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Sustainability of the Juan Fernández lobster fishery (Chile) and the perils of generic science-based prescriptions

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ABSTRACT

Lobster fishing is the main source of income for the people from the Juan Fernández Archipelago (population ca. 770), located more than 700 km off central Chile. An artisanal fishery has operated uninterruptedly for more than a century with few harvest controls (season, size, no egg-bearing females). Access to the resource has long been regulated by an informal but well structured traditional sea tenure system, which has effectively constrained the growth of fleet size. Nevertheless, and in spite of a lack of impending crises, assessments conducted over the last 40 years have recurrently diagnosed that effort is well above the optimum level. On that basis, generic "solutions" (quotas, marine protected areas, closures) have been prescribed with no attention to their possible impacts on the users and on traditional tenure arrangements. We discuss the merit of those diagnostics and prescriptions, and conclude that the disruption created by their eventual implementation would threaten the sustainability of the fishery. An analysis of the entire social-ecological system is needed before drastic solutions are prescribed. We investigate the factors that favor sustainability using Ostrom's framework for the analysis of social-ecological systems. Those factors have to do with the resource system (a productive stock with well defined boundaries and divisibility of fishing spots among users), governance (traditional tenure and simple operational rules), the users (few, strongly dependent on the resource, and sharing a detailed mental model of the resource system), and interactions (self-organization and partnerships). The resilience of the system was tested by the devastating tsunami that hit the islands in February 2010. This case study illustrates the need to attend to the interactions among resources, users and institutions in the search for effective solutions and to avoid disruptive management interventions.

1. Introduction

Natural scientists in academia and providers of scientific support for management often respond to indications of overfishing with prescriptions that narrowly address the biological aspects of sustainability. Metaphorically, the most usual diagnostics and prescriptions attend to the symptoms rather than to the disease to be cured (Hilborn et al., 2004). Yet, overfishing is the proximate manifestation of problems rooted in the complex interaction matrices of Social-Ecological Systems (SESs, Berkes et al., 2001), notably those pertaining to fishers's behavior in response to access rules and incentives. Thus, assessments conducted in support of sustainable management need to encompass multiple dimensions, not just the resource system (Castilla and Defeo, 2005), i.e., fisheries should be assessed as SESs.

The perils of focusing narrowly on resource-centered science is perhaps most obvious in the case of small-scale fisheries, for which command-and-control management is largely ineffective. Providing scientific advice to management within the stock assessment-based paradigm is often considered challenging because these fisheries are typically data-poor by the standards of classical fishery science (Garcia et al., 2008). The most frequent "solution" to this problem has been to adjust conventional assessment-driven approaches, resorting to oversimplified stock assessment protocols (e.g., Pauly, 1983; Sparre and Venema, 1992). Narrowly focused diagnostics result in science-based generic prescriptions which, if implemented, may prove disruptive of the SES, aggravating rather than alleviating the problem intended to be solved. Quoting Ostrom (2009), "*theoretical predictions of the destruction of natural resources due to the lack of recognized property systems have led to*

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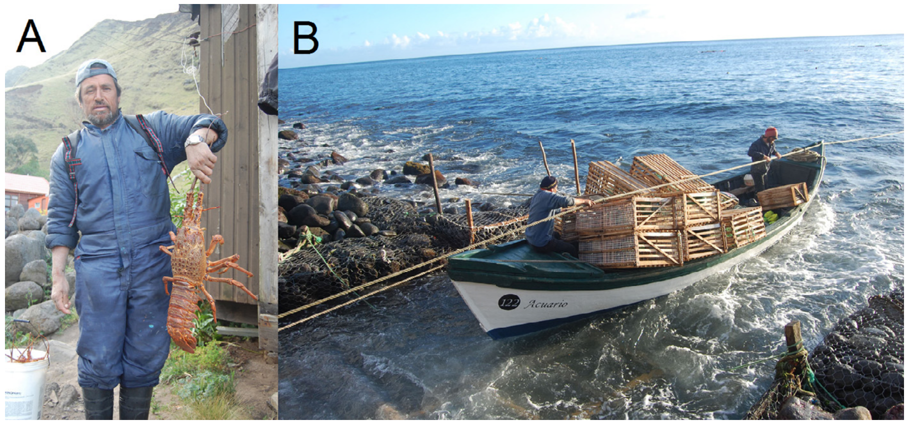

Fig. 1. (A) Mr. Alberto González, a fisherman from Selkirk Island, holding a male Juan Fernández lobster (*Jasus frontalis*). (B) A lobster fishing boat loaded with traps goes to sea.

one-size-fits-all recommendations to impose particular policy solutions that frequently fail".

In this contribution we investigate tension between challenges to sustainability and generic science-based prescriptions in an artisanal fishery that targets spiny lobsters (*Jasus frontalis*, Fig. 1A) in the Juan Fernández Archipelago, 700 km off central Chile (Fig. 2). The archipelago is formed by three groups of islands: Robinson Crusoe ("Robinson"), Santa Clara and Alejandro Selkirk ("Selkirk") (Fig. 2). The only village (San Juan Bautista), with a population close to 770, is located in Robinson. A small temporary settlement (about 25 fishermen and their families) is occupied on Selkirk during the fishing season. A few boats fish occasionally around the Desventuradas Islands located about 820 km north of Juan Fernández. The fishery has been the backbone of the local economy for more than one century (Arana, 1987, 2010).

While most artisanal fisheries from southern South America have been through cycles of uncontrolled effort expansion and subsequent collapses (Orensanz et al., 2005), the Juan Fernández lobster fishery has sustained the livelihoods of most islanders since the 1890s, uninterruptedly. The size of the fleet (57 boats active during the 2011/12 season), and the basic design of the boats and trap gear (Fig. 1B; Arana, 1983) have changed little in decades, even before the introduction of a preventive moratorium in 2004 (Ernst et al., 2010b). While some fishing seasons have been better than others, there is no collective sense in the fishing community of ever having been a crisis. Paradoxically, scientific inquiries on the fishery, focused largely on biological sustainability, have recurrently diagnosed overfishing (Yáñez et al., 1985; Henríquez et al., 1985; Yáñez et al., 2000), giving rise to societal concerns (Reyes, 1987). Symptomatically, a recent study (Eddy et al., 2010) opens with reference to over-exploited fisheries.

Diagnosed overfishing has lead to three generic prescriptions: catch quotas, marine reserves, and a complete closure of the fishery. Catch quotas, a common management tool in the case of industrial fisheries, have been repeatedly prescribed for the Juan Fernández lobster fishery on the basis of stock assessments suggestive effort being excessive (Larrain and Yáñez, 1983; Arana, 1983; Yáñez et al., 1985, 2000; Henríquez et al., 1985). Marine

