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Monitoring the sustainability of *Lessonia nigrescens* (Laminariales, Phaeophyceae) in northern Chile under strong harvest pressure

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Abstract In the last decade, exploitation of *Lessonia nigrescens* in northern Chile has been carried out using the best practices agreed upon by consensus between fishermen, industry, government, and scientists. These practices focus on the selective harvest of sporophytes to allow the maintenance of a reproductive stock, facilitating recruitment and minimizing grazing of benthic herbivores. To improve coverage and accessibility, enforcement of administration measures along the northern coast of Chile requires ecological indicators to monitor the sustainability of *Lessonia* kelps. Over 2 years, density, biomass, recruitment, and size structure of *Lessonia* were sampled seasonally in coastal areas with different regimens of harvesting administration as follows: (1) Management Areas for Exploitation of Benthic Resources (MAEBR), (2) Open Access Areas (OAA), and (3) Marine Protected Areas without human intervention. The use of demographic parameters as ecological indicators allows discrimination between kelp beds where good harvesting practices have been applied by users (MAEBR), and areas where management recommendations have not been put in practice (OAA). The ecological indicators reinforced the concept of co-management in MAEBR as a viable harvesting administration system along the Chilean coast, and indicated a high-harvesting pressure in OAA. Moreover, together with other harvesting parameters, they could be useful to justify the application of other administration strategies, such as quotas or bans.

Keywords Kelp harvesting · Natural populations · Intertidal beds · Management · Conservation · Administration policies

Introduction

Globally, various species of brown macroalgae are cultivated or harvested for the extraction of alginic acid, which is used in diverse industrial applications (Bixler and Porse 2011). In Chile, brown macroalgae are exploited in natural populations and exported to international markets as raw material for the production of alginates (Vásquez et al. 2012). Only a minor fraction of the annual harvest is used by the Chilean national gel industry or as feed for invertebrate cultures (Vásquez 2008). International demand for Chilean kelps has produced a sustained increase in harvest during the last decade, reaching more than 300,000 dry t with an economic return of more than US$ 70 million (Vásquez et al. 2012). Brown macroalgae of economic interest are: *Lessonia nigrescens* species complex (*Lessonia berteroana* and *Lessonia spicata*—see González et al. 2012; hereafter referred as *L. nigrescens*), *Lessonia trabeculata*, *Macrocystis pyrifera*, and *Durvillaea antarctica*. However, it is mainly wild populations of *L. nigrescens* which are exploited in northern Chile (ca. 26° and 32° S; Vásquez et al. 2012), while *Macrocystis* is locally harvested for feed-cultured invertebrates and *Durvillaea* is used as food for human consumption in coastal zones south of 33° S. This fishery (harvesting and plant collection) is focused in northern Chile because of the proximity of the desert, decreasing production costs of raw material processing (Vásquez 2008).

In Chile, brown macroalgae harvesting is socially important (Vásquez and Westermeier 1993): in the north of Chile, more than 15,000 people depend directly or indirectly on the harvest and collection of this marine resource. Although legally, only authorized artisanal fishermen are allowed to harvest kelp (Vásquez 2008), enforcement is difficult due to

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limited accessibility and the extension of the coastline (Frangoudes 2011). Ecologically, brown seaweeds are foundation species in coastal marine ecosystems which help maintain foci of high biological and genetic diversity (Graham et al. 2007); however, they are also sensitive to natural and anthropogenic disturbances (Vásquez et al. 2006, Thiel et al. 2007).

Considering the economic, social, and ecological importance of brown macroalgae, and the substantial increase in harvest, the Chilean government has implemented a co-management and conservation plan, surveying the available and harvestable biomass, the strength of harvesting (Capture per Unit Effort—CPUE), and characterizing the chain of production (Vásquez 2008). Apart from the valuable information related to standing stock and standing crops of wild beds of brown seaweeds of economic importance, the national management program includes the following bio-ecological recommendations: (1) to harvest the entire plant including the holdfast; (2) to harvest plants larger than 20 cm in diameter; (3) to harvest plants selectively, selecting only larger specimens; (4) rotation of harvesting areas; and (5) for *Macrocystis*, to cut the canopy 1–2 m from the surface.

Considering that Chile is the country with the greatest harvest of natural kelp forests in the world (see Vásquez et al. 2012), these management recommendations constitute a sustainable exploitation strategy under the assumption that stability of demographic processes assures the persistence of wild kelp beds of *L. nigrescens*. Demographic attributes allowed the evaluation of the effect of harvesting in natural populations of brown macroalgae (e.g., Thompson et al. 2010, Omoregie et al. 2010, Ugarte 2011, Ugarte and Sharp 2012), as well as the effects caused by natural disturbances (Martínez et al. 2003, Vega et al. 2005, Vásquez et al. 2006) or anthropogenic activities (Correa et al. 2006). Recently, Vásquez et al. (2012) suggested that the sustainability of wild populations of *L. nigrescens* in northern Chile would be supported by "good harvesting practices." In this context, demographic parameters used for *L. nigrescens* could serve as ecological indicators for: (1) evaluating the application of good harvesting practices agreed upon by fishermen, (2) comparing the effect of harvesting in areas with different administration measures, (3) monitoring the sustainability of exploited kelps, and (4) establishing precautionary or recovery measures in relation to the abundance and distribution of commercially important brown macroalgae.

The administration of the Chilean coast includes two basic schemes (see Castilla et al. 2007, Gelcich et al. 2009, Marín et al. 2012): (1) Management Areas for Exploitation of Benthic Resources (MAEBR), in which organized artisanal fishermen receive usage rights for a section of the coast, establishing co-management measures (government–fishermen) regarding the resources that they extract and (2) Open Access Areas (OAA), which are sections of the coast where access for artisanal fishermen is unrestricted. Almost 95 % of total landing of brown macroalgae (26° to 32° S) comes from OAA, and only 5 % from MAEBR (Subsecretary of Fishing and Aquaculture 2012). On the other hand, several marine protected areas (MPA) located in the area of main brown seaweed production restrict the harvest and collection of brown seaweeds of economic importance (Tognelli et al. 2009).

