Y | Relative size at MA >= 0.4 | 0.378 |
| Sce. 5    | Effectiveness = moderate to very high | Other activities = Y | Relative size at MA >= 0.6 | 0.394 |
| Sce. 6    | Other activities = Y | Distance to surveillance = close | Illegal proportion <= 0.3 | 0.991 |
| Sce. 7    | Effectiveness = very high or high | Distance to surveillance = close | Illegal proportion <= 0.3 | 0.987 |

In order to attain a good state of the fishery resource, with an illegal proportion of limpet catch below 30% and the relative median size in the MA over 60% (i.e., larger limpets in the MA in reference to neighbouring OA), the optimal combination of variables indicate that 1) availability of OA area should be high to very high (probability of 0.53), 2) the enforcement should be high to very...
high (probability of 0.80), 3) the effectiveness can be maintained at moderate (probability of 0.77), 4) the distance to surveillance should be short (probability of 0.59), 4) while the presence or absence of other activities does not have a major effect (Table 2).

Table 2. Probabilities for a specific biological response: illegal proportion <= 0.3 & Relative size in MA >= 0.6.

| Availability of OA | Enforcement level | Effectiveness | Distance to surveillance | Alternative economic activities |
|--------------------|-------------------|---------------|--------------------------|--------------------------------|
| Very high: 0.236   | Very high: 0.575  | Very high: 0  | Close: 0.594              | Presence: 0.461                |
| High: 0.295        | High: 0.228       | High: 0.002   | Average: 0.275            | Absence: 0.539                 |
| Moderate: 0.118    | Moderate: 0.050   | Moderate: 0.775 | Far: 0.130               |
| Low: 0.147         | Low: 0.146        | Low: 0.031    |                          |
| Very low: 0.204    | Very low: 0.191   |               |                          |

**DISCUSSION**

To disentangle SSF complex dynamics, innovative approaches are necessary to deal with the scarcity of data and the need to take advantage of both scientific expertise and fishers’ knowledge [4]. Bayesian-belief networks are useful for SSF research due to flexibility in incorporating data of different nature, where expert knowledge plays a key role. The BBN exercise on a TURF system in central Chile allowed identifying the role of multiple external socio-economic and geographical context drivers on the sustainability of the fishery resource. Our BBN provided evidence of the absence of a direct link between the level of MA enforcement and the state of the benthic resource, with other socio-economic (e.g., alternative economic activities) and context variables (e.g., fishing effort pressure or distance to surveillance authorities) playing important roles. The interviews with fishers evidenced high variability in enforcement protocols and also 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 is in charge of more than one MA, which prompts the allocation of the limited enforcement 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 enforcement” and the model evidenced the importance of this variable in the state of the resource, as in some cases the level of enforcement achieved by the fishermen association was lowered by an uneven and non-effective enforcement across 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 [23].

The relationship between the enforcement level and the number of poaching
events per year reported by the fishers was not consistent, although an opposite relationship was observed in several coves. The observed lack of consistency in these results might be showing a bias due to the negative fishers’ perception on the effectiveness of the poaching sanctioning system [23]. 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 a government authority) improved the willingness of resource users to invest in enforcement, ending up with a reduction in poaching [40]. Compliance-monitoring agencies in Chile concentrate on access control with much less emphasis on compliance to quotas, bans or minimum legal size. According to the national fisheries law, the National Fisheries Service SERNAPESCA has to publicly deliver an annual report of enforcement actions, which, in its last edition reveals the low percentage of enforcement work achieved in the central coast of Chile (8.8% of the total field enforcement actions in the country), where the present study focuses [41]. This might be related with the geographic location of coves, several of them very distant from the closest city, where enforcement agencies are usually based. The implementation of local enforcement tools must be necessarily considered to address this difficulty. The sustainability of SSF is a complex socio-economic and ecological problem [42], with many local variables playing an important role and no bullet-proof solution. In fact, illegal fishing of Chilean SSF has been termed as a wicked problem by Nahuelhual et al. [43], as it is characterised by its complexity, uncertainty and interdependence of factors. Therefore, a multi-dimensional assessment, such as the one presented here, is necessary to address the illegal fishing of benthic resources in Chile.

A Bayesian-belief network is a strong tool to address multi-dimensional problems, as it nourishes from expert knowledge and it is flexible to be used for scenario analysis by local actors. In our study, the optimal model included most of the links predicted by expert knowledge (Fig. 3 vs. Fig. 7). However, some links were rather unexpected. For example, the existence of alternative economic activities is probably 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. 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: i) improving authority surveillance mechanisms and rules (in order to increase effectiveness of anti-poaching controls and reduce the negative consequences of higher distances to surveillance authority bases); ii) specific actions in marine spatial planning of the TURF system (in order to increase the availability of OAs around each MAs).