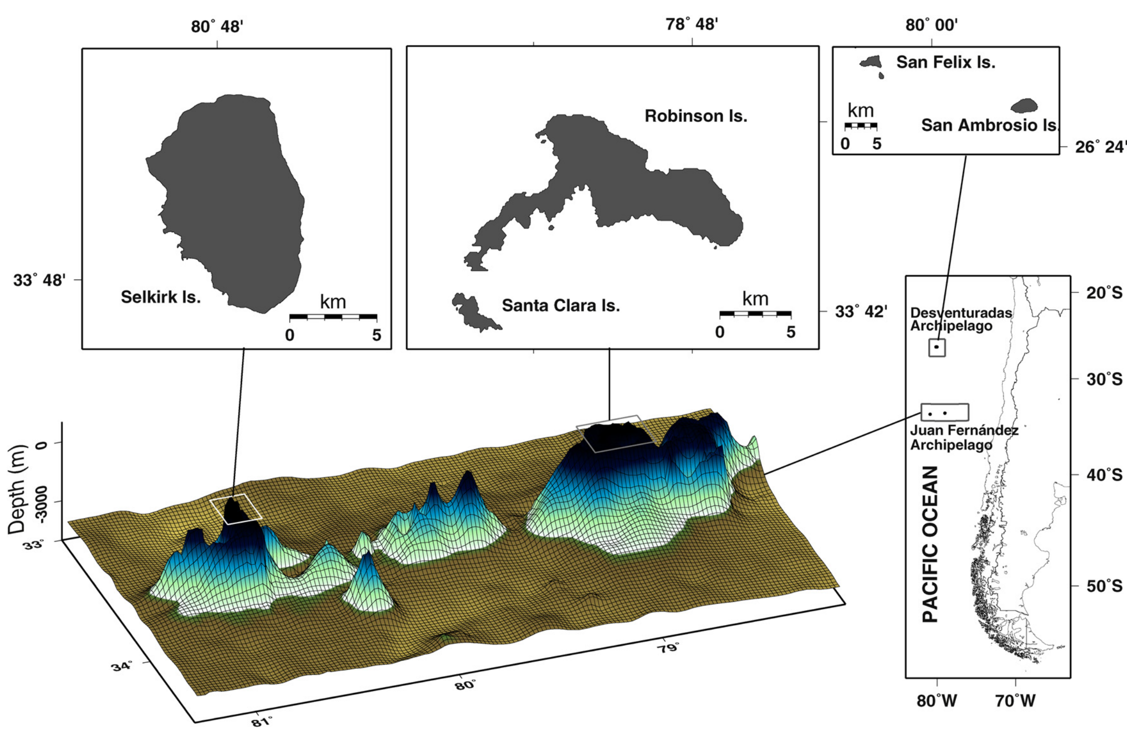

Fig. 2. The Juan Fernández Archipelago. Robinson/Santa Clara and Selkirk Islands are peaks of a continuous submarine ridge extended in the east–west direction.

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reserves have attracted much attention in recent years as a safeguard against overfishing (Gaines et al., 2010), and have been found to be an effective tool in a New Zealand relative of the Juan Fernández lobster (*Jasus edwardsii*; Kelly, 2001; Freeman et al., 2009). Eddy et al. (2010), based on projections of a simulation model, concluded that "*stewardship of catch coupled with 30% area closure provides the best option to reconstruct historic baselines*" in Robinson. They also suggested that a complete closure, although not "*a practical management strategy*", "*may be required [...] in the not too distant future as stock size will not be given a chance to rebuild*". Complete closures are a draconian measure of last resort and dubious results. The main effect of the well-documented three-year closure of the loco snail (*Concholepas concholepas*) fishery in continental Chile (1989–1992), for example, was the marginalization of fishers, forced to sell in the black market while illegal fishing continued unabated (González et al., 2006).

Generic science-based prescriptions offered for the Juan Fernández lobster fishery have not been accompanied by an assessment of the broader consequences of their eventual implementation, not only for the resource but also in terms of social and economic impacts. A traditional sea-tenure system, which has effectively regulated access to fishing spots since before the memory reach of the oldest living fishermen, was largely ignored (Ernst et al., 2010b). In this informal tenure system each fisherman or fisherman's family member may "own" a number of fishing spots known as "marcas" where traps are deployed, one per marca. Access to marcas is regulated by unwritten but well-established internal rules. We hypothesize that the comparative success of the Juan Fernández lobster fishery is attributable to the confluence of multiple factors: isolation of the fishery (resource and users, which minimize exclusion problems), some simple formal operational rules (which safeguard biological productivity), and the traditional tenure system (which resolves issues of access, improves equity and prevents a race for fish).

Beyond sustainability, resilience of the SES was tested by the tsunami of February 27, 2010, which devastated the exposed sectors of San Juan Bautista, whipping out the building of the maritime authority, very good facilities belonging to the local fishermen's organization ("syndicate"), and the workshop where wooden boats were built and repaired (Fig. 3; Ernst et al., 2010a).

In what follows we re-examine the information available on trends in several indicators used in previous stock assessments (fleet size, landings, catch per unit effort) to discuss the overfishing diagnostics. We then re-visit the informal tenure system, and characterize the fishery as a SES within the framework offered by Ostrom (2007, 2009). We discuss several science-based prescriptions advanced to enhance sustainability (quotas, marine reserves, complete closure), and attend to their possible implications for the functioning of the informal tenure system which – we argue – has contributed to make the fishery sustainable and resilient for more than a century. Based on this specific inquiry we discuss some general aspects of Ostrom's framework as it applies to fishery SESs.

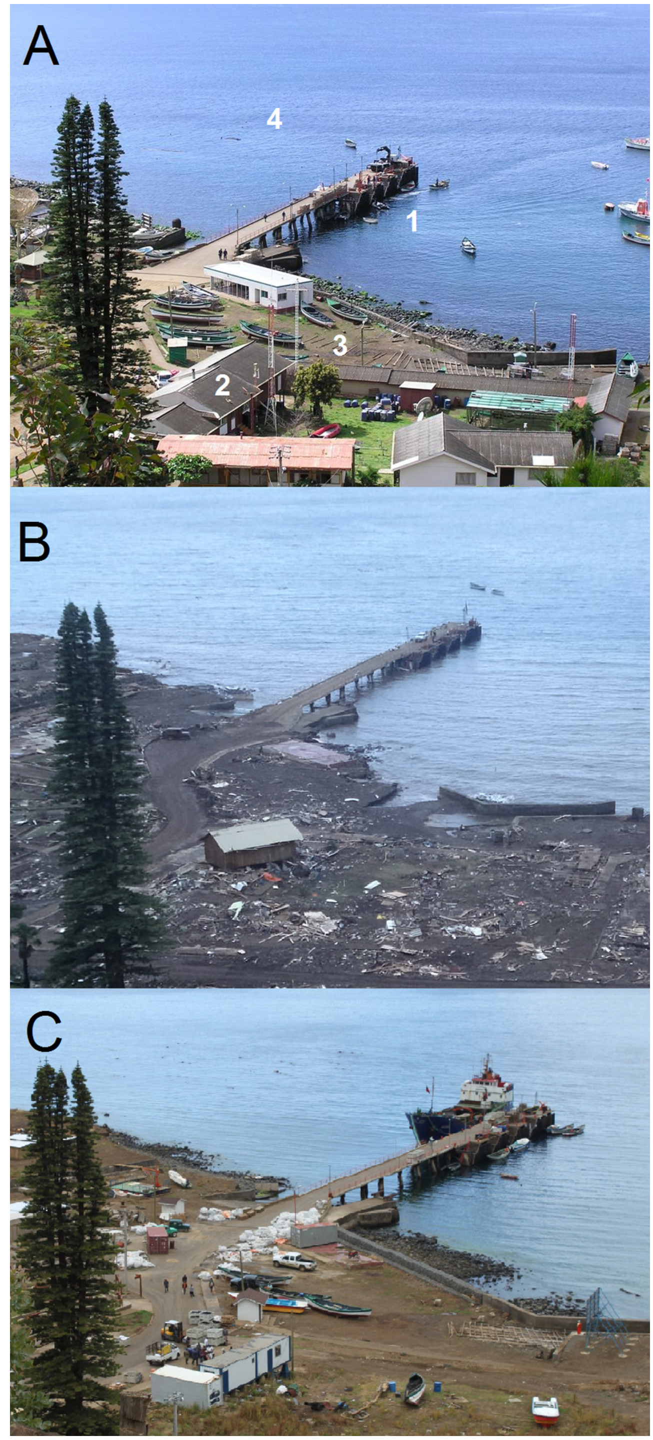

Fig. 3. San Juan Bautista, facilities significant to the lobster fishery before and after the tsunami of February 27, 2010. (A) Before (2004); (B) immediately after (early March 2010); (C) present. (1) Dock, (2) maritime authority, (3) syndicate, (4) holding pens for the short-term storage of lobsters.