Considering that (1) the management program of economically important brown macroalgae has a non-preventive focus based on "good harvesting practices" of artisanal fisherman (see Vásquez 2008), and (2) good harvesting practices are regulations that should be applied both in OAA and MAEBR, and (3) there are areas with restricted harvest and collection (MPA), these scenarios offer a unique opportunity to evaluate the operation of the management plan of *L. nigrescens*, based on the "it is more important how you harvest than how much you harvest" strategy (see Vásquez 2008, Vásquez et al. 2012).

Given that harvesting done by artisanal fishermen affects the demographic parameters of natural populations of *L. nigrescens* strongly in OAA, less in MAEBR, and not at all in MPA, this study evaluates the use of demographic parameters (density, biomass, and size structure) of *L. nigrescens* as ecological indicators to monitor brown macroalgae harvest in northern Chile. With these ecological indicators, preventive harvesting limits are proposed to facilitate decision of stakeholders and policy makers to contribute to the sustainability of natural kelp forests, especially in areas with free access for artisanal fisherman.

Materials and methods

Study area This study was carried out along the northern Chilean coast between 26° and 32°S (Fig. 1), where historically most of *L. nigrescens* harvesting is done (see Tellier et al. 2011, Vásquez et al. 2012). *L. nigrescens* makes up a continuous belt in the exposed rocky intertidal area, and varies in vertical extension and relative abundance depending on the extension of rocky intertidal platforms and wave exposure (Vásquez and Vega 2004).

Four study areas were selected: Totoral Bajo (27,757° S–71,064° W), Caleta Angosta (28,250° S–71,163° W), Lagunillas (30,103° S–71,383° W), and Talquilla (30,864° S–71,683° W). For the evaluation of harvested populations, we considered MAEBR and OAA (Fig. 1). Also, two MPAs with prohibition of extraction and harvesting (Tognelli et al. 2009) were evaluated: Isla Grande de Atacama (27,248° S–70,974° W) and Isla Choros Marine Reserve (29,259° S–71, 535° W).

Landings of the *L. nigrescens* harvest between 1980 and 2011 were obtained from the National Fishery Service (www.sernapesca.cl).

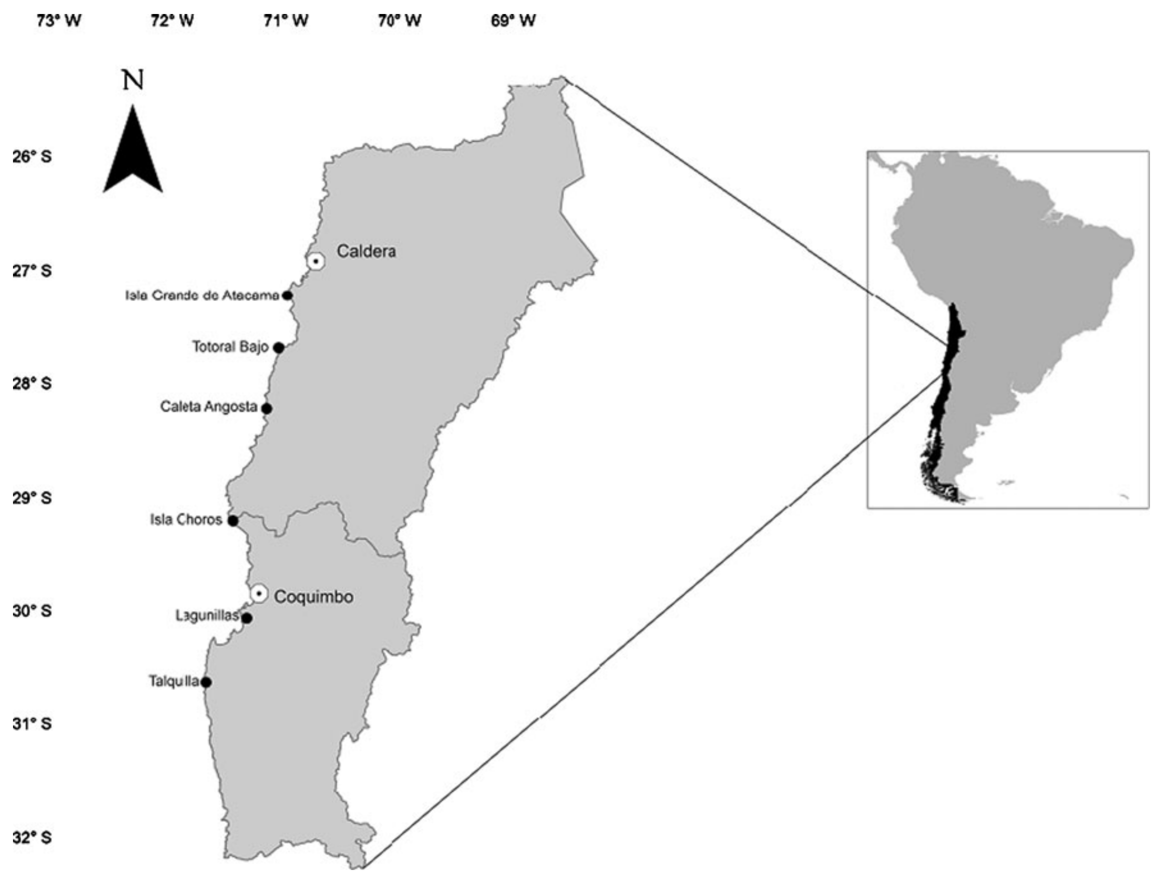

Fig. 1 Study area and sites

In each study site, density and biomass were evaluated for adult plants (>20-cm holdfast diameter), juveniles (>5- to <10-cm holdfast diameter) and recruits (<5-cm holdfast diameter). Size structure was established using the largest diameter of the holdfast. Also, the number of stipes and the total length of the plant were evaluated. The population parameters were monitored seasonally during 2 years and compared between *L. nigrescens* populations in OAA, in management areas for exploitation benthic resource MAEBR, and in marine protected areas MPA.