An additional administrative issue is the closure of the delivery of artisanal fishing permits for more than 10 years, that has let young generations of fishers with no choice but to fish illegally [43]. Fishers 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 fulfil the cost-benefit balance. The recurrent idea among different stakeholders (i.e., fishers, government and intermediaries of resource value chain) is that illegal fishing is a consequence of the lack of opportunities and economic needs [43,44], 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 on the socio-economic well-being of the cove. But, bearing in mind the later as a necessary long-term task, immediate actions on preventing poaching must be considered. Unmonitored and unsanctioned poaching in TURFs may impede fishers of sustaining their resources and benefit from harvesting surplus. Contrastingly, higher sanctions to poaching may both help fishers to defend their TURF resources and improve un-associated fishers’ willingness to bind to a TURF system [40]. Nevertheless, a strengthening in the sanctions to poaching must be framed in the artisanal SSF perspective [12], where non-compliance is strongly conditioned by local socio-economic contexts, as mentioned above [14]. Currently, fishers must cover the (increasingly high) cost of surveillance of their TURFs but rely on the administration to punish poachers [24]. Although the legislation considers formal sanctions to poaching and illegal practices, these are informally allowed by the enforcement agencies. 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 [8].

From our results, we can suggest that illegal fishing on key-hole limpet in central Chile arises from a complex network of drivers, from methodological to logistic problems, which appear to be linked to monitoring of compliance, lack of support of government agencies in the co-management process, socio-economic context of fishers, and an unsuitable spatial planning of the TURFs. These results are in line with observations focusing in other benthic resources like the highly valuable loco or Chilean abalone [27] and the king crab [43]. A change in paradigm to a local perspective in the implementation of mechanisms to overcome enforcement and planning weaknesses is needed. This change in paradigm should be aided by suitable diagnosis of local socio-economic contexts of fishers, and the improvement of local and regional governance tools (e.g., Management Committees, which are already considered in the national regulation).

In the current TURF system in Chile, fishers select an area, 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 on the planification of the system that might lead, for example, to high fishing pressure in adjacent open access areas [22,26]. Ospina-Alvarez et al. [45] showed the benefits of a planned network of MAs in the central coast of Chile that would have positive effects on both fisheries and biodiversity conservation. However, this spatial modelling exercise also evidenced the importance of enforcement for the effective functioning of the restricted areas network and the need to
consider all environmental and human factors in the optimization criteria. High fishing pressure on the OA areas, with overexploited benthic resources [37], has a negative feedback on the MAs that are exposed to illegal extraction of a benthic resource that is generally in a better condition than neighbouring OA areas [46]. A systematic and science-based spatial planning of the fishery restricted areas would avoid high concentrations of MAs in sections of the coast, generally those more densely populated, while identifying the most productive areas for the placement of fishery restricted areas [45]. 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 MA.

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) and fishers’ traditional ecological knowledge [6], so the conservation of the ecosystem is a priority over the individual interests to exploit the resources [47]. 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. In Chile, and in SSF in general, the balance of the fishermen-administration role must be planned to ensure a fully democratised system that is able to 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.

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Author contribution

Silvia de Juan: conceptualization, investigation, methodology, formal analysis, writing-original draft. Dulce Subida: conceptualization, investigation, formal analysis, writing-original draft. Andres Ospina-Alvarez: methodology, software, formal analysis. Ainara Aguilar: investigation. Miriam Fernandez: conceptualization, writing-review and editing, funding acquisition.

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Figure S1 - Length-frequency distributions (in %) of keyhole limpets for the OA and different MAs and of each cove, sorted from north to south. Solid grey line indicates the MLS (=6.5 cm) for this benthic resource. Dashed black lines indicate the median size of the catches for each sampling site.
Table S1 – Data gathered in the Management Areas and considered as potential drivers for illegal fishing in SSF in central Chile.

