
MODELLING SHORT-TERM DYNAMIC BEHAVIOUR OF THE SURF CLAM (*Mesodesma donacium*) FISHERY IN NORTHERN CHILE USING STATIC AND DYNAMIC CATCHABILITY HYPOTHESES

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Ideally, fishery modeling may be used to predict the effects of management methods and regulations applied to a given fishery (Hilborn and Walters, 1992; Seijo *et al.*, 1997). All models are, however, based on fundamental assumptions. One of these is related to the spatial/temporal constancy of the catchability coefficient (q), defined as a technical coefficient that represents the proportion of individuals of a stock captured per unit effort applied (Peterman and Steer, 1981; Gulland, 1983).

From this point of view the catch per unit effort (CPUE) is the result of a relation between the level of biomass of the stock and the catchability coefficient (Arreguín-Sánchez, 1996). Thus, in absence of a direct assessment (fishing surveys, for example) the biomass of the population, an important variable in fisheries management that cannot be directly observed, may be inferred by means of an observable indicator such as the CPUE and from knowledge of the catchability coefficient (Richards and Schnute, 1986; Crecco and Overholtz, 1990; Ye and Mohammed, 1999). However, there have been failures with the assumption of constant catchability (Winters and Wheeler, 1985; Crecco and Overholtz, 1990). In fact, a large variability of this coefficient can be

found in the literature due to, among other factors, the behavior of the resource in aspects such as reproductive aggregation, patterns of abundance in space and time (Ulltang, 1976; Peterman and Steer, 1981), changes in fishing power (Gulland, 1983) or in the distribution area (Winters and Wheeler, 1985) associated with environmental factors (Swain *et al.*, 2000). These factors should influence the proportion of stock removed per unit of effort applied. Simultaneous space-time variability has been reported for q . Evidence was recently presented (Pérez and Defeo, 2003) which suggested spatial and temporal variability in q in the fishery of the nylon shrimp *Heterocarpus reedi* in Chile's northern zone. The implications of this variability of q in modelling of fisheries have not been evaluated as yet, although it has been proposed that the biomass would decrease at a higher rate than calculated following a model based on the supposition of a constant q (Pérez, 1996; Chávez, 2000). Also, the effect on estimates of the performance variables of the model based on the variability of the estimations of q (static or dynamic) needs to be evaluated. In general, only the trajectories of the performance variables which have been obtained by deterministic analyses have been reported, without considering errors associated with the models.

In order to evaluate the effect of uncertainty associated with the estimation of q on two indirect estimates of a stock of the bivalve *Mesodesma donacium* in Coquimbo Bay, Chile (29°55'S), two methods based on different hypotheses or assumptions about q were used: i) assumes this coefficient to be constant over time, and as such it is used to evaluate the dynamics of the stock, while ii) supposes a density dependence in the local abundance of the resource; that is, as the biomass of the resource declines, the catchability increases. The alternatives concerning the static or dynamic nature of the catchability were separately incorporated into a modified depletion model which utilized data from the *M. donacium* fishery. Finally, the expected values for the models based on each one of the hypothesis and its uncertainty associated with direct observations from the fishery under typical conditions in the field were compared.

Materials and Methods

M. donacium and its fishery

The surf clam *Mesodesma donacium* inhabits sandy beaches 0-5m deep. In Chile, fishermen operating from 24ft boats with outboard motors harvest the clam using a semiautonomous