Adult and recruit plant density (Number of plants square meters) were estimated using three 10×1-m belt transects parallel to the coast, which spanned the average width of the intertidal belt of *L. nigrescens*. Plants greater than or equal to 20 cm in holdfast diameter with or without reproductive structures were considered adults (Santelices 1982, Vásquez et al. 2012). In accordance with the management plan, the adult plants represent the harvestable segment of the population (Vásquez 2008). Inside each transect, three 1-m^2 quadrats were randomly selected to measure the different morphological variables of the sporophyte (holdfast diameter, maximum length, and number of stipes). Biomass was estimated indirectly from measurements of holdfast diameter in each quadrant using an exponential regression model (Santelices et al. 1980). This function uses the largest holdfast diameter (Dl) to estimate the total wet weight (Wt) of the plant (kg) using the equation $Wt = a \cdot Dl^b$, wherein a is the intercept and b is the slope of the exponential equation. In each kelp population a minimum of 50 plants of all sizes was harvested randomly to create a size-weight relationship curve.

Due to recent studies that have described holdfast fusion between *L. nigrescens* sporophytes (González et al. 2013, Rodriguez et al. 2013), for the purposes of this study, an individual was defined as a sporophyte made up of a group of stipes that come from one holdfast.

Statistical analyses Plant density (adults and recruits) and biomass were contrasted between *L. nigrescens* populations under different resource administration regimens (OAA, MAEBR, MPA) or between kelp beds (OAA and MAEBR: Totoral bajo, Caleta Angosta, Lagunillas, and Talquilla; MPA: Isla Grande de Atacama and Isla Choros), and between seasons using a two-way analysis of variance (ANOVA; Sokal and Rohlf 1981). The study sites were grouped into OAA, MAEBR, and MPA to evaluate the effects of administration measures on demographic parameters. The normal distribution and homoscedasticity of the variance were verified using a Barlett test and a Lilliefors test (Sokal and Rohlf 1981).

Results

The temporal tendency of the brown macroalgae harvest shows an accelerated increase since the year 2000 (Fig. 2a). During the last decade, almost 80 % of the annual landing comes from harvest of *L. nigrescens* (Fig. 2a). The landing of this resource is throughout the year, and has a seasonal pattern with maximum harvest during the summer and minimum harvest during the winter (Fig. 2b). In the last decade, the *L. nigrescens* landing in the study area (26 to 32° S) has had a similar trend to the national landings, representing 66±10 % of the monthly harvest during the year (Fig. 2).

The temporal variation of adult and recruit *L. nigrescens* plant density varies according to the type of administration regime of the studied population (Fig. 3, Table 1). In MPA, the annual renewal of kelp populations has a seasonal cycle wherein the natural mortality of adult plants is compensated by intense recruitment (Fig. 3a). In MAEBR, the density of adult plants decreases during the maximum harvest period, preferably executed in spring and summer; however, recruitment of juvenile plants post-harvest maintains the annual cycle of kelp renewal (Fig. 3b). In OAA, where the kelp harvest occurs all year, adult plant density is maintained significantly lower (Fig. 3c, Table 1).

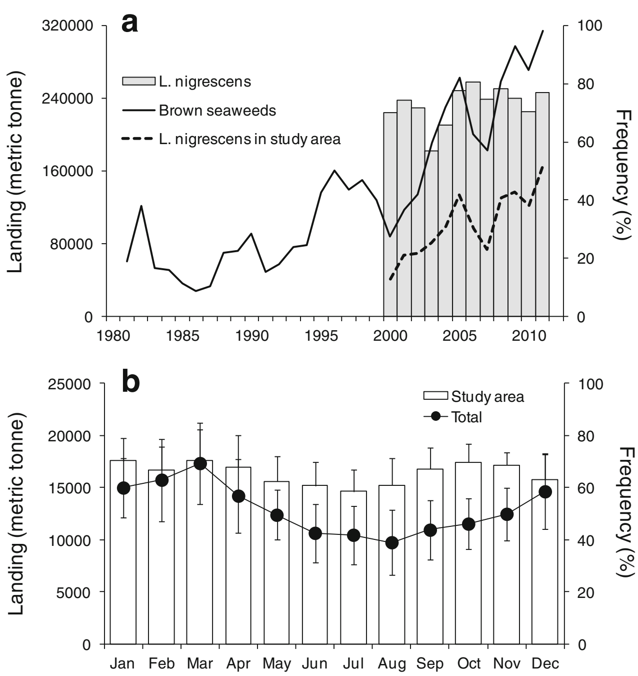

Fig. 2 Annual landing of brown macroalgae in Chile and study area (1980–2011) and percentage of annual participation of *Lessonia nigrescens* in the total yearly harvest since the year 2000 (**a**). Average monthly variation in the harvest of *L. nigrescens* and monthly percentage of participation in the total harvest in the study area (**b**). Mean±2 SE (2000–2011)

