AN ECOTROPHIC MODEL OF SOUTHERN BRAZIL CONTINENTAL SHELF AND FISHERIES SCENARIOS FOR *ENGRAULIS ANCHOITA* (PISCES, ENGRAULIDIDAE)

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RESUMO
Os modelos ecotróficos de balanço de biomassa vem sendo utilizados cada vez mais como ferramentas para melhorar o entendimento da estrutura e funcionamento dos ecossistemas afetados pela pesca. Neste sentido foi construído um modelo preliminar, para entender a estrutura e os processos da plataforma continental do Sul do Brasil. Foram incluídos apenas os principais grupos para poder observar a importância relativa de cada um deles, testar cenários de exploração pesqueira e assim avaliar as possíveis conseqüências da pressão pesqueira sobre um recurso ou grupo em particular e o tipo de detalhamento que deverão ter os modelos futuros. Um exercício de simulação mostrou que a eventual pressão pesqueira sobre o pequeno peixe pelágico anchoíta (*Engraulis anchoita*) poderia também ter efeitos negativos na biomassa de seus predadores, mas favoreceria outros grupos de peixes competidores e camarões também explorados.

PALAVRAS CHAVE: modelo eco-trófico, simulação, manejo pesqueiro, sul do Brasil plataforma continental.

ABSTRACT
Ecotrophic models are becoming a useful tool to understand the structure and dynamics of aquatic ecosystems affected by fisheries. In the present paper a preliminary Ecopath model was built to allow the understanding of the structure and biomass dynamics of the Rio Grande do Sul (Brazilian southernmost state) continental shelf ecosystem. Only the main groups were included to analyse their relative importance and to test some fisheries scenarios in order to observe the consequences of fishing pressure over one particular group and the detail requirements for future models. A fishing scenario for the small pelagic anchoita (*Engraulis anchoita*) using Ecosim, showed that this fishery would have negative impacts on the biomass of its predators and positive impacts on the competitor fish groups also exploited and on shrimps.

KEYWORDS: ecotrophic models, simulations; fisheries management, southern Brazil, continental shelf.

INTRODUCTION

In recent years, several scientists have discussed about the necessity of putting fisheries management in an ecosystem perspective to allow better understanding of its processes and of fish stocks abundance trends (Bakun 1996, Walters et al*.* 1997, Pauly et al*.* 2000, Vasconcellos & Chuenpagdee 2000, Pitcher 2001). In this sense, mass-balance ecotrophic models are becoming useful and reliable tools for understanding the structure of the ecosystem, its biomass flux and allowing dynamic modelling of fisheries (Walters et al. 1997, Pauly et al. 2000, Pitcher 2001, Pauly & Christensen 2002). Through the biomass and production rates data and the trophic interactions knowledge, we may be able to understand the possible fluctuations of groups' abundance under the influence of fisheries or natural impacts. In this way, it is possible to create fishery scenarios to assess the impact of fishing mortality variations by fleets or gears and even shifts in predator/prey relationships (Christensen & Walters 2000).

We present here a preliminary model for the continental shelf of southern Brazil, from Santa Marta Grande Cape (28°40' S, 48°50'W) to Chuí (33°40' S, 53°20' W) (Fig. 1). This area (c.a. 100,000 Km^2) is under the influence of the subtropical convergence formed by the southward flowing Brazil Current (Tropical water) and the northward flowing Malvinas current (Sub-Antarctic water) forming the so called Sub-Tropical Convergence (Garcia 1997, Piola et al. 1999). The region is also favoured by the continental water runoff of Patos Lagoon and the La Plata River (Garcia 1997, Odebrecht & Castello 2001).