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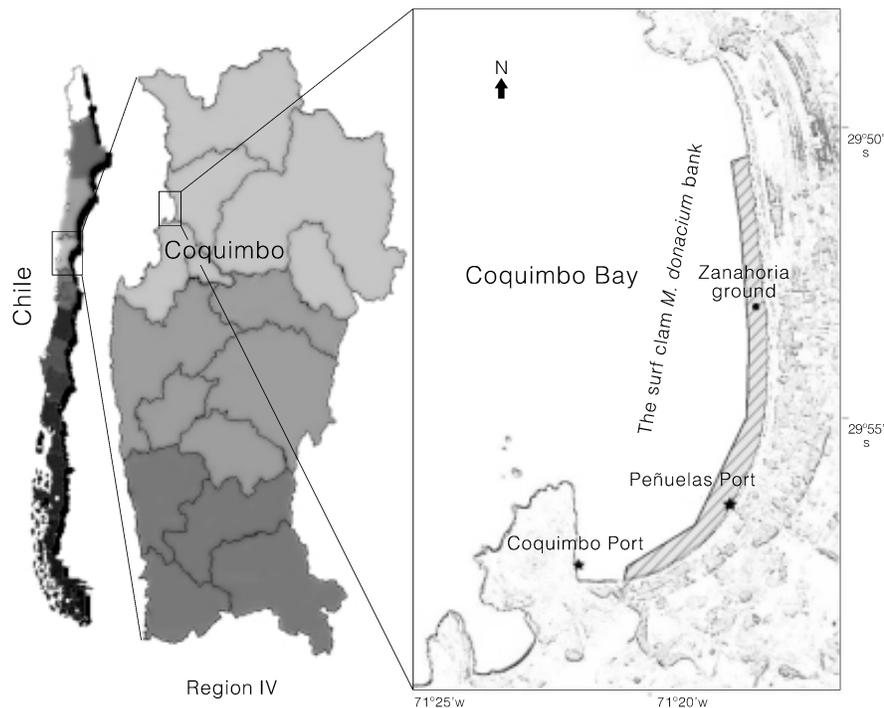


Figure 1. Location of Coquimbo Bay, ports and fishing grounds mentioned in the text.

diving hookah. In many localities, in addition to divers, fishermen operating from the beach, called “orilleros”, exploit that fraction of the resource at depths of 0-1.5m. The fishery operates under an open-access regime with one regulation: a minimum size restriction of 60mm of valve length. There is an exception, however, in Coquimbo Bay (Figure 1; Pérez, 1996), where the resource has been subject to a community based management since 1989 (Ariz *et al.*, 1994). The community has established a license quota of 64 small-scale boats. This voluntary collective action has been recognised and backed by the New Law of Fishery and Aquaculture, in force since 1991 (Castilla, 1994). Nevertheless, the law establishes that this method of self-regulation can be legal only if there has been a technical analysis previously approved by authorities. As a consequence, some fleet dynamic analyses and sample programs have been implemented. In Coquimbo Bay the fleet operates an average of 3 days per week (156 days per year) with annual landings of around 1500tons per year. There is no information about the activity of “orilleros”, but total landings of 600ton per year are estimated (Pérez *et al.*, 1998).

The area of distribution of the resource on the bank is approximately $1.5 \times 10^6 \text{m}^2$ (Ariz *et al.*, 1994; Pérez, 1996; Chávez, 2000). The intensity of the fishery is spatially heterogeneous (Pérez, 1996) and different harvesting

grounds can be clearly identified based on the CPUE of each area (Chávez, 2000). The method of operation of a diver includes collecting *M. donacium* individuals and placing them in tubular collector bags (“chinguillos”) which extend over the substrate as the diver advances. Once the bag is completely extended the diver returns to the initial position and repeats the collection in a different direction. The process is continued until the diver’s daily quota is filled. Pérez (1996) suggested that as the biomass diminished within a fishing ground, the area harvested by each diver was increased until a satisfactory capture was obtained; in this case the coefficient of catchability (*sensu* Baranov, 1918) increased as the resource decreased. This hypothesis was evaluated with the fishermen, and the length and width of the swept area by each diver was measured during his fishing operation. With this information it was possible to place a value on q over time in relation to the swept area, and thus obtain a value for q independent of its relation to either the CPUE or the biomass.