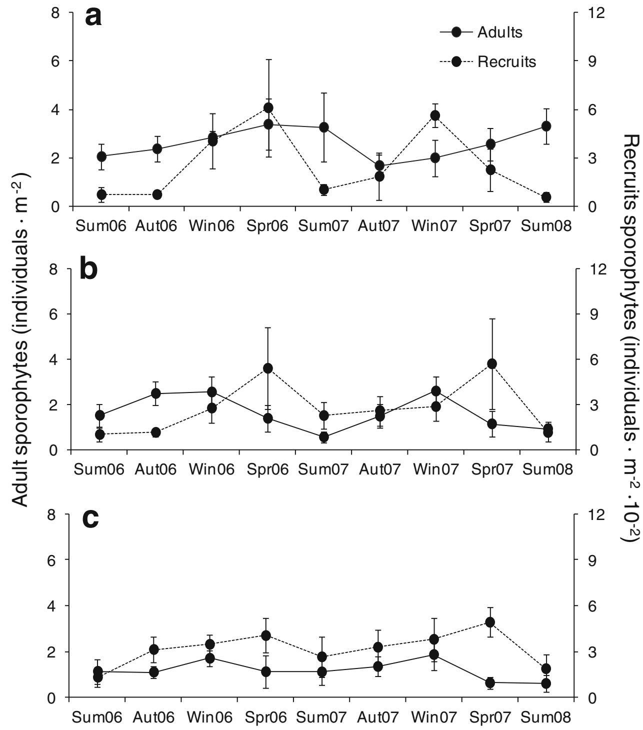

Fig. 3 Temporal variation in the density of *Lessonia nigrescens* plants adults and recruits in kelp beds located in marine protected areas (**a**), management areas for exploitation of benthic resources (**b**), and open access areas (**c**). Mean±2 SE

The density of adult plants is greatest in populations in the interior of MPA, in contrast to adult population densities in OAA (Fig. 4a, Table 1). In MAEBR, the seasonal harvest of *L. nigrescens* decreases the density of adult plants; however, the effect of harvesting is significantly less than that observed in OAA (Fig. 4a, Table 1). In open access areas studied, the density of adult plants is significantly less (Fig.4a, Table 1). One exception to this pattern observed in OAA is the population of *L. nigrescens* in Lagunillas, where the difficulty of access to the coastline generates a barrier to permanent harvest. However, average abundance of this OAA is similar to that found in Lagunillas MAEBR (Fig. 4a). Thus, Lagunillas represents an artificial management area because of the effect of geographically restricting artisanal fisherman access to coastline.

The density of *L. nigrescens* recruits inside MPA and MAEBR is similar in the two scenarios (Fig. 4b). In contrast, in OAA areas recruit density increased significantly in comparison to MAEBR (Table 1, Fig. 4b). In this context, the accumulated annual recruitment of *L. nigrescens* is almost 20 % greater in OAAs than in MAEBRs or MPAs.

In MPA, the available biomass of *L. nigrescens* is relatively constant throughout the annual cycle, oscillating around 50 kg m^{-2} (Fig. 5a). In contrast, the available biomass in MAEBR has a marked seasonality with an annual cycle of renewal of the kelp post-harvest during spring and summer (Fig. 5b). A

Table 1 Analysis of variance (ANOVA two-way) using the fisheries management regime or study sites (kelp beds), and time (season) as main factors to evaluate the hypothesis that the changing demographic parameters of *Lessonia nigrescens* in Open Access Areas is due to strong pressure from harvest

Factor	Sums of squares	df	Mean square	*F* value	*p* Value
Adult density					
Administration Regimen (AR)	10.34	2	5.17	48.62	0.0001
Time (T)	3.86	8	0.48	4.54	0.0001
AR × T	6.45	16	0.40	3.79	0.0001
Error	24.56	231	0.11		
Factor	Sums of squares	df	Mean square	*F* value	*p* Value
Kelp bed (KB)	14.40	9	1.60	26.04	0.0001
Time (T)	6.84	8	0.85	13.91	0.0001
KB × T	17.29	72	0.24	3.91	0.0001
Error	11.06	180	0.06		
Recruit density					
Factor	Sums of squares	df	Mean square	*F* value	*p* Value
Administration Regimen (AR)	3.46	2	1.73	10.97	0.0001
Time (T)	14.59	8	1.82	11.57	0.0001
AR × T	7.19	16	0.45	2.85	0.0003
Error	38.30	243	0.16		
Factor	Sums of squares	df	Mean square	*F* value	*p* Value
Kelp bed (KB)	12.21	9	1.36	14.15	0.0001
Time (T)	11.62	8	1.45	15.16	0.0001
KB × T	19.49	72	0.27	2.82	0.0001
Error	17.26	180	0.10		
Biomass					
Factor	Sums of squares	df	Mean square	*F* value	*p* Value
Administration Regimen (AR)	138.00	2	69.00	173.79	0.0001
Time (T)	47.15	8	5.89	14.84	0.0001
AR × T	30.94	16	1.93	4.87	0.0001
Error	310.87	783	0.40		
Factor	Sums of squares	df	Mean square	*F* value	*p* Value
Kelp bed (KB)	178.17	9	19.80	70.30	0.0001
Time (T)	74.56	8	9.32	33.10	0.0001
KB × T	98.90	72	1.37	4.88	0.0001
Error	202.74	720	0.28		

AR Administration Regime, *OAA* Open Access Area, *MAEBR* Management Area, and *MPA* Marine Protected Area

similar tendency is observed in OAA, but with a significantly less available biomass that does not surpass 25 kg m^{-2} (Table 1, Fig. 5c). Available biomass is greatest in MPA populations and least in OAA populations (Table 1, Fig. 6). In MAEBR and OAA, the available biomass decreases by 50 and 65 %, respectively, in comparison to the stocks in MPA. The size structure of *L. nigrescens* populations varies according to the type of administration regime (Fig. 7). In MPA, 20 % of the populations are recruits and 35 % are juveniles, and the rest of adults had a mode of 27.5-cm holdfast diameter with a tail in the size distribution due to large-sized plants (Fig. 7). In MAEBR and OAA, the recruits represent 35 % of the population, while juvenile plants represent 45 % in MAEBR and 55 % in OAA (Fig. 7).

Considering that the minimum size of harvest in the management plan corresponds to plants of *L. nigrescens* with a diameter of 20 cm of the holdfast, in MPA, the portion of adult plants available for harvesting was 45 % of the population (Fig. 8). In MAEBR, the harvestable portion was 25 % of the total available biomass. By contrast, in OAA the available biomass for commercial harvesting did not exceed 10 % of the total plants in any studied population, except in Lagunillas, where the available and harvestable biomass in OAA was similar to that of MAEBR.