2. Sources of information and methods

2.1. Landing statistics

Keeping of annual landing statistics started in the early 1930s. Landings are reported in tons (rather than numbers) and pooled by calendar year (as opposed to fishing season). Low landings reported for 2002 (9 mt) and 2003 (1 mt) seemed unrealistic. An inquiry made with the agency in charge of collecting fisheries statistics indicated that those low values reflected a recording error related to a change in the database platform used to record catch slips filled by the fishermen. The corrected figures (23.6 mt and 34.4 mt) are not exceptional compared to preceding years. The quality of the records is likely to have improved since 2007, when the national fisheries service (SERNAPESCA) stationed an agent in the island.

2.2. Fleet structure and dynamics

Historical records on fishing-boat construction and ownership started in the mid 1970s and were meticulously kept at the Juan Bautista detachment of the national maritime authority (Capitanía de Puerto). We transcribed valuable information in 2004 (Ernst et al., 2010b). The detachment (and with it the records) was destroyed by the tsunami of February 2010.

2.3. Catch and effort records

Natural effort units in the Juan Fernández lobster fishery are trips and individual trap hauls. Because all the traps are basically of the same size and design, and are serviced in a similar way, the trap haul is considered the most convenient unit. The longest continuous time series of catch and effort data corresponds to information on catch per trip recorded by the island's fishing cooperative from 1972 to 1980 (when its activities were terminated), and extended through 1983 by the local police detachment. Catch-per-trip data (1972–1983) were converted to catch-per-trap assuming an average of 21 traps lifted by trip (Arana, 1976, 1983; Arana and Toro, 1985). The number of traps lifted by trip increased after the introduction of winches, starting in 1998. A series of projects monitored seven fishing seasons in Robinson/Santa Clara (1970/71, 1971/72, 1981/82, 1984/85, 1996/97, 2005/06, 2011/12) and four seasons in Selkirk (1984/85, 2008/09, 2009/10, 2011/12)(see Supplementary Materials for details), collecting information on catch (including sex and size of lobsters) and effort (trips and trap hauls). The most recent period has been covered by an ongoing voluntary logbook program started in 2006 through collaboration between the syndicate and scientists (Ernst et al., 2010b), and by a government-funded project during the 2011/12 season.

2.4. Survey of the tenure system

Information on the informal tenure system was obtained through structured interviews and participant observation (Hay, 2005; Bernard, 2006) between 2004 and 2012. The latter was facilitated by two of the authors (JC and PM) being themselves members of fishermen families and local syndicates. A survey of lobster marcas, on which the tenure system is based, was conducted in Robinson/Santa Clara during three consecutive fishing seasons (2004–2007), in collaboration with Robinson's syndicate (Ernst et al., 2010b). During 2008–2009 a survey targeted Selkirk with collaboration of the local syndicate (STIPIAS; Ernst et al., 2010c). Information gathered included the geographical coordinates of the marcas and their individual "owners". A catalog of more than 350 toponyms used by fishermen was compiled to assist in the geolocation of verbal or anecdotal historical information on catch and effort.

2.5. Fishers' perception of science-based prescriptions

During January–April 2012 we conducted structured interviews with 35 skippers fishing in Robinson/Desventuradas (out of 47) to inquire about their perceptions of stock status, as well as their knowledge and opinions about different science-based prescriptions (catch quotas, protected areas, escape vents) that have been offered to improve the biological sustainability of the fishery (see Supplementary Materials for details). A complete closure was not mentioned as an option during the interviews, for obvious reasons. Skippers were selected as the focal group because they tend to be the most experienced fishers and own a large fraction of the documented marcas. Various materials reporting the position held by fishermen organizations were screened (e.g., records of participatory meetings).

2.6. Characterization of the SES

We used the framework of Ostrom (2007, 2009), complemented by reference to conditions compiled by Agrawal (2001, see Supplementary Materials), to characterize the Juan Fernández lobster fishery as a SES. To that end we screened a broad range of published and unpublished documents. Early snapshots (Segerstrale, 1931; Lobell et al., 1947; Bahamonde, 1948; Canessa, 1965; Ulloa, 1968) provide valuable information on the origins and evolution of the fishery, the fleet, the gear and the fishing process, as well as a tenuous baseline of some aspects of population biology (size structure, distribution, catch per unit of effort). Reports produced by the Fondo de Investigación Pesquera (FIP, www.fip.cl) are a major source of information on the resource and the fishing process. Several recent studies contain updated information on social and economical aspects (FAJF and OIT, 2011; Municipalidad de Juan Fernández, 2009; Servicio País, 2003). A detailed assessment of the impact of the tsunami on the fishery (fleet, gear, facilities, services) was conducted early on by one of us, at the request of the local syndicate (Manríquez-Angulo, 2010).

3. Results

3.1. Fishing force and effective fishing effort

The lobster fishery started during the 1890s. Motors were introduced in 1919 (Segerstrale, 1931), facilitating access to all areas around Robinson/Santa Clara. Segerstrale (1931) counted 24 fishing boats in 1930, and Lobell et al. (1947) 41 in 1945; total fleet size remained at close to 50 boats since the early 1970s until 2004 when a nominal moratorium was introduced by the fisheries authority. The basic boat design did not change over at least a century: wood-made, 8–11 m long and double-ended (Fig. 1B), equipped with 15 or 18 HP outboard motors (a few boats had inboard motors). Starting in 2007, maintenance costs motivated replacement of some wooden boats by fiberglass hulls, a process that accelerated after the 2010 tsunami destroyed or severely damaged 10 boats; 13 motors were lost. Donations resulted in the replacement of 10 old boats by new ones with hulls made of laminated wood or fiberglass, and 18 motors – six of 20 HP and 12 of 50 HP (donated by Honda). In spite of the moratorium, the number of active boats grew to 57 in the 2011/12 season (Fig. 4B); 42 operated in Robinson/Santa Clara, 11 in Selkirk, and 5 in the Desventuradas. That increase in fleet size was made possible by administrative loopholes and inaccuracies in the registry of boats kept by the fisheries authority. In addition to the active boats, there are currently 14 inactive permits, including six boats now rigged for tourism services, and eight that were destroyed or are disabled. Prospective candidates to enter the fishery if there were an opportunity are registered in a "waiting list" kept by the fisheries authority. Some of the boats replaced after 2007, and particularly following the tsunami, were repaired and are now in the waiting list.

While modest, some technological innovations have gradually increased fishing power of individual boats in spite of stability in the size of the fleet. "Baskets" (described by Segerstrale, 1931) were replaced by traps between the 1940s and early 1960s, and a change in trap design (which improved their efficiency; Arana, 1983, p. 81) occurred during the period 1979–1981. Finally, small winches used to lift the traps gained wide acceptance between in 1998–2002, increasing the number of traps that can be handled during a fishing trip (Henríquez et al., 1985). More recently, sounders have been used to find new fishing spots, and GPS is becoming popular among the younger fishermen to locate marcas during foggy days.