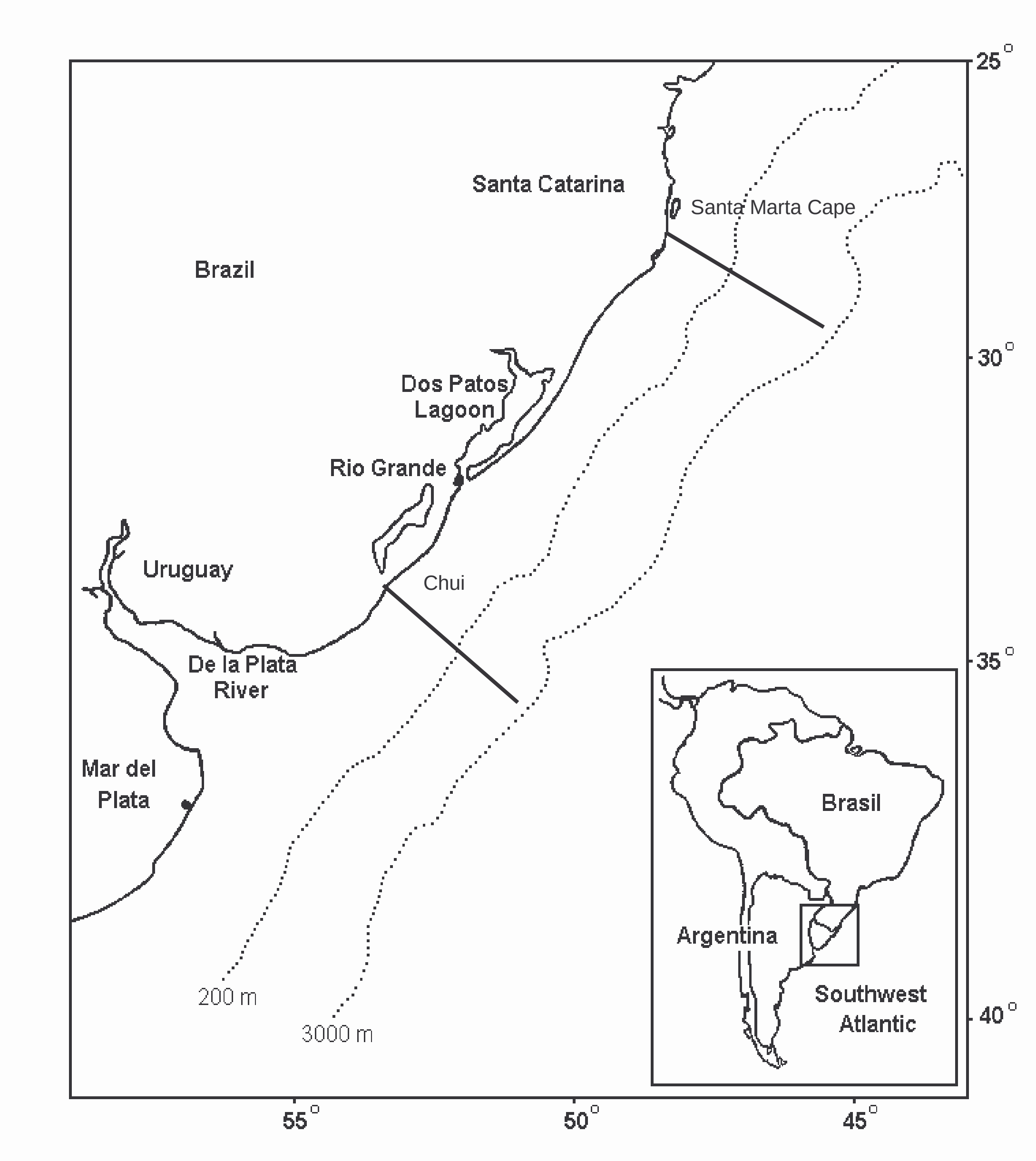

FIGURE 1 – Study area: the continental shelf of southern Brazil (c.a. 100,000 Km^2)

The continental shelf in this region is relatively wide compared with the rest of Brazil and is considered a productive area (Castello 1990, Haimovici et al. 1997, Odebrecht & Castello 2001). Seasonal changes are observed in water masses and in part of the fauna. Several authors (Seeliger et al. 1997, Martins 2000) describe two different and opposite conditions: winter-spring and autumn-summer. However, the main groups targeted by the fishing fleets are the same all year round, with only minor changes between seasons (Haimovici et al. 1997).

The dominant fisheries in this region are bottom and pair trawling, both for several Sciaenidae fishes (like the whitemouth croaker *Micropogonias furnieri*, the weakfish *Cynoscion guatucupa* and the king-weakfish *Macrodon ancylodon*), flatfishes (*Paralichthys* spp.) and shrimps (Haimovici 1997 *a*). Also, there is a gillnet fishery for blue-fish *Pomatomus saltatrix* and whitemouth croaker (Reis 1992, Haimovici et al. 1997) and a bottom long-line for wreckfish *Polyprion americanus* and other large fish such as *Pseudopercis* spp and *Lopholatilus villarii* (Haimovici & Velasco 2001). Along the upper slope area and the adjacent oceanic region, a long-line fishery for tunas and pelagic sharks has been developed (Castello 1997).

Since 1985, trawling fisheries' yields have been declining while the effort applied to the same resources by alternatives methods like gill-netting and long-line have been increasing (Reis 1992, Haimovici et al. 1997, Haimovici & Velasco 2001). Demersal landings represent 71 %, in average, tunas and other pelagic species make around 10 %. The rest of the catches is composed by elasmobranchs and shrimps.

Vasconcellos & Gasalla (2001) explored Brazilian SE and South coast with other simple models, including 12 living groups for the southernmost region, trying to asses the carrying capacity and quantify the amount of available primary production appropriated by fisheries catches, mainly.

In the present paper we introduce a simple ecotrophic model to represent the trophic interactions between the main fishes and invertebrate groups inhabiting specifically the continental shelf and upper slope of Rio Grande do Sul state. In addition, the model here created is used to analyse some fisheries scenarios, particularly the exploitation of *Engraulis anchoita* since there is a growing interest in exploiting this species mainly to make fish-meal with high and standard quality.