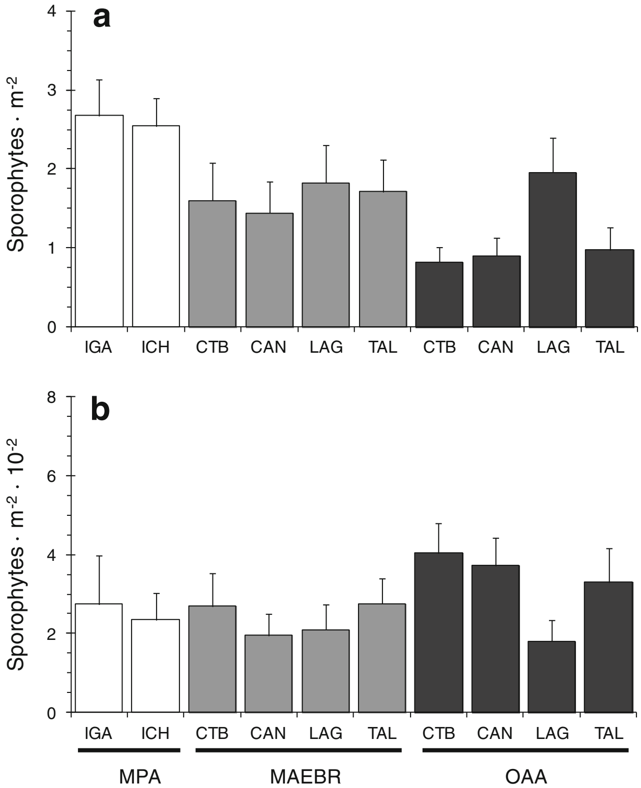

Fig. 4 Spatial variation in the density of *Lessonia nigrescens* adult plants (**a**) and recruits (**b**) in kelp beds located in marine protects areas (*MPA*), management areas (*MAEBR*), and open access areas (*OAA*). Acronyms for the study sites are *IGA* Isla Grande Atacama, *ICH* Isla Choros, *CTB* Totoral Bajo, *CAN* Caleta Angosta, *LAG* Lagunillas, and *TAL* Talquilla. Mean±2 SE

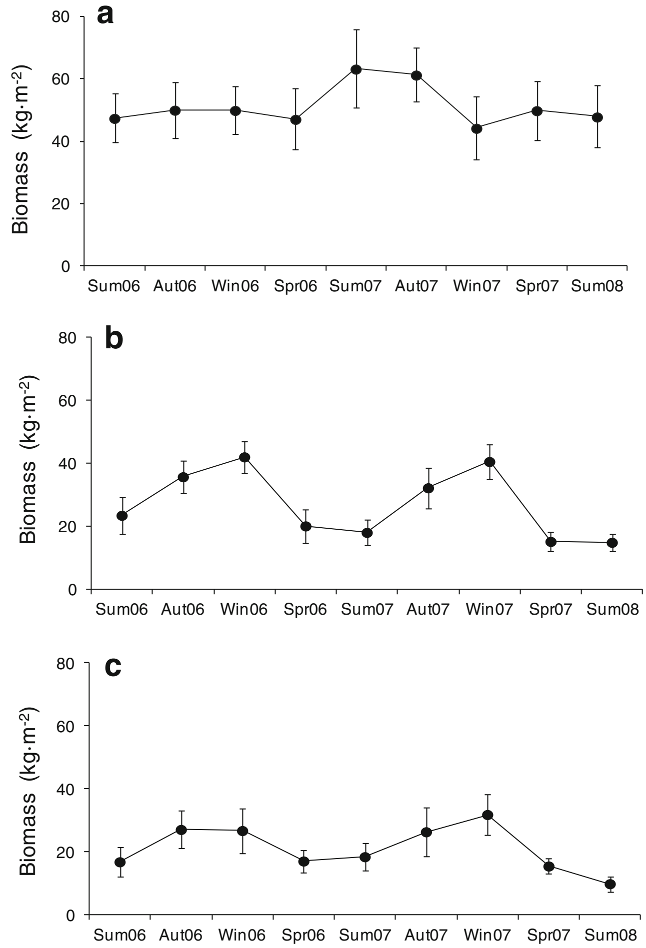

Fig. 5 Temporal variation of *Lessonia nigrescens* biomass in kelp beds located in marine protected areas (**a**), management areas for exploitation of benthic resources (**b**), and open access areas (**c**). Mean±2 SE

Discussion

The demographic parameters that allow characterization of natural populations of *L. nigrescens* vary according to the effect of artisanal harvests in coastal areas with different administration regimes along the coast of northern Chile. Inside marine protected areas (MPAs or "no harvest" marine reserves), recruitment, density, and biomass of *L. nigrescens* have temporal patterns similar to those described at the start of brown macroalgae extraction in Chile in the year 2000 (see Santelices et al. 1980 Santelices 1982, Santelices and Ojeda 1984, Camus 1994, Westermeier et al. 1994). These seasonal patterns persist in *L. nigrescens* populations in benthic resource management areas (MAEBR), where harvest is regulated according to "good practices" and surveillance by users (see Gelcich et al. 2009). However, the harvest selectively affects size structure of populations and fluctuation of available biomass. By contrast, in OAAs, which also use "good harvesting practices," the lack of surveillance or assignments of use and property to artisanal fisherman organizations promotes an indiscriminate harvest, significantly affecting size structure and the population dynamic of *L. nigrescens*. In OAAs, density, available biomass of adult plants, and other demographic parameters are significantly different than those of MAEBRs and MPAs.