3.2. Landings

Recorded annual landings averaged 89 mt between 1930 and 1965, and then declined during the following decade to an average of approximately 30 mt during the period 1975–2003 (Fig. 4A). A marked drop during 1943–1946 was coincidental with World War II. Based on an error in the official landing statistics (discussed

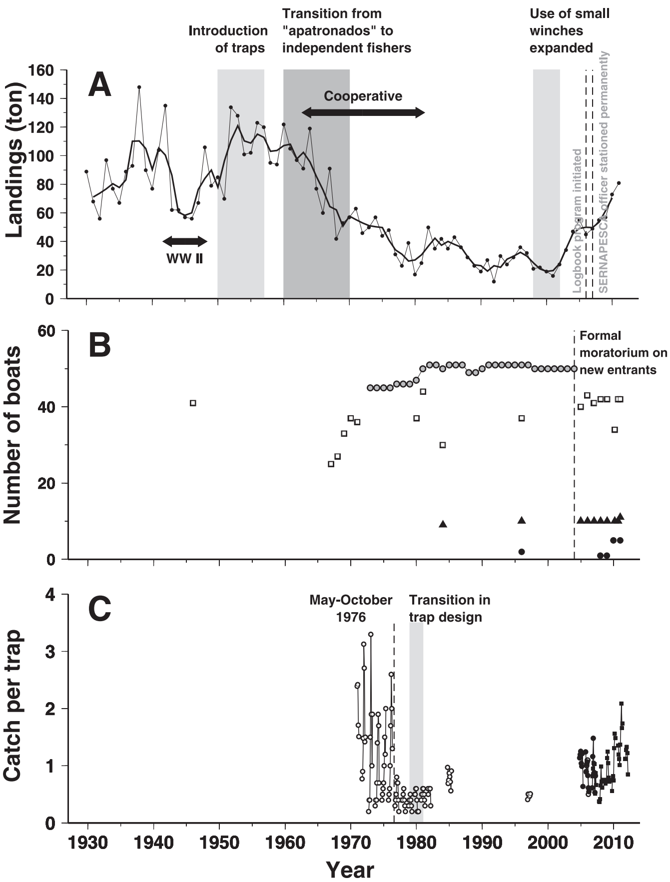

Fig. 4. Historical trends in the Juan Fernández lobster fishery. (A) Landings (in metric tons, by calendar year), with indication of significant events in the history of the fishery; solid line: X3 moving average. (B) Fleet size; (○) number of lobster fishing boats registered with the maritime authority (1970–2004), (□) number of lobster boats operating in Robinson/Santa Clara at the time when various research projects were conducted, (▲) Ibid., Selkirk. (C) Average CPUE (catch per trap, composite of information from various sources); (○) data compiled by the cooperative (1970–1980), the police department (1981–1983) and five intensive research projects (see text); (●) data from the marcas project and the logbook program (see text). Vertical dashed line: sudden drop of CPUE in the cooperative time series (see text).

earlier) for 2002–2003, Eddy et al. (2010) interpreted that the fishery had been closed by SERNAPESCA for one season to allow stocks to recover, resulting in high catches in the subsequent seasons. Such closure never occurred. Natural fluctuations in lobster productivity led to a rebounding of the catches, from a minimum of 19 mt in 2001 to 81 mt in 2011. Over the last five decades this figure was second only to the catch reported for 1967 (91 mt). According to fishermen, the relatively low landings in preceding years (1998–2002) corresponded to a period of low abundance, as perceived through catch per unit of effort (CPUE). Catches during 2010 were affected by the tsunami, with a partial cease of activities after February in Robinson (directly affected) and a total cease in Selkirk, as the Selkirk fleet returned early to Robinson to assist in the aftermath. To compensate for the losses due to the tsunami the following season started one month earlier than usual. Records from 2009 on incorporate catches made by a few boats in the Desventuradas. Given that CPUE has been historically higher around the Desventuradas, this factor may contribute to increase landings in recent years.

3.3. Catch per unit of effort (CPUE)

A composite time-series of CPUE (monthly average catch-per trap) clearly shows within-year seasonal variation and long-term trends (Fig. 4C). Data compiled by the cooperative show a sudden drop between the 1975/76 and 1976/77 seasons. Interviews with fishermen that were active at the time, conducted in 2004, failed to identify an explanation for a phenomenon which could not have gone unnoticed. Catch-per-trap data compiled during the intensive studies of 1970/71 and 1981/82 (about 4 years before and after the drop) match the cooperative catch-per-trap series, dispelling suspicion of a recording artifact. Average catch-per-trap has increased since 2004, reaching a level comparable to that of the early 1970s (Fig. 4C).

3.4. The marcas tenure system

Marcas are fishing spots identified by alignments of land features and "owned" by individual fishermen or members of their families (never by organizations or fishing companies). A total of 3762 marcas have been identified for Robinson/Santa Clara, and 993 for Selkirk (Ernst et al., 2010b, and unpublished results). Use and transfer of rights over marcas are regulated by informal but well-established internal rules. Marcas are not sold but can be transferred with a boat if the latter is sold, can be inherited by family members, and are often lent to other users under a variety of arrangements, mostly by fishermen that leave others "in charge of" the marcas while they are temporarily absent or fishing elsewhere (e.g., in the Desventuradas). When a boat is sold with its marcas, it is customary for the former owner to introduce the buyer to his marcas by fishing together with him during a rather prolonged time known as "instalación". The instalación is important not only for the buyer to learn to locate the marcas, but also for his peers to watch it; otherwise it would be difficult for the buyer to claim ownership and his rights to be honored. It is practically impossible for a newcomer to discover and claim ownership on new marcas without knowing the location of existing marcas (owned by others), and without this knowledge being recognized by his peers. In fact, as informed during the interviews, some fishing permits granted to boat owners with no history in the lobster fishery (Section 3.1) have not been activated because their boats do not have associated marcas. These permit-holders avoid conflict with established fishermen. The marcas system has contributed stability to the size of the fishing fleet (Fig. 4b).

During a given season each boat fishes a package of marcas that includes those belonging to the skipper, the deckhands, their family members, and/or borrowed marcas. Average number of marcas available to a team is approximately 80 (maximum around 200), but only a subset (30 on average) is active at any given time. Some boats may be limited in the effective fishing effort they exert by the number of marcas they hold, while others have more marcas than they can tend to. Typically the package includes marcas located nearshore and offshore within a given sector, and not all are tended to at the same time. A strategy of intra-season effort allocation has been practiced at least since the 1940s (Bahamonde, 1948): gear is deployed in shallow areas at the beginning of the season (spring), and gradually shifts to deeper areas toward the summer. This could be explained by two non-exclusive hypotheses, namely offshore lobster migration during the spring, and serial depletion (onshore–offshore) during the fishing season. Fishermen favor the first, which is also consistent with results from mark-recapture experiments conducted in Robinson (Arana, 1991/1992) and Selkirk (Ernst et al., 2010c), with the caveat that those results could be confounded by the spatial allocation of fishing effort. Short-range seasonal inshore–offshore migrations have been demonstrated in the congeneric *J. edwardsi* from New Zealand and Australia (Booth, 1997; Kelly, 2001; Freeman et al., 2009).

In addition to lobster marcas, fishermen identify locations suitable for secondary bait fishing (known as "pesqueros" or "marcas de pescado"): trapping moray eels and longlining for whitefish, both used as lobster bait. Differing from lobster marcas, access to secondary bait marcas is open and information about their location is not shared among fishermen. Primary bait (used to catch secondary bait species) is a pelagic fish (“jurelillo”), not associated with marcas.

The traditional tenure system survived intact the tsunami of 2010, and was clearly a determinant factor in a quick and orderly resumption of fishing operations. Fishermen shared boats and motors to compensate for lost equipment, fishers with operating boats checked the traps left unattended by relatives who had lost their gear, and the Selkirk teams returned to Robinson to help in the recovery.

3.5. Fishers’ perception of science-based prescriptions

Out of 35 skippers interviewed, 32 expressed a negative view of a quota system, and three were ambiguous. Some pointed to the difficulties of allocation of individual quotas, given differences in productivity among boats. One warned of the risks of increased effort in a classical “race for fish” if the quota were unallocated. Most considered that the size limit and the closed season were sufficient to protect the resource. Six, however, indicated that capping the number of traps could be a possible effort control option, although some acknowledged implementation difficulties.