Dynamics of the CPUE with constant catchability

If the catchability does not change over time, the biomass at each time t is given by

$$B_{t+1} = (B_t + R_t) \exp^{-M} - C_t \quad (1)$$

where B_t : biomass (tons) and C_t : the previous capture at time t (in weeks, for this particular model), R_t : recruitment (in biomass terms) in time t , and M : natural weekly mortality as obtained by Pérez (1996) for the *M. donacium* bank in Coquimbo Bay ($M_t = 0.00865$ per week). The use of the expression $B \exp^{-M/2}$ in equation (1) is based on the assumption that all individuals in the stock have an average length and weight. This lets the above expression be equivalent to $B_t = N_{\text{long}} \bar{w} \exp^{-M}$, where N_{long} is the number of individuals of average length, and \bar{w} is the average weight at that length. In this way equation (1) becomes equivalent to the usual expression in terms of number of individuals (Kirkwood *et al.*, 2001; Restrepo, 2001).

The catch is obtained as

$$C_t = q E_t B_t \quad (2)$$

where q : catchability (per hour) and E_t : effort observed (hours of collection by diving) in time t .

The CPUE (kg per hour) is obtained using

$$\text{CPUE}_t = B_t q \quad (3)$$

The DeLury estimator was used for calculation of the static coefficient of catchability (Hilborn and Walters, 1992). This is based on a linear model to obtain the coefficient by relating the CPUE values observed and the cumulative effort observed by means of the expression

$$\ln(\text{CPUE}_t) = \ln(q B_t) - q \sum_{j=1}^{j=t} f_{j,t} \quad (4)$$

where $\ln(\text{CPUE}_t)$: natural log of the observed CPUE (kg per hour of diving) at time t , q : slope, B_t : biomass available before the first harvest, and $\sum_{j=1}^{j=t} f_{j,t}$: cumulative effort observed (hours diving) of divers from port j at time t . This is required since two organizations of artisanal fishermen operate in Coquimbo Bay. The main group operates in the Peñuelas sector using approximately 50 boats; a second fleet of about 14 boats operates in the Coquimbo sector about 8km north from the first (Figure 1). The efforts of both fleets were summed and considered in the calculations.

Dynamic of the CPUE with variable catchability

The variability of the catchability coefficient was calculated weekly using the equation of Baranov (1918) which established that

$$q_t = a_t / A \quad (5)$$

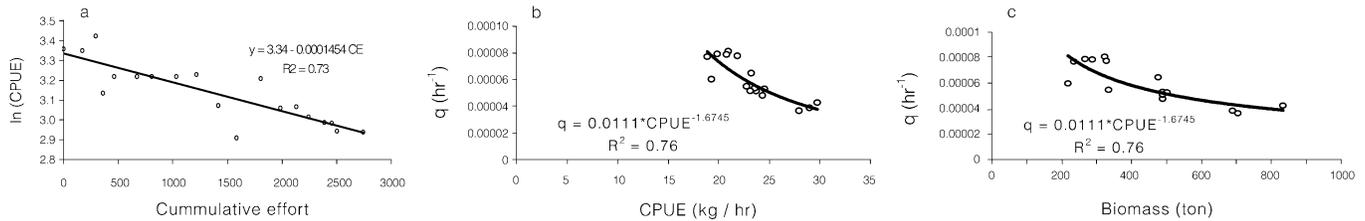


Figure 2. a: Static catchability coefficient calculated by DeLury method. b: Relation between CPUE and catchability. c: Relation between estimated biomass and catchability. All slopes are significant at $p < 0.05$.

where a_t : area harvested by the diver at time t . The expression A denotes the area of distribution of the resource. Caddy (1975) and Seijo *et al.* (1994) recommended this as a useful calculation tool for bottom-resource fisheries. Following this, the change in the value of q would be given by the function proposed by Pérez (1996), who defined the harvesting area of the diver as

$$a_t = (\text{SLC} \cdot W) \text{NCC}_t \quad (6)$$

where SLC: standard length of the collector bag used by the diver, W : width of the strip harvested by the diver in meters ($W = 1\text{m}$; Pérez, 1996), and NCC: number of changes in the position of the bag effected by the diver during his collection over time t . The data required for the calculations were obtained in coordination with divers according to a design agreed upon for collecting the information. The area of distribution of the resource (A) was taken from Ariz *et al.* (1994) and Chávez (2000).