In MAEBRs and OAAs, the densities of adult *L. nigrescens* plants diminish during spring and summer, coinciding with the period of greatest extraction pressure. The availability of substrata post-harvest favors continued recruitment throughout the year. In OAAs, recruitment of sporophytes is constant throughout the year, boosted by the constant removal of adults which generates free primary space for propagule settlement. This continuous recruitment pattern differs from the seasonal recruitment pattern observed in MAEBRs and MPAs. Thus, the accumulated annual recruitment of *L. nigrescens* is almost 20 % greater in OAAs than in MAEBRs or MPAs. This constant recruitment is a population strategy meant to reestablish the fraction of adult *L. nigrescens* plants in populations subjected to successional and ecological processes that facilitate settlement and growth of recruits (Santelices and Ojeda 1984 Camus 1994). A guild of intertidal grazers (e.g., *Tegula atra*, *Fissurella* spp.,

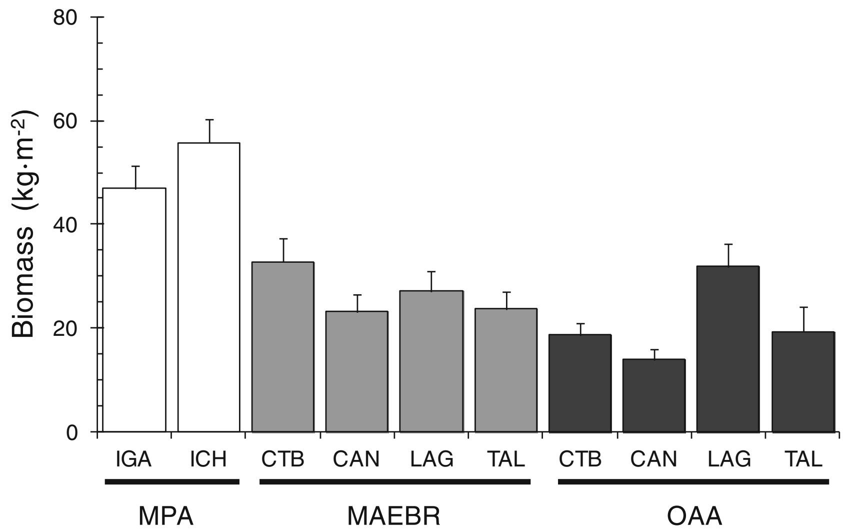

Fig. 6 Spatial variation of *Lessonia nigrescens* biomass in kelp beds located in marine protected areas (*MPA*), management areas (*MAEBR*), and open access areas (*OAA*). Acronyms for the study sites are similar to Fig. 4. Mean±2 SE

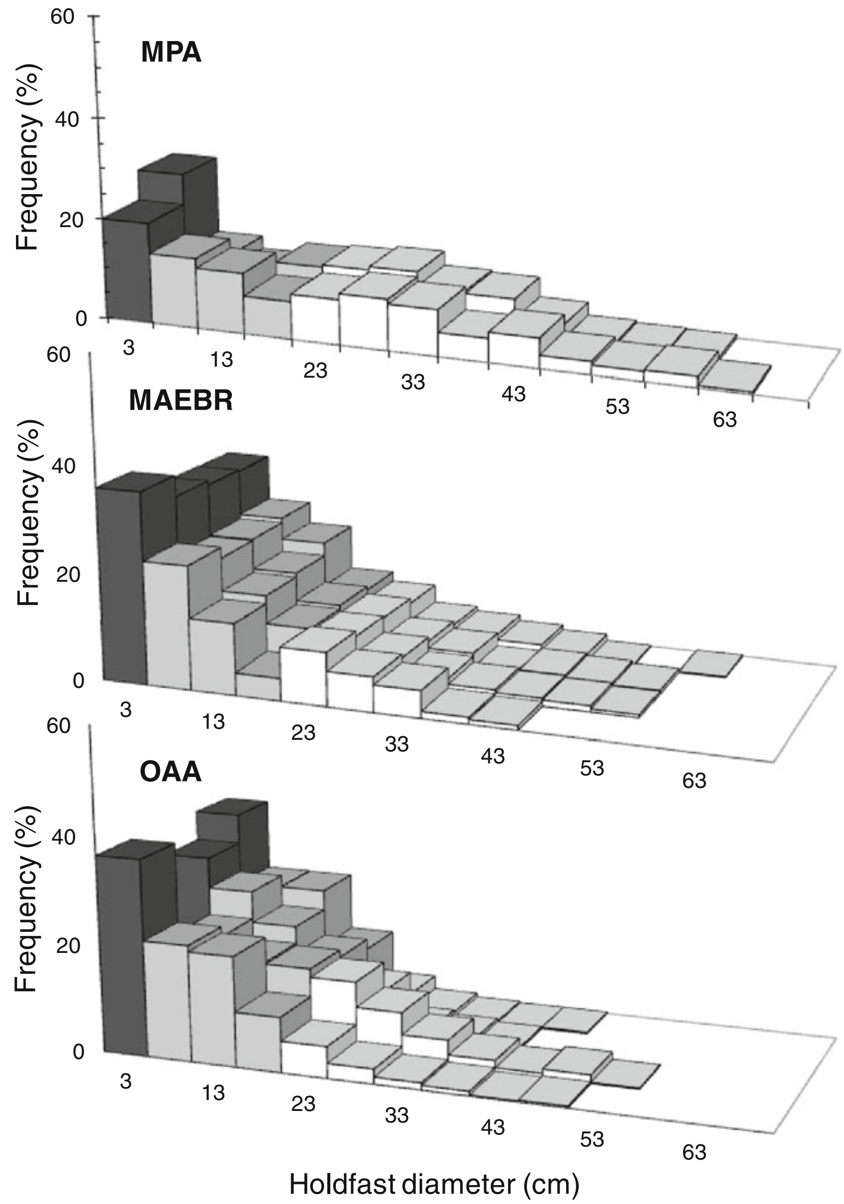

Fig. 7 Population structure of *Lessonia nigrescens* in kelp beds located in marine protects areas (MPA), management areas (MAEBR), and open access areas (OAA). The *black bars* indicate recruits (<5 cm), the *gray bars* indicate juvenile plants (without reproductive structures, <20 cm in holdfast diameter), and the *white bars* indicate adult plants (with reproductive structures, > 20 cm in holdfast diameter). Acronyms for the study sites are similar to Fig. 4