Model projections by Eddy et al. (2010) included scenarios in which 10% and 30% of the fishing ground area was closed to fishing. In both cases, the closed area was centered around Cumberland Bay (where San Juan Bautista is located, Fig. 5). None of the 35 skippers interviewed had a notion of such marine reserves; 33 had a definitely negative opinion, and two said that the idea could be good in principle, but impossible to implement. Reasons for a negative view predictably relate to social problems created by the displacement of fishermen that own marcas within the proposed closed areas, several of which would be effectively left out of work or might try to set their traps in areas already in use by other fishermen, creating major conflicts in the fishery. Superimposing the proposed marine reserves with our spatial survey of marcas (Fig. 5) it was found that, among 41 boats whose crews own marcas in Robinson, 35 have marcas within the proposed “30% area closure”; five among them have more that 50% (55–85%) of their marcas in that sector.

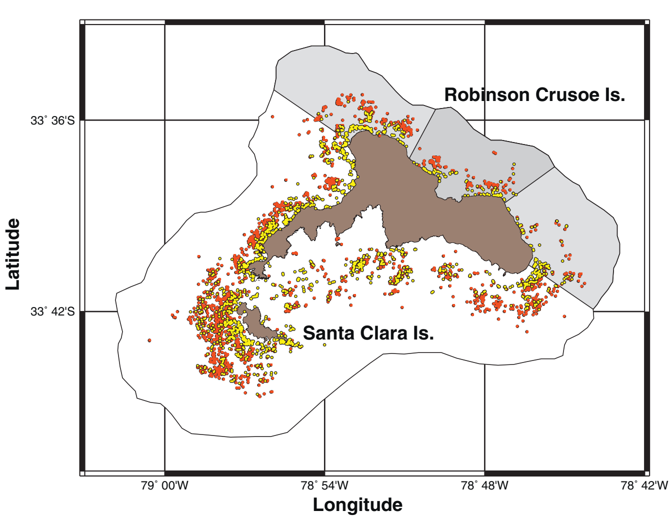

Fig. 5. Marine reserves proposed by Eddy et al. (2010) superimposed to fishing spots mapped during the marcas project. Dark and light shading: 10% and 30% of lobster habitat scenarios. Light (yellow) and dark (red) spots: marcas operated (respectively) early and late during the fishing season. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The option of implementing escape vents is well known to the fishermen, as it has been presented by scientists in the context of workshops (e.g., Arana et al., 2006b). Among the 35 skippers interviewed, 22 had already incorporated vents in at least some traps, and were generally positive about the results, 5 had a positive opinion but had not tried them yet, and 4 thought that vents were not needed because the spacing of the bars was enough to ensure selectivity. Interestingly, two of the skippers expressed concern about possible contamination, considering that the vents are made of plastic. The vent prescription is scientifically well supported, has been discussed with fishermen, and is a potentially significant contribution to the sustainability of the fishery.

3.6. Characterization of the SES

We use Ostrom’s diagnostic framework to characterize the Juan Fernández lobster fishery as a Social-Ecological System (SES). In this framework, SESs have several core subsystems, including: the Resource System (RS), Resource Units (RU), the Governance System (GS), and Users (U) (Fig. 6). Interactions (I) among these components lead to Outcomes (O), which can be influenced by external drivers such as climate, markets, catastrophes, and the broader social, economic, and political settings. The hierarchical nature of the framework means that each of the first-level core subsystems can be broken down into second-, third-, and even forth-level variables. Below we describe the core subsystems and second- and third-level variables that we identified as most significant for the sustainability of the Juan Fernández lobster fishery (Table 2; Fig. 6); we refer to Supplementary Materials for a complete characterization. In the tables and in the narrative below we use for reference the codes introduced by Ostrom (2007, 2009; see Supplementary Materials).

Governance System (GS). The Governance System can be conceptualized as the interplay of formal and informal arenas and rules, by reference to Ostrom (1990, pp. 50–55) (Table 1). In the formal arena, Chile’s fisheries authority is shared by the highly centralized Undersecretary of Fisheries (SUBPESCA) and National Fisheries Service (SERNAPESCA), the latter in charge of enforcement and compiling landing statistics (see Supplementary Materials). The collective-choice rules used by the fisheries authority to make policies in the formal arena are contained in the General Fisheries and Aquaculture Act of 1989, and its modifications. Formal operational rules include (among others) a minimum legal size (115 mm from the base of the antennae to the posterior edge of the carapace), a closed season (May 15th through

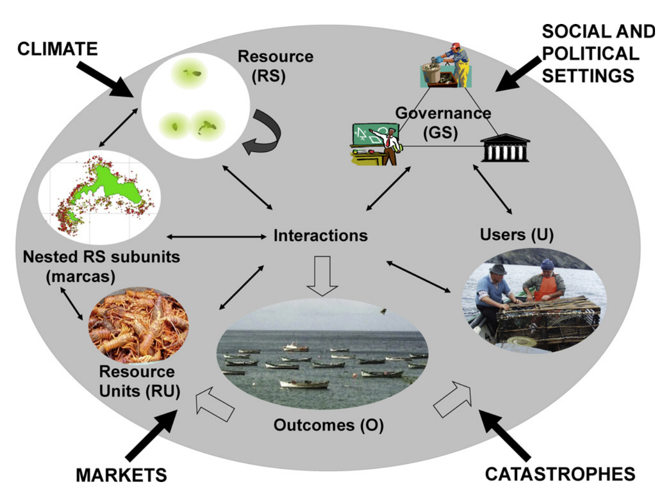

Fig. 6. Core subsystems of the Juan Fernández lobster fishery, according to Ostrom’s (2009) framework for analyzing social-ecological systems (see also text and Table 2). Factors outside the gray area correspond to external drivers.

Table 1
Arenas and rules in the Juan Fernández lobster fishery. Collective-choice rules affect operational activities and results through their effects in determining who is eligible to be a participant and the specific rules to be used in changing operational rules. Operational rules directly affect day-to-day decisions made by the participants in any setting (Ostrom, 2005).

Arenas		Collective-choice rules	Operational rules
Formal	Legislature Fisheries authority (SUBPESCA, SERNAPESCA) Courts	National Fisheries Act[a]	Closure of registry[b] Maximum size of boats Size limit[c] Seasonal closure[d] No berried females[e] Traps only gear allowed[e]
Informal	Long history of social interactions Syndicates	"Ownership" and transferability of fishing spots	

[a] Ley General de Pesca y Acuicultura (LGPA).
[b] SUBPESCA executive resolutions 3856 (2004) and 4011 (2009).
[c] Decree by Ministerio de Fomento 1584 (1934), according to Arana (1985).
[d] Decree by Ministerio de Agricultura 223 (1963), although earlier resolutions incorporated seasonal closures (Arana 1985).
[e] SUBPESCA executive resolution 957 (1992).

September 30th) and no keeping of egg-carrying ("berried") females (Table 1); the latter was honored by fishermen as an informal operational rule long before it was formalized (Segerstrale, 1931). These rules are in addition to the moratorium of 2004. In the informal arena, the traditional sea-tenure system of marcas has effectively regulated access to fishing spots since before the memory reach of the oldest living fishermen (Ernst et al., 2010b). Trap gear ease enforcement of territorial rights, as fishers can effectively sanction intruders by cutting and/or emptying their traps (Wilson et al., 2007) (GS8). Both formal and informal rules have contributed to the fishery's sustainability. The traditional tenure system has constrained the growth of the fleet, preventing overcapacity and providing for the sustained and uninterrupted operation of the fishery (GS4). Formal operational rules (size, season and not keeping berried females) provide for effective protection of the reproductive stock (GS5).