In this case the dependency relationship between CPUE and catchability over time is given similarly to MacCall (1976), using CPUE as an indirect biomass index

$$q_t = \alpha \text{CPUE}_t^{-\beta} \quad (7)$$

where α and β are parameters. Given that CPUE_t is, in our interpretation, an indicator of relative abundance of the resource in time t , then the biomass at time t may be expressed as

$$B_t = \text{CPUE}_t / q_t \quad (8)$$

Substituting Eq. (4) in (5) leads to

$$B_t = \text{CPUE}_t / \alpha \text{CPUE}_t^{-\beta} \quad (9)$$

Similarly, in Eq. (2) and (4) the relation between biomass and catchability over time t can be directly modeled using equation (7) from MacCall (1976):

$$q_t = \chi B_t^{-\delta} \quad (10)$$

where χ and δ are parameters.

Analogous to the dynamic biomass model described for the catchability constant (Eq. 1) the model that

considers q as a variable, which is a function of the availability of biomass, would be given by

$$B_{t+1} = \{ [R_t + (\text{CPUE}_t / \alpha \text{CPUE}_t^{-\beta})] e^{-M_t} - \sum_{j=1}^{j=n} f_{0,j,t} \} B_t (\chi B_t^{-\delta}) \quad (11)$$

where $f_{0,j,t}$: observed effort for the port j at time t . From Eq. (8) the CPUE can be estimated as

$$\text{CPUE}_t = \{ B_t (\chi B_t^{-\delta}) \} \quad (12)$$

Thus, the term $\sum_{j=1}^{j=n} f_{0,j,t} \{ B_t (\chi B_t^{-\delta}) \}$ represents total catch at all ports j . The weekly catches, as well as the effort of both fleets were summed and considered in the calculation.

Inclusion of variability in estimations of the q parameter

The standard error (Zar, 1995) for the parameters of Eq. (4), (7) and (10) was calculated using non linear fit routines available in the SYSTAT 8.0 software. From these estimates of variability, 800 possible values of q were calculated by Monte Carlo analysis (Manly, 1991). Each of these values was entered into the respective simulation model, and the results were interpreted using “box and whiskers” plots.

Eq. (1) and (10) were parameterized using information based on the *M. donacium* fishery in Coquimbo Bay on the Northern Chilean coast (Figure 1).

More than 20 collecting grounds were identified within the bank

(Pérez, 1996; Chávez, 2000). However, in order to evaluate the usefulness of Eq. (1) and (11) only one of the important grounds (termed “Zanahoria” by the fishermen, Figure 1) was selected for study, based on its area and number of boat trips observed (Chávez, 2000).

Comparisons among the observed data and simulated output were made using percentiles and medians.

Results

Estimation of static and dynamic catchability

The analysis performed showed lower values when q was estimated through a dynamic approach. The DeLury method gave a catchability value of 0.0001454h^{-1} (Figure 2a), while the method based on Eq. (7) showed an inverse relation with lower values, between 0.00003 and 0.0008h^{-1} (Figure 2b). The same tendency was evident when contrasting catchability with estimated biomass (Figure 2c).

Error associated with the estimations

The standard error of the estimations of Eq. (4) was less (Table I) than those calculated for Eq. (7) and (10). Thus, for the slopes of these equations, the error with respect to the values estimated were 1% in the case of static q (Eq. 4) and 19% and 21%, respectively, for Eq. (7) and (10) in which a dynamic q was assumed.