| Caleta          | MA name                  | Nº MA per caleta | Access from land | Wave exposure | Surface MA (ha) | Other activities | Availability OA | Enforcement | Effectiveness | Distance from surveillance | Nº of poaching events |
|-----------------|--------------------------|------------------|------------------|---------------|----------------|-----------------|-----------------|-------------|---------------|----------------------------|-----------------------|
| Chungungo       | Chungungo E              | 3                | Moderate         | Protected     | 21,45          | No              | 0,02572         | low         | low           | far                        | <20 (low)             |
|                 | Chungungo D              | 3                | Difficult        | Exposed       | 18,82          | No              | 0,02572         | low         | very low       | far                        | <20 (low)             |
|                 | Temblador                | 3                | Difficult        | Moderate      | 20,42          | No              | 0,02572         | low         | very low       | far                        | <20 (low)             |
| San Pedro – Los Vilos | Ñague                  | 2                | Moderate         | Moderate      | 280,77         | Yes             | 0,03251         | very high   | high          | close                     | 50-100 (high)          |
|                 | Ñague B                  | 2                | Difficult        | Exposed       | 56,49          | Yes             | 0,03251         | very high   | high          | close                     | 50-100 (high)          |
| Las Conchas     | La Cachina               | 2                | Moderate         | Moderate      | 116,2          | No              | 0,03287         | high        | moderate      | close                     | 20-50 (moderate)       |
|                 | Los Vilos Sector C       | 2                | Easy             | Moderate      | 60,21          | No              | 0,03287         | high        | moderate      | close                     | 20-50 (moderate)       |
| Hornos          | Hornos                   | 2                | Moderate         | Moderate      | 370,76         | No              | 0,03496         | very high   | moderate      | average                   | >100 (very high)       |
|                 | Hornos B                 | 2                | Difficult        | Exposed       | 84,32          | No              | 0,03496         | very high   | moderate      | average                   | >100 (very high)       |
| Chiguñaloco     | Caleta Boca del Barco    | 3                | Moderate         | Exposed       | 112,17         | No              | 0,03789         | moderate    | low           | close                     | 50-100 (high)          |
|                 | Chepíquilla              | 3                | Moderate         | Exposed       | 81,8           | No              | 0,03789         | moderate    | very low       | close                     | >100 (very high)       |
|                 | Chiguñaloco              | 3                | Easy             | Exposed       | 343,11         | No              | 0,03789         | moderate    | low           | close                     | >100 (very high)       |
| Huentelauquén   | Huentelauquén            | 1                | Difficult        | Exposed       | 309,74         | No              | 0,04815         | high        | high          | average                   | <20 (low)             |
| Los Molles      | Los Molles               | 2                | Easy             | Exposed       | 95             | Yes             | 0,10035         | very high   | high          | average                   | 20-50 (moderate)       |
|                 | Playa Los Molles         | 2                | Moderate         | Exposed       | 63,18          | Yes             | 0,10035         | very high   | high          | average                   | 20-50 (moderate)       |
| Algarrobo       | Algarrobo A              | 3                | Easy             | Protected     | 34,8           | No              | 0,11637         | very high   | moderate      | close                     | 20-50 (moderate)       |
| Location       | Rating | Exposure | Rating | Prob. | Level | Duration | Distance | Condition |
|---------------|--------|----------|--------|-------|-------|----------|----------|-----------|
| Algarrobo C   | Easy   | Exposed  | Yes    | 62.87 | 0.11637 | very high | high     | close     |
| Pichidangui   | Easy   | Exposed  | Yes    | 93.6  | 0.120033 | low       | very low  | close     |
| Horcón        | Easy   | Exposed  | Yes    | 98.71 | 0.13074 | low       | very low  | close     |
| Pichicuy      | Moderate| Exposed  | Yes    | 189.16| 0.14445 | very high | moderate  | close     |
| Papado        | Moderate| Moderate | Yes    | 187.26| 0.1891 | very high | moderate  | close     |
| Punta Pite    | Difficult| Exposed | Yes    | 112.72| 0.1891 | very high | low       | close     |
| Quintay A     | Moderate| Protected| Yes    | 53.42 | 0.34513 | very high | very high | average   |
| Quintay B     | Moderate| Exposed  | Yes    | 105   | 0.34513 | very high | very high | average   |

Notes:
- Level: very high, high, moderate, low, very low
- Duration: close, moderate, high
- Distance: 20-50, 50-100, >100
- Prob.: 0.11637, 0.120033, 0.13074, 0.14445, 0.1891, 0.34513
Table S2. Results from the Wilcoxon rank tests (W) comparing medians of the length of the catch of keyhole limpets (*Fissurella* spp.) between management regimes (MA indicates management areas and OA open access areas) at each cove (from south to north). N indicates sample size and includes the percentage of individuals below the minimum legal size (rounded). The index of availability of open areas is shown between parentheses for each cove. *P*-values are shown between parenthesis and values <0.05 in bold. Sites where the % of illegal catch (below MLS) was ≥ 49% are marked with a *.