Resource System (RS): the lobster population. Scientists generally agree that this is a "recruitment fishery" (Arana and Martínez, 1982; Henríquez et al., 1985), meaning that the annual catch is based mostly on individuals reaching legal size during the year, and implying that those "recruits" are subject to high harvest rates. By that account the Juan Fernández lobster stock, like other spiny lobsters, can be considered highly productive (RS5), even when individual lobsters grow slowly (RU2). The species is endemic to the Juan Fernández/Desventuradas islands, implying that the resource is geographically isolated (RS2) and self-sustaining (RS9).

Nested RS subunits: marcas. Predictable association of lobsters with rocky reefs implies that fishing spots are discrete, can be marked and are thus divisible among users (RU6). The marcas can thus be considered subunits of the Resource System (RS). The evolution of the marcas system was facilitated by critical attributes of the resource and the fishing gear. The use of passive fishing gear lends itself to the partition and allocation of fishing spots or territories among fishers, as has been documented in several other trap and gillnet fisheries (Begossi, 1995; Cordell, 1989; Acheson, 2003; Wilson et al., 2007).

Resource Units: individual lobsters. Reproductive output is mainly contributed by undersized females and legal-size females that carry eggs early during the fishing season and get to spawn before being harvested (Arana et al., 1985). Maturity is reached at 6–7 years and commercial size at 8–10 years after larval settlement (Arana and Martínez, 1982; Arana et al., 1985) (RU2).

Unlike stereotypical artisanal fisheries from developing countries, this is a cash, export-oriented fishery, and the economic value of the RUs is high (RU4). Average ex-vessel price of individual lobsters from Robinson was U$S 20 during the 2011–2012 season; total annual exports (mostly live lobsters) reached U$S 3.92 million in 2012 (www.prochile.cl). The value of lobsters may continue to increase as fishermen identify new markets (Juan Fernández lobsters were targeted as a product by Slow Food) and pursue certification (Marine Stewardship Council [MSC] pre-certification is under way).

Users. The lobster fishery of the Juan Fernández archipelago has been the main support of the small resident community for over a century (U3). Throughout its history, insularity and remoteness have imposed relative isolation (U4) and high dependence on the local resource base (U8). Locally rooted leadership and self-organization go back five decades (U5-I7). A traditional tenure system incorporates norms for interactions in a small (U1) tightly knit community of users (U6). Fishermen share a comprehensive, spatially-explicit mental model of lobster biology (U7).

Interactions. Strong partnerships with scientists, the fisheries authority and NGOs (I8) have strengthened institutional sustainability, leading to recognition of the informal sea tenure system, establishing a monitoring program (Ernst et al., 2010b), and having a proactive role in the planning of a marine protected area (CONAMA et al., 2011), certification by Marine Stewardship Council, and promotion by Slow Food.

Outcomes. In terms of social performance (O1), the marcas system has ensured a rather equitable distribution of fishing spots among teams. Although the number of marcas vary among teams, and between skippers and other marcas holders, ownership of marcas is by no means concentrated in a few hands. The marcas system also keeps interference conflicts and transaction costs at a low level. More than a century of uninterrupted operation, basically unsubsidized and free of major crises, is a measure of sustainability. Rapid recovery after the 2010 tsunami attests to resiliency.

Regarding ecological performance (O2), lobsters that attain legal size are subject to high harvest rates, preliminarily estimated at 88% for males and 54–64% for females in Selkirk (Ernst et al., 2010c). It is not unlikely that the fishery has been sustained at a suboptimal bioeconomic level. This is often the case in small, lightly regulated fisheries, where social sustainability has been achieved with relatively modest economic rent (Beddington et al., 2007).

External forcing. While Ostrom's framework is mainly concerned with attributes of the SES that may be more or less conducive to self-organization and sustainability, external drivers may also play a critical role. In the Juan Fernández lobster fishery, the entire SES is affected by large-scale external forcing, the main drivers being international markets, climate, and catastrophic events. Historically, exports were destined to European markets (Spain, Italy and France), where they compete with other spiny lobster suppliers. Since 2009 the market has been rapidly expanding into Asia, to 63% of total export shares in 2012. Climate

Table 2
Characterization of the Juan Fernández lobster fishery based on Ostrom's (2009) framework and Agrawal's (2001) conditions; variable coding matches the systems introduced by those authors. Nested within the resource system are the marcas, discrete fishing spots where traps are deployed. O: Ostrom's framework, A: Agrawal's critical enabling conditions for sustainability. Further descriptive variables that contribute to characterize the system are provided in Supplementary Materials.

First-level core subsystems	Second and third-level variables	Variable codes	
RS – Resource System	Location and clarity of system boundaries	O-RS2 & RS9	Lobster stock is geographically isolated and self-sustaining
		A-1.ii	
	Productivity	O-RS5	High
Nested RS subunits: marcas	Discreteness		Because of lobster's predictable association with rocky reefs, fishing spots owned by fishers are relatively discrete
	Distinctive markings	O-RU6	Marcas are located by alignments of land features; fishers know their marcas and those of others in the region
RU – Resource Unit	Mobility	O-RU1	Short-term low mobility; lobsters intercepted by traps (passive gear)
		A-1.iii	
	Growth and turnover rate	RU2	Slow
	Economic value	RU4	High
GS – Governance System	Property-rights systems	O-GS4	Informal but effective sea tenure system of marcas constrains fishing power
	Operational rules	O-GS5	Simple formal harvest rules (size limit, season, no berried females) effectively protect reproduction
		A-3.i	
	Monitoring and sanctioning	O-GS8	
	Ease of enforcement of rules	A-3.iii	Seasonal closure and "ownership" of marcas are easy to enforce; size and no-berried lobster rules may be cheated
	Sanctions	A-3.iv	Trap cutting effectively sanctions unauthorized use of marcas
U – Users	Number of users	O-U1	Small, 57 boats
		A-2.i	
	History of use	O-U3	Long (more than a century)
	Location and boundaries	O-U4	Remote and isolated, clearly-defined boundaries, exclusion problems minimized
		A-1&2.i	
	Leadership/entrepreneurship	O-U5	Strong; educated and well-connected leaders
		A-2.v	
	Norms/social capital	O-U6	Tight community, shared norms, substantial social capital
		A-2.iii & A-2.iv	
	Knowledge of SES/mental models	O-U7	High, strong, sharing a spatially-explicit mental model of spatial distribution of lobsters and habitat, and seasonal migrations
	Dependence on resource	O-U8	Strongly dependent on the resource
		A-1&2.ii	
I – Interactions	Self-organizing activities	O-I7	Significant, well organized
	Networking activities	O-I8	Active partnerships with scientists and NGOs leading to documentation of marcas system, participatory monitoring and conservation initiatives
O – Outcomes	Social performance measures	O-O1	
	Equity	A-1&2.iii	Fair allocation of benefits given homogeneous fleet and spread of marcas ownership among users
	Efficiency		Ownership of marcas allows fishers to more efficiently "manage" their fishing spots. Adherence to the tenure system reduces interference among fishing units, conflicts and transaction costs
	Sustainability and resilience		High
	Ecological performance	O-O2	High sustainability, high harvest rates perhaps suboptimal

is likely to drive low-frequency fluctuations ("cycles") in lobster recruitment and abundance, as well as year-to-year changes in catch rate due to variation in catchability and growth rate of cohorts entering the fishery.