TABLE I
SUMMARY OF PARAMETER ESTIMATIONS AND VARIABILITY
FROM EQUATIONS (4), (7) AND (10)

Equation	Parameter	Estimate	St. Error	Confidence Interval (95%)	
				Lower	Upper
(4)	a	3.34	0.0348	3.26	3.41
	b	-0.0001454	0.0000213	-0.0001902	-0.0001005
(7)	a	0.0092385	0.0086063	-0.0092203	0.0276972
	b	-1.6138215	0.3012282	-2.2598917	-0.9677512
(10)	c	0.0011725	0.0007301	-0.0003934	0.0027385
	d	-0.4980744	0.1056820	-0.7247398	-0.2714086

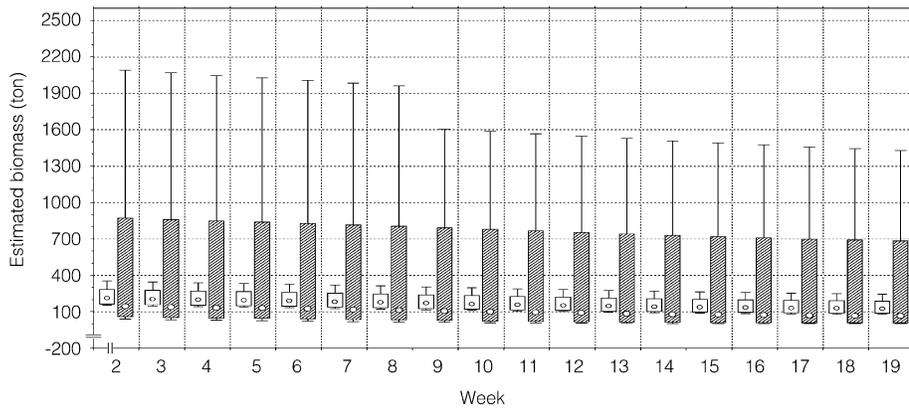


Figure 3. Dynamic trajectories of the biomass expected by the static (open boxes) and the dynamic (stripped boxes) model of q . The box represents 90% of the information, while the whisker represents 5% of the obtained value for the models. The symbols within the box indicate the median.

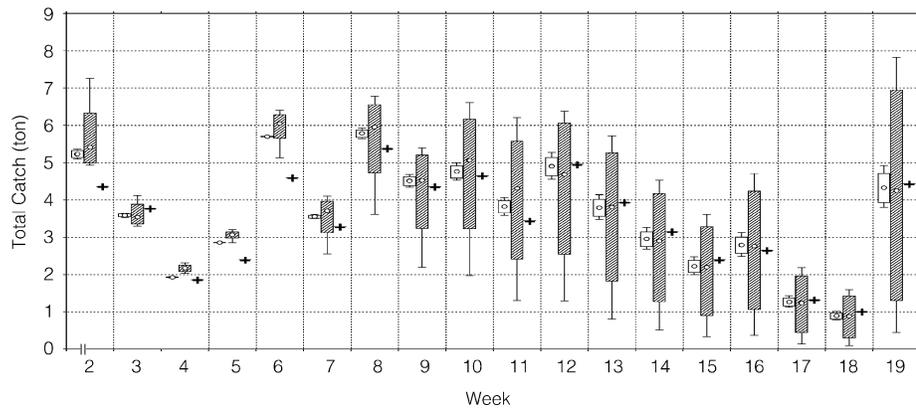


Figure 4. Dynamic trajectories of captures, showing directly observed catch (+), and catch predicted by the static (open boxes) and the dynamic (stripped boxes) model of q . The box represents 90% of the information, while the whisker represents 5% of the obtained value for the models. The symbols indicate the median.