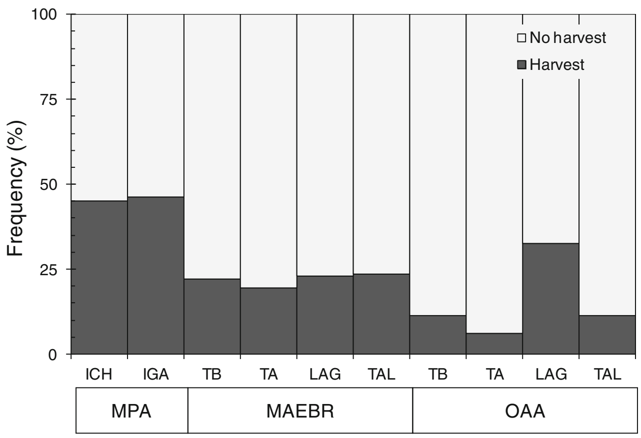

Fig. 8 Percentage of non-harvestable *Lessonia nigrescens* plants (<20 cm in holdfast diameter) and harvestable plants (>20 cm in holdfast diameter) in kelp beds located in marine protected areas (*MPA*), management areas (*MAEBR*), and open access areas (*OAA*). Acronyms for the study sites are similar to Fig. 4

Enoplochiton niger) produces an aggregate spatial distribution of juvenile plants of *L. nigrescens* (Santelices and Ojeda 1984, Camus 1994). Recently, Rodriguez et al. (2013) showed that this grouped distribution promotes fusion between individuals. These fusion or coalescence processes (see González et al. 2013) increase holdfast size, forming individuals of harvestable size (>20-cm holdfast diameter), but which, however, lack reproductive structures and have not contributed to replacement of the population (Rodriguez et al. 2013), putting at risk renewal of kelp bed. Experiments done with *Postelsia palmaeformis* suggest that a reduction in population size because of harvesting can modify demographic processes, increasing the risk of extinction of local kelp beds (Wootton and Pfister 2013).

González et al. (2012) suggested that *L. nigrescens*, a cryptic species recently separated into two other species (see Tellier et al. 2011), has also different responses to harvesting pressure. This study shows no differences on the demographic parameters of both species used as ecological indicators to test the effects of harvest on MAEBRs and OAAs scenarios. However, study on population dynamics of *L. berteroana* and *L. spicata* would be necessary to solve this question, mainly in coastal areas with high impact of brown seaweed fishery.

In MAEBR, good harvesting practices allow temporal sustainability of *L. nigrescens* populations. The fraction of reproductive adults in the population is renewed yearly due to recruitment, with a biomass production that represents a good indicator of the permissible limit for sustainable exploitation. By contrast, in OAA, the strong harvesting pressure on local populations produces a decrease in the portion of adults and also enables dominance of juveniles and recruits in the population structure. The lack of the capability of populations of other kelp species to renew their adult fraction has had deleterious effects on biomass production for productive purposes (Omoregie et al. 2010, Thompson et al. 2010, Frangoudes 2011, Ugarte and Sharp 2012, Wootton and Pfister 2013). These effects tend to worsen over time and have negative impacts for the ecosystem (Seeley and Schlesinger 2012). One way to avoid the negative effects of intensive harvesting in benthic resource populations is by rotating areas, establishing recess periods between harvesting periods (Vásquez 1995, 2008; Ugarte 2011, Ugarte and Sharp 2012). In this scheme, seasonal monitoring of demographic parameters gives fishermen and administrators criteria to decide when to start to harvest and when to stop. At the same time, these criteria inform the recommendable length of the recess period, which is necessary for the growth of juvenile plants, recruitment, renewal of the harvested population, and the start of productive activities.

The management recommendations were spread among fishermen and adopted voluntarily as an alternative to the traditional preventive method, in which the fishing authority imposes a capture quota of a percentage of the total available biomass (Subsecretary of Fishing and Aquaculture 2012, Vásquez et al. 2012). However, the correct application of the management recommendations in MAEBR seems to be related to the social capital that co-management generates (Marín et al. 2012), a concept that does not make sense in OAA where harvesting activity is individual and difficult to enforce (Vásquez 2008). The length of the littoral zone and restrictions to access increase the cost of enforcement and decrease the efficacy of control of the fishing authority (Frangoudes 2011). Therefore, the construction of participative awareness is a key factor in the conservation of natural populations of brown macroalgae and the sustainability of this resource in Chile (Vásquez et al. 2012). Thus, it will be necessary to make progress in areas such as: (a) perfection of the capacities of commercial management by using social capital, (b) optimization of control mechanisms and enforcement considering the idiosyncrasy of artisanal fishermen, (c) improvement of information flow between and among the different actors in the productive chain and the authorities, and (d) establishment of controlled extraction of brown macroalgae by using management plans from territorial perspective.