Catastrophic events are epitomized by the tsunami of 2010, which tested the resilience of the SES (O1). Soon after the tsunami, a prompt and detailed assessment of damage to the fishing fleet and land facilities, commissioned by the syndicates (Manríquez-Angulo, 2010), facilitated orderly fishery-specific relief assistance by different organizations (Food and Agriculture Organization of the United Nations [FAO], Honda, Alaska Crab Coalition, Slow Food Foundation, Fondo de Fomento de la Pesca Artesanal; Ernst et al., 2010a), minimizing the sequels of competitive humanitarianism (Stirrat, 2006) and distortive replacements (Tewfik et al., 2008) typical of post-disaster experiences. The case of Juan Fernández constitutes a micro-scale experiment that yields some lessons in the field of post-disaster economic security and livelihood recovery, currently at the forefront of policy research in humanitarian and development cooperation circles (Régnier et al., 2008). While a centralized warning system proved dysfunctional (O'Riordan, 2010), a tightly knit community, fishermen organization, and the traditional tenure system were significant factors in the quick reorganization of the fishery (Ernst et al., 2010a).

4. Models, overfishing diagnostics and science-based prescriptions

Two modeling approaches have been followed to investigate the dynamics of the exploited lobster stock as a basis for advancing management prescriptions. First, data collected in a series of discontinuous projects have been used in formal stock assessments using simplified generic approaches (Pauly, 1983; Sparre and Venema, 1992; see Supplementary Materials): (i) aggregated biomass models fitted to catch and effort data (Larrain and Yáñez, 1983; Arana, 1983; Yáñez et al., 1985; Henríquez et al., 1985; see

Section 2.3), (ii) yield per recruit analysis (Yáñez et al., 1985), and (iii) size-based models based on snapshot size-frequency distributions under equilibrium assumptions (Yáñez et al., 2000; Espejo and Yáñez in Arana et al., 2006a). Second, Eddy et al. (2010) conducted a bioeconomic simulation analysis of the Robinson/Santa Clara sector using an aggregated biomass model to represent the dynamics of the stock (see Supplementary Materials for critical comments). The intrinsic rate of population increase was inspired on estimates for the congeneric *J. edwardsii* from New Zealand, and carrying capacity was guessed based on the interpretation of historical anecdotal accounts. Spatial explicitness was added by partitioning the region and allowing lobster movements among adjacent regions (parameters inspired by *J. edwardsii*). Spatial effort allocation was incorporated through a form of so-called "stewardship" ("*following a season with a lower catch, fishers fish less in order to maintain stock biomass*"). The model was fitted to the historic time series of landing data, and projections were made under various scenarios (*status quo*, effort reduction, "stewardship", marine reserves).

Our reconstruction of trends (Sections 3.1–3.3; Fig. 4) highlighted serious limitations of key indicators used in diagnostics. A reporting error in landing statistics was misconstrued by Eddy et al. (2010) as a two-year closure that never happened. Stock assessments conducted at various times concluded that effort was 32–136% above the optimal level. Trends in abundance have defied predictions of imminent collapse ("*the stock may be showing a resistance to extinction*", Yáñez et al., 1985). Eddy et al.'s (2010) model predicted "*the 'business as usual' scenario to result in the lowest stock biomass at all times*". As discussed earlier (Sections 3.2 and 3.3), landings and CPUE increased dramatically (rather than collapsing) over the last eight years, to levels not seen in more than five decades.

In addition to being based on simplistic stock assessments or misguided model projections, the generic prescriptions proposed to deal with the diagnosed overfishing – catch quotas, marine protected areas, and a complete closure of the fishery – present serious problems. Implementation of a quota is demanding in terms of stock assessment and enforcement (Walters and Pearse, 1996; Parma et al., 2003), and its allocation requires attention to social issues (particularly equity). In the case of the Juan Fernández lobster fishery, allocation of a quota would be disruptive of the traditional tenure system which we found to be the core element of the fishery's sustainability (Section 3.4). In the Australian lobster fishery, which recently went through a transition from effort allocation (number of traps) to catch quota allocation, quota was partitioned in equal shares per trap. Partition of the quota in equal fractions among marcas would be close to impossible, as fishermen know well that marcas vary greatly in their average yield. A technical panel convened to discuss the lobster fishery unanimously agreed not to recommend catch quotas as a viable option (Arana et al., 2006b, p. 183). The fishery was declared "fully exploited" in 2004 (SUBPESCA, Executive Resolutions 3356/2004 and 4011/2009), but while many fisheries in that status have been placed under a quota system, the later is not required by the current act (Ley General de Pesca y Acuicultura, LGPA, and its modifications, www.subpesca.cl).

Model projections by Eddy et al. (2010) considered area closures of variable extension centered around Cumberland Bay, which "was suggested by lobster fishers to be the best location because it is the area most depleted in abundance and most easily enforced and monitored by 'the eyes of the village'". Dr. Eddy (personal communication) indicated that about ten fishermen were present at the meeting where the marine reserve was presented and discussed. Nevertheless, the specific design of a marine reserve prescribed by Eddy et al. (2010) as an option to be considered in a co-management context was unanimously dismissed by interviewed fishermen as a viable alternative (Section 3.5).

Eddy et al. (2010), commenting on a purported fishery closure that never existed (discussed earlier), concluded that "the higher catches in the two years immediately after this enforced closure suggest that this type of action may be required again in the not too distant future as stock size will not be given a chance to rebuild", although they acknowledged that "the enforced closure of the fishery as occurred in [2002/03] is not a practical management strategy". Contrary to the aforementioned expectations, landings have steadily increased over the last eight years, the catch from the 2010/11 being the second highest in five decades. This rebound is indicative of factors other than fishing as significant drivers of the cycles of abundance well known to fishermen. Four of the skippers emphasized cycles of abundance in their responses; in fact autocorrelation is evident in the historical series of landings (Fig. 4A). A complete closure is not a realistic option for the foreseeable future.

5. Discussion

Generic science-based prescriptions proposed to manage the Juan Fernández lobster fishery misrepresented sustainability by (i) narrowly focusing on diagnosed overfishing, with only cursory attention given to the possible implications of implementing the prescriptions, and (ii) ignoring that the fishery has been successful in sustaining the livelihoods of most islanders since the 1890s, uninterruptedly, basically unsubsidized and with no collective sense in the fishing community of ever having been a crisis. Even if the fishery were at times sustained at a suboptimal bioeconomic equilibrium, this would be a minor problem compared to the disruptive consequences to be expected were quotas, marine reserves, closures or other top-down drastic measures ever introduced without attention to the informal tenure system. If anything is evident from our inquiry it is that the entire fishery (not just the resource system), understood as a SES, needs to be assessed in order to provide support to sustainable management. We found Ostrom's (2007, 2009) framework to be a good starting point in that direction.

Ostrom (2007) illustrated the application of her framework with two common property resource (CPR) systems: a pasture (the classical exampled used by Harding, 1968) and the lobster fishery of Maine (Acheson, 2003), similar in many respects to the Juan Fernández lobster fishery. In both the pasture and the lobster fisheries the yield of the Resource System (RS) is driven by ecosystem productivity, involving light, nutrients, primary producers and low-level consumers (on which lobsters forage) in the case of the fisheries, and light, nutrients and water in the case of the pasture (Fig. 7). The Resource Units (RUs) generated by these systems are, respectively, the individual lobsters and the sheep. Although both are mobile animals, sheep and lobsters are not completely analogous in the context of CPRs. Individual sheep bear "distinctive markings" (RU6) and are privately owned; the CPR in Harding's tragedy of the commons is the pasture. In the case of the fisheries, by contrast, the free roaming lobsters (RUs) are themselves units of the CPR. Lobsters are distinctively marked and individually owned only after having been caught (Fig. 7). Traps (physical objects) are distinctively marked and owned by individuals. Although similar to each other in some respects, the Juan Fernández and Maine lobster fisheries differ on significant aspects. Informal territorial access rights are present in both systems, but while members of Maine lobster gangs have access to a common territory (Acheson and Gardner, 2005), Juan Fernández fishermen individually own specific fishing spots (marcas). The distinctive marking of fishing spots where traps are deployed provides a means to divide up the CPR among individual users,