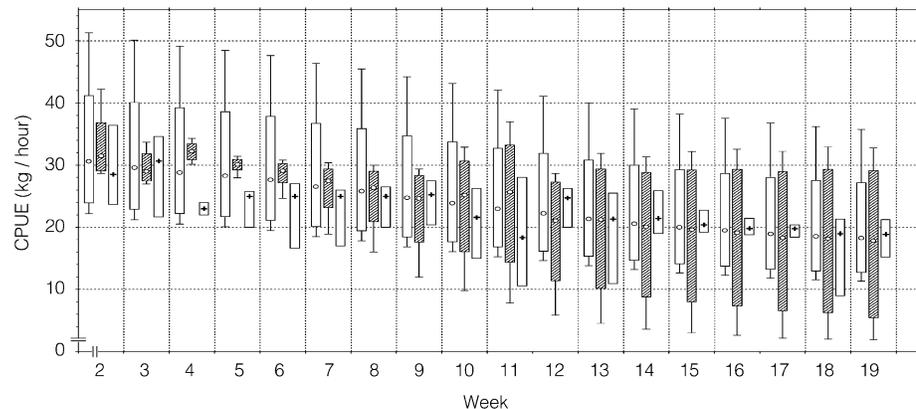


Figure 5. Dynamic trajectories of the directly observed CPUE (open box and +) and that predicted by the static (open box) and by the dynamic (stripped box) model of q . The box represents 90% of the information, while the whisker represents 5% of the obtained value for the models. The symbols within the box indicate the median.

As a result of the above, Eq. (7) and (10) produced negative values for the confidence interval, which was lower than the parameters a and c respectively (Table I). This implies a result of

negative biomass, which is obviously without meaning. Of the 800 iterations, 38 values fell within this category for each week simulated. These values were omitted from all subsequent calculations.

Comparison between results from the models and observations

Biomass. Figure 3 shows the distribution of 95% of the calculated data. Each “whisker” represents 2.5% of the information, while the “box” represents the remaining 90%; within this is represented the median of the results obtained using the Monte Carlo simulation. A larger variability was observed in the model that included a dynamic q , with respect to the alternative model in which q was static. With the latter condition, the range of biomass values was 78-352tons (median=166ton), while with a dynamic q , this range was 2-5907tons (median=103ton).

Catch. In most of the cases the catch observed was within the range of values expected from both models (Figure 4). As observed for biomass, the dynamic q model showed greater variation, while the variation was reduced with the static q model. Another aspect to note is that with the dynamic q model the tendency for the variability in the catch estimation increases from the 7th week, a fact which was not observed with the other model.

Catch per unit of effort. The range of values for the CPUE observed was within the range of variation expected from both models (Figure 5), although its variability is smaller. The tendency with this indicator showed that, in the case of the dynamic q model, its variability increased progressively beginning at the 5th week, a pattern that was not observed with the static q model.

Discussion

The results support the hypothesis of temporal variability in the catchability coefficient, associated with variations in local abundance of the resource, as higher q values were associated to lower biomass levels. This finding is against the general assumption that this coefficient is a constant. On the other hand, the standard error associated with the estimation of parameters by regression analysis caused the variability calculated for the performance variables to be higher with the variable q model than for those obtained with the static q model.

Although temporal variation in catchability has been demonstrated in diverse pelagic and demersal fisheries (MacCall, 1976; Peterman and Sterr, 1981; Bannerot and Austin, 1983; Crecco and Savoy, 1985; Gordo and Hightower, 1991; Swain *et al.*, 2000), and for crustaceans (Ye and Mohammed, 1999; Pérez and Defeo, 2003), we have

found no references to the behavior of q in artisanal fisheries for benthic resources, specifically mollusks.

Various explanations have been proposed for the observed variability. Atran and Loesch (1995) carried out an analysis of weekly fluctuations in catchability of *Brevoortia tyrannus*, assuming that variations in the q coefficient could remain relatively constant when measured on an annual scale. This condition is generally violated, if ever fulfilled at all, when the analysis is carried out seasonally, as is verified in the present study by the finding of temporal variations in catchability when analyzed over short periods of time. This fact raises questions about the correct time scales needed to account for small variations in catchability which may affect the evaluation of the resource under study.