A participative, adaptive, and multidisciplinary management plan requires ecological indicators that monitor administrative measures agreed upon by the direct users of *Lessonia* resource. Considering that these ecological indicators need to be validated (Garcia and Cochrane 2005), they can be selected from administrative measures regarding brown macroalgae such as volume harvested, capture per amount of effort, and minimum legal size of capture (Tapia 2002, Vásquez 2008, Table 2). Landing of volume harvested is an easy indicator to monitor and verify but requires an efficient, participative recording system, in real time, that allows for use of the information at the right moment (Table 2). Recently, a pilot program for

Table 2 Fisheries variables proposed to monitor the harvest of *Lessonia nigrescens* in Open Access Areas (OAA) of northern Chile

Resource variable	Description	Time regime	Decision policy	Verification source	Additional requirements	Investment items
Landing (kg)	Fishing/harvesting area	Permanent (daily capture)	When the fishing quota is reached, stop the harvest	Artisanal fishing form (DA)	Implementation of an electronic registration system for harvest/landing	Implementation, maintenance of electronic equipment. Training
Capture per unit effort (CPUE)	Capture per unit effort (Kg/hour/fisherman) per bed or area. Fishing gear: "barreta"	Permanent (monthly)	When the CPUE is >150 kg/fisherman/ hour (Fishing ban, extraction area rotation, change fishing gear)	Scientific survey, landing register, fishermen statistics	Implementation of a CPUE registration system by area	Monitors for recording landing information. Training
Minimum legal size of capture (MLS)	Morphological variable: holdfast diameter. MLS 20 cm	Permanent (seasonal)	When MLS of holdfast diameter is ≤20 cm (change harvesting area, fishing ban)	Scientific survey, landing register, fishermen statistics	Implementation of a registration system of MLS by area	Monitors for recording landing information. Training

electronic self-service to find out the accreditation of the origin of fishing resources has been implemented (Vásquez 2013), generating, among other advances, improvements in landing statistics in real time. Capture per amount of effort and minimum legal size are indicators that are comparatively more complex to monitor and enforce, because they depend on the participation of scientific observers and the interest of fishermen to create these types of records (Table 2). These indicators are useful tools to assign harvest quotas, establish rotation areas, or to establish extractive or biological bans.

In a scenario of high demand for biomass, the effect of harvesting in OAA has been explained by the absence of preventive management measures (Vásquez and Westermeier 1993, Thiel et al. 2007, Thompson et al. 2010, Ugarte 2011). Thus, management based on a "good harvesting practice" requires ecological indicators sensitive to harvesting pressure, and which permit the establishment of decision criteria that are easy to observe, communicate, and measure by scientific observers and/or artisanal fishermen. Demographic attributes such as density of adult plants, biomass per unit of area, recruitment, and size structure are indicators that are easy to obtain and can be evaluated along spatial and temporal gradients (Table 3).

The rule based on demographic indicators establishes that the harvest in OAA should begin when the abundance and biomass per square meter of a population is close to biomass or demographic levels detected in an un-intervened population (e.g.. MPA), where there is a minimal density of recruits, the portion of adult plants is above 40 % of the total population,

Table 3 Demographic variables proposed to monitor the harvest of *Lessonia nigrescens* in Open Access Areas (OAA) of northern Chile

Demographic variable	Description	Time period	Decision policy (criteria)		Verification source	Additional requirements	Investment items
			Harvest	No harvest			
Density of adult plants >20-cm holdfast diameter	Number of plants per square meter	Permanent (seasonal)	When the adult plant density is ≥2.0 plants m^{-2}	When the adult plant density is ≤1.5 plants m^{-2}	Landing from fishermen, Scientific survey	Implementation of a registration system by harvesting area, zone, or region	Training for registration system. Scientific survey.
Biomass	Kilograms per square meter		When the biomass is ≥25 kg m^{-2}	When the biomass is<20 kg m^{-2}			
Recruitment	Number of recruits square meter ≤1-cm holdfast diameter		When the number of recruits is ≤5 plants square meter	When the number of recruits is >40 plants square meter			
Size structure of populations in natural beds	Population size structure using holdfast diameter as morphological indicators		When the standing crops is ≥30 % of standing stock	When the standing crops is ≤20 % of standing stock			

and the percentage of remaining adult plants in the area is enough to generate post-harvest recruitment (Table 3). Afterwards, once the abundance and biomass per square meter in the population reaches levels similar to those found in a population under intense harvesting pressure (e.g., OAA), the sustainability of the population will depend on the stability of the frequency of recruits, on the maintenance of a stock of reproductive adults, and on whether the harvesting frequency is not intensified. Once these indicators have been exceeded, the harvesting period should end, followed by a recess period (ban or quotas), until pre-harvest levels have been reached (Table 3). Thus, the installation of a permanent monitoring program of the populations of *L. nigrescens* in OAA and in MAEBR, using demographic indicators, will allow the following: (a) validation of the application of management plans, (b) detection of the deleterious effects on population dynamics produced by exogenous disturbances in the harvest, (c) respect of the necessary period to renew the kelp to optimal harvesting levels, and, if necessary, (d) determination of extraction quotas by sector, and (e) establishment of extraction bans in a justifiable, participative, and localized way.

The landings of brown macroalgae in Chile reaches 300, 000 wet t year^{-1} (Vásquez et al. 2012) and is the world's largest landings from natural populations. This fishery is managed under the concept of "good practices," based on biological and ecological knowledge of the species (Santelices et al. 1980, Santelices 1982, Santelices and Ojeda 1984, Vasquez and Santelices 1990, Camus 1994; Martínez et al. 2003, Thiel et al. 2007, Vásquez 1995, 2008). Most of the brown macroalgae are foundation species of marine ecosystems (Graham et al. 2007), form the basis of coastal food webs (Halpern et al. 2006), contribute significantly to the total biomass of the ecosystem (Santelices et al. 1980, Santelices and Ojeda 1984), and are highly connected with all trophic levels (Seeley and Schlesinger 2012), providing shelter, food, nursery, and breeding areas (Santelices et al. 1980, Vásquez and Santelices 1984, Vásquez and Vega 2004). Indiscriminate harvest of foundation species as *L. nigrescens* can generate a significant impact on the ecosystem with unknown effects (Seeley and Schlesinger 2012). In this context, ecological indicators proposed in this study are tools for stakeholders and policy makers, enabling greater sustainability of exposed rocky shores in cold temperate seas of the world where brown macroalgae of economic importance are dominant organisms in cover and biomass.

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