Through model simulations, we show that the removal of this small pelagic and foraging fish at the industrial levels required for reduction purposes could affect the present state of southern Brazil continental shelf ecosystem.

MATERIAL AND METHODS

The *Ecopath with Ecosim* package works with the main groups in the ecosystem, here considered as species or groups of ecologically similar species, the trophic linkages among them (predation as a natural mortality component), and the fishing mortality, mainly. The basic inputs for each group are biomass data (*B*), the production/biomass (*P/B*) (equivalent to the instantaneous rate of total mortality *Z*) and consumption/biomass (*Q/B*) ratios, the ecotrophic efficiency (*EE*) (a measure of how much of a group's biomass is used within the ecosystem), fisheries landings and diet for each group (Pauly & Christensen 1993, Pauly et al. 2000). With this information, three basic data matrixes are built and used to analyse the energy flux in the ecosystem: 1) a matrix containing data on biomass, *P/B*, *Q/B*, and *EE*, 2) a matrix with fisheries landings per fleet and / or gear type, and 3) a diet matrix (Christensen & Walters 2000).

These parameters are inputs to solve a system of linear equations (as many equations as groups in the model) relating biomass, production and consumption (detailed in Christensen & Walters 2000 and Pauly et al. 2000):

$$B_j * (P/B) * EE - \sum_{j=1}^{n} B_j * (Q/B)_j * DC_j - Y_i - E_i - BA_i = 0 \qquad \text{(Equation 1)}$$

where: B_i is the biomass of group (*i*), *P/B* is the production/biomass ratio, *Q/B* is the consumption / biomass ratio, DC_{ji}, is the fraction of prey (*i*) in the average diet of predator (*j*), Y_i represents the fisheries landings of group (*i*), E_i the immigration / emigration ratio and BA_i the biomass accumulation (generally set to 0 to represent equilibrium situations).

The following 13 groups were considered essential in order to build a basic *Ecopath* model: 1) Phytoplankton, 2) Zooplankton, 3) Benthos 1 (including infauna and epifauna), 4) Benthos 2 (the shrimps *Artemesia longinaris* and *Pleoticus muelleri*), 5) Anchoita (the small pelagic *Engraulis anchoita*), 6) Loligo (the coastal longfinned squid *Loligo sanpaulensis*), 7) Benthophagous fish (several demersal benthophagous fishes, such as croakers and drums), 8) Juvenile benthophagous fish, 9) Nektophagous fish (several nektophagous fishes, such as weakfish, hake and flounders), 10) Juvenile nektophagous fish, 11) Tuna-like fishes (we include under this generic name several migratory pelagic fishes including tunas, billfishes, skipjack tuna and also bluefish *Pomatomus saltatrix*), 12) Oceanic squids (several oceanic pelagic squids such as the Ommastrephidae, Argonautidae, etc., and the demersal-pelagic squid *Illex argentinus*), 13) Detritus. The groups and the basic data entered are shown in Table 1.

TABLE 1 – Basic input database for the ecotrophic model of the continental shelf of southern Brazil ecosystem. B = Biomass, P = Production, Q = Consumption, EE = Ecotrophic Efficiency,

Groups / Parameter	B ($t/Km^2/year$)	P/B ($year^{-1}$)	Q/B ($year^{-1}$)	EE	BA ($t/Km^2/year$)
Phytoplankton	160.0	100.0			0
Zooplankton		64.0	324.0	0.6	0
Benthos 1		5.0	23.0	0.9	0
Benthos 2		4.0	15.0	0.6	0
Anchoita	12.0		6.0	0.6	0
Loligo	1.8	3.0		0.9	0
Juv. benthophagous fish		2.0	4.0	0.9	0
Benthophagous fish	2.0	0.6	2.5		0
Juv. nektophagous fish		3.2	6.5	0.9	0
Nektophagous fish	0.8	0.64	2.5		0
Tuna-like		0.5	3.0	0.7	0
Oceanic squids		3.0	6.0	0.9	0
Detritus					

These groups are believed to represent the most important trophic links of this system (Haimovici et al. 1997, Odebrecht & Castello 2001). Two groups, nektophagous and benthophagous fishes, were divided into juveniles and adults because of the shift in the trophic level these groups have during their ontogeny and their importance in the ecosystem and in the commercial landings.

To run the model, only one of the parameters in the first matrix (Table I) can be unknown. Data on biomass were obtained mainly from Castello (1997 *a*, *b*), Haimovici (1997 *a*, *b*), Haimovici et al. (1997), Odebrecht & Garcia (1997), Rocha (1998) and Vasconcellos & Gasalla (2001). Complementary data on ratios (*P/B*, *Q/B* & *EE*) were extracted from Pauly & Christensen (1993), Rocha (1998) and Vasconcellos & Gasalla (2001). Phytoplankton biomass was calculated from Odebrecht & Garcia (1997), based on a primary production rate of 160 t Km^{-2} $year^{-1}$ and assuming a production/biomass rate of 100/year following Vasconcellos & Gasalla (2001