A second explanation has been associated with behavioral aspects of the resource (Arreguin-Sánchez, 1996, Godo *et al.*, 1999; Swain *et al.*, 2000). Species that form schools show strong inverse correlation between biomass and catchability (Paloheimo and Dickie, 1964; MacCall, 1976; Ulltang, 1976; Peterman and Steer, 1981; Crecco and Savoy, 1985; Angelsen and Olsen, 1987; Crecco and Overholtz, 1990; Hansen *et al.*, 2000). Following drops in abundance per unit area after extraction efforts, the schools tend to regroup and maintain their density. When maintaining density with declining biomass, each unit of effort extracts a greater proportion of the remaining stock, so that as catchability increases, the stock is reduced. The preceding becomes evident as a strong density-dependent relationship.

In the case of *M. donacium*, however, the explanation seems to be related to the behavior of the divers, more than to the behavior of the resource. Pérez (1996) postulated a density-dependent effect between q and the abundance of this resource, since upon declines in abundance the diver must harvest a greater surface area to obtain the same catch. In this way the numerator in Eq. (11) increases, the denominator remaining constant. Thus, the catchability increases. This characteristic is present in the dynamic estimations of catchability in each fishery ground; as CPUE increases catchability decreases and vice-versa (Chávez, 2000).

Another aspect that emerges from the results obtained relates to the assumption that establishes that the CPUE would be a relative estimator of the resource abundance. Seijo *et al.* (1997) indicated that the assumption that the CPUE was a relative index of abun-

dance for sedentary species would be limited, given changes in the value for catchability (Collins, 1987; Swain *et al.*, 2000). Thus, in quantitative terms, the CPUE estimated on the basis of the dynamic model of q (Eq. 10) always showed a better fit of CPUE to the values obtained directly than did the CPUE obtained for these values using constant catchability. Thus, the CPUE may be considered as an efficient estimator of the abundance if and only if the b parameter in Eq. (7) is significantly less than and statistically different to zero. This conclusion is the same as that reached by Ulltang (1976) for *Clupea harengus*.

However, despite the above statements, the results suggest that although there was a significant inverse relation between biomass and catchability, the variability in the observations that serve as inputs to the regression equations cause the dynamic q model to have weaknesses (*ie.* negative biomass values) associated with the high standard error of the calculated parameters. In contrast, although the hypothesis of the constancy of q was falsified, the results of the model based on this assumption produced numbers within the range of values observed for the performance values (catch, CPUE) with greater precision than that of the model using dynamic q . As a consequence, for the case of the *M. donacium* fishery in Coquimbo Bay, it is possible to work with a "biomass depletion" model using a static q without making an important estimation error. In this sense, this result represents an advantage, as it is simpler to estimate this coefficient from routine information of fishery activities instead of producing new records for the area harvested by each diver. In relation to the variability in the harvested area, it is possible that within the fishery zone analyzed (known to the fishermen as "Zanahoria") there are *loci* characterized by particular density and size structures. *Loci* were defined under the basic assumption that the stock can be subdivided into different such *loci*, each assuming different resource densities. A *locus* becomes the smallest geographical unit considered in which the population density can be considered effectively uniform (Caddy, 1975). Each *locus* would contain several age classes, all of which would have different densities. Thus, the distribution of the resource may be heterogeneous, even within the same fishery area, and may produce a high degree of variability within the area harvested by each diver and, therefore, a higher error in the model.

In a management context these results can be useful to make

decisions with a relatively simple predictive model. This is particularly important when only historical data about CPUE are available for fisheries analysts. Furthermore, CPUE requires lower costs (in money and time consumed) compared with a more sophisticated statistical design. In order to evaluate the best tools to support management decisions, all these aspects must be considered in discussing a fishery monitoring system.

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