| Cove      | Site / Regime | Lapa (*Fissurella* spp.) | N_total (N_undersize; % undersize) | W statistic for the catch (P value in parenthesis) |
|-----------|---------------|--------------------------|------------------------------------|---------------------------------------------------|
| Algarrobo | MA 1- Sector A | 303 (20; 7%)              | 31226 (9.105e-09)                  |
|           | MA 2- Sector C | 204 (5; 2%)               | 39626 (4.027e-12)                  |
|           | OA             | 284 (22; 8%)              | -                                  |
| Quintay   | MA 1- Sector A | 215 (0; 0%)               | 31031 (1.798e-08)                  |
|           | MA 2- Sector B | 245 (3; 1%)               | 35041 (2.237e-08)                  |
|           | OA             | 220 (9; 4%)               | -                                  |
| Horcón    | MA 1- Horcón   | 220 (27; 13%)             | 40352 (< 2.2e-16)                  |
|           | OA *           | 222 (131; 59%)            | -                                  |
| Papudo    | MA 1– Papudo   | 255 (2; 1%)               | 35973 (5.339e-14)                  |
|           | MA 2– Pta. Pite| 217 (8; 4%)               | 32034 (< 2.2e-16)                  |
|           | OA             | 200 (28; 14%)             | -                                  |
| Pichicuy  | MA 1– Pichicuy | 250 (28; 11%)             | 45290 (< 2.2e-16)                  |
|           | OA             | 240 (59; 25%)             | -                                  |
| Los Molles| MA 1– Los Molles | 272 (51; 19%)          | 40408 (3.348e-14)                  |
|           | MA 2– Playa Los Molles | 322 (43; 13%)  | 51168 (< 2.2e-16)                  |
|           | OA *           | 212 (104; 49%)            | -                                  |
| Pichidangui| MA 1– Pichidangui | 224 (0; 0%)          | 55114 (< 2.2e-16)                  |
|           | OA             | 250 (0; 0%)               | -                                  |
| Las Conchas| MA 1– La Cachina | 241 (0; 0%)            | 52041 (< 2.2e-16)                  |
|           | MA 2– Sector C | 207 (71; 34%)             | 32832 (9.612e-06)                  |
|           | OA *           | 256 (137; 53%)            | -                                  |
| San Pedro | MA 1– Ñague    | 284 (27; 9%)              | 41984 (< 2.2e-16)                  |
|           | MA 2– Ñague B  | 204 (12; 6%)              | 29778 (1.185e-13)                  |
|           | OA             | 205 (41; 20%)             | -                                  |
| Area          | Phase  | Code | Distance (m) | Magnitude | Location |
|---------------|--------|------|--------------|-----------|----------|
| Chigualoco    | MA 1–  | 255  | 36099        | 1.207e-07 |          |
|               | MA 2–  | 261  | 35964        | 2.935e-06 |          |
|               | MA 3–  | 181  | 20818        | 0.4811    |          |
|               | OA     | 221  | -            |           |          |
| Huentelauquen | MA 1–  | 225  | 22904        | 0.288     |          |
|               | OA     | 192  | -            |           |          |
| Hornos        | MA 1–  | 211  | 39924        | < 2.2e-16 |          |
|               | MA 2–  | 263  | 44646        | < 2.2e-16 |          |
|               | OA     | 201  | -            |           |          |
| Chungungo     | MA 1–  | 271  | 19143        | 7.177e-10 |          |
|               | MA 2–  | 210  | 13124        | 7.108e-13 |          |
|               | MA 3–  | 257  | 30382        | 0.01919   |          |
|               | OA     | 210  | -            |           |          |
QUESTIONNAIRE: TURFs enforcement: implementation level and associated costs

Date: 
Cove: 
Fisher’s organization: 
President’s name: 
TURF’s name: 

1. Do you have hired a surveillance service?  
   a. Yes  
   b. No. Who does the surveillance?

2. Duration and frequency of surveillance  
   a. Only during the day  
   b. Day and night  
   c. Only in weekdays  
   d. Only with calm seas  
   e. Other

3. This situation was different 10 years ago?

4. There is any protocol to carry out the surveillance? (e.g. patrol route, person who contact with NAVY)  
   a. Yes. Who decided the protocol?  
   b. No

5. Who pays the surveillance? Is the fisher’s organization or another external entity?  
   a. Fisher’s organization  
   b. External entity (Who?)  
   c. Both

6. If the fisher’s organizations must pay the surveillance. How much it cost?  
   a. More than 75% of the organization budget  
   b. More than 50% of the organization budget  
   c. More than 25% of the organization budget  
   d. Less than 10% of the organization budget

7. If the fisher’s organizations have more than one TURF. The surveillance is the same for all?  
   a. Yes  
   b. No  
      i. What TURF has more surveillance?  
      ii. Why those differences?
8. In the last year. How many cases of poaching did the organization register in each of the TURFS?

9. In a scale 1 to 7. What is the effectivity of the surveillance?

10. In a scale 1 to 7. What is the importance of the surveillance in a TURF for its good working?

11. What need your organization to have a good surveillance?
   a. More money
   b. More cooperation between members
   c. Less necessity for people that need to poach
   d. SUBPESCA and SERNAPESCA provide more staff in regions and coves
   e. Effective punishments