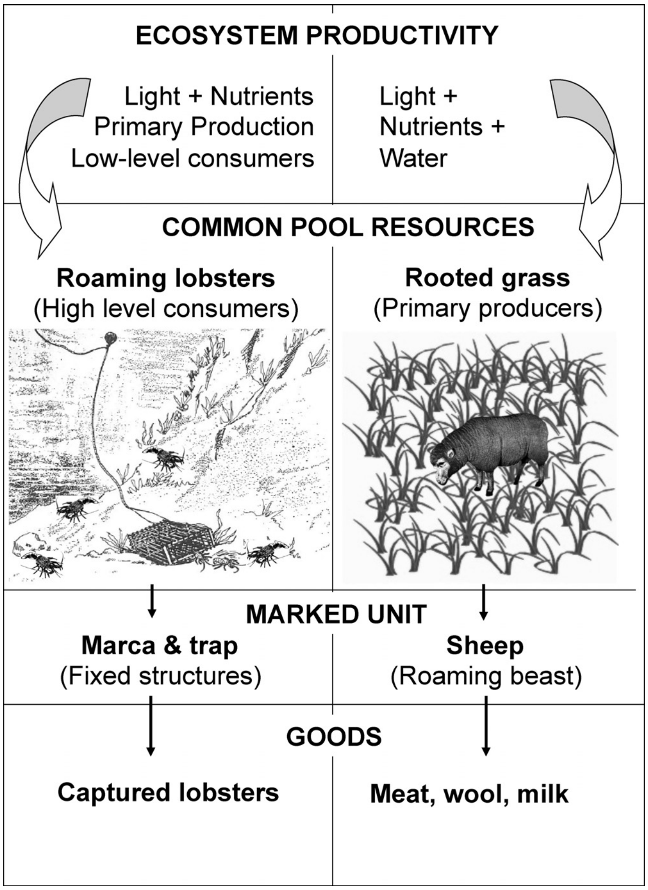

Fig. 7. Comparison of two CPR systems: Juan Fernández lobster fishery (left) and a sheep pasture (right). See text for discussion.

giving them long-term access to a share of resource system productivity. According to Ostrom (2007, p. 15185) "*distinctive markings of resource units have not received sufficient attention in the theoretical literature, although they are frequently used as an important attribute of resource units in constructing effective property-rights systems*". In our case, distinctive markings apply not to the RUs (individual lobsters) but to subunits nested within the Resource System. In general, any diagnosis of a CPR problem needs to recognize the units associated with the basis for establishing ownership of the common resource, and in turn with conditions enabling sustainability and self-organization. In fisheries systems, this may apply to any actual or possible form of allocation of access to the resource through (i) formal "input controls" such as individual effort quotas or a cap on the number of gear units in use (e.g., maximum number of traps per boat in some lobster fisheries; Linnane et al., 2011), (ii) formal "output controls", like a share of the allowable catch, or (iii) fishing spots or territorial partitions. The latter is the basis for access regulation under the informal tenure system of the Juan Fernández lobster fishery.

Until recently, lack of recognition by external authorities (and scientific advisors) of the ability of users to create their own access and harvesting rules (highlighted as a general problem by Ostrom, 1990) made the informal system vulnerable to the introduction of disruptive formal operational rules. It was only recently that the informal tenure system of the Juan Fernández lobster fishery became known and discussed outside the local community, and its relevance to the sustainability of the system recognized by scientists and managers. Indeed, gaining recognition by management authorities of the existence of these up-to-then unwritten rules was one of the motivations of fishermen leaders to embark in a joint project with scientists to document the workings of the marcas system.

While these are remarkable achievements, the lobster fishery faces a new tier of challenges. Main current risks pertain to the potential growth of effective fishing effort, including both the number of boats and the fishing power of individual boats. Given that the number of marcas available to fishing teams is very variable (Section 3.4), teams with a surplus of marcas would have incentives for acquiring larger/faster boats. Introduction of larger boats by one fisherman would disrupt an informal rule (maximum boat size) that is perceived to contribute to equity and to limit effort. For those reasons fishermen have repeatedly raised concerns about legal boat dimensions (Arana et al., 2006a, pp. 188–190; Arana et al., 2006a; Ernst et al., 2010a,b,c). Although under the provisions of the current moratorium license replacements are only permitted within boat class (defined by length), the fisheries act establishes a maximum length of 18 m for artisanal boats, substantially larger than the boats currently in use in the lobster fishery (8–10 m). The moratorium, however, did not prevent a moderate increase in the number of boats that occurred in connection to replacements before and after the tsunami (Section 3.1). Additionally, if one of the replaced boats that were repaired and are now on the "waiting list" were granted a permit, it could enter the fishery provided that the crew includes local fishermen who own marcas.

In addition to boat size there are other operational rules that can contribute to limit effort. Six of the skippers interviewed (Section 3.5) indicated a cap in the number of traps as a possible effort control option, although acknowledged implementation difficulties. Escape vents designed to improve trap selectivity, whose effects have been well demonstrated (Arana and Ziller, 1994; Arana et al., 2011), have gained some acceptance. Since the measure is not enforceable (vents can be easily disabled while at sea) it has to be implemented on a voluntary basis.

The lobster fishery has been declared as "fully exploited", and according to the fisheries act is required to develop a formal management plan (Article 8 of the LGPA) which would specify, among other things, the access regime and conservation-oriented operational rules. A management plan for the Juan Fernández lobster fishery, yet to be developed, could provide the legal means to incorporate locally-devised operational rules such as a self-imposed limit on the size of boats, more restrictive than definitions contained in the fisheries act. Formalization of customary practices, however, must proceed with caution (Cinner and Aswani, 2007). In contrast to formal systems, informal systems are the result of a protracted process of adaptive adjustment. While recognition of customary systems is desirable in principle, formalization is risky because (in the absence of effective feedback and flexibility) it can be a straight-jacket when resilience is conditioned on adaptability. Informal (yet effective) tenure systems are vulnerable to top-down experiments in institutional engineering (e.g., Gelcich et al., 2006).

6. Conclusions

Lobster fishing has sustained the economy of the Juan Fernández Islands over more than a century, uninterruptedly. We investigated factors leading to sustainability of the fishery using the framework proposed by Ostrom (2007, 2009) for the analysis of SES. Sustainability, we conclude, has been the result of a combination of variables in the systems that conform the SES: (i) the resource system: a productive stock with well defined boundaries and geographically isolated; (ii) divisible fishing spots; (iii) the governance system: traditional tenure that regulates access, and simple operational rules that protect the reproductive contribution of females; (iv) the users system: few, strongly dependent on the resource, and sharing a detailed, spatially-explicit mental model of the resource system; (v) interactions: self-organized, active partnerships with NGOs and scientists. Outcomes include equity (fair allocation of benefits), efficiency (low level of interference, resource-related conflicts and transaction costs), sustainability, and resilience (tested by the tsunami of 2010).

Assessments and academic inquiries conducted over the last 40 years have recurrently diagnosed that effort is well above the optimum level, and on that basis have prescribed generic "solutions": catch quotas, marine protected areas, closures. We conclude that those measures, if ever implemented, would severely disrupt the traditional tenure system and, consequently, fishermen livelihoods and ultimately the sustainability of the fishery itself. We strongly support the notion that this and other small-scale fisheries should be assessed along the multiple axes that determine the sustainability of SESs, with attention to interactions among resources, users and institutions.

Our exploration of the fishery using Ostrom's framework suggests that the scope and definition of variables, as well as their concatenation to characterize SESs, need to attend specifically at the units upon which the CPR (or benefits derived from it) is divisible among users. These units are directly associated with appropriation of the CPR, and in turn with conditions enabling sustainability and self-organization.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.08.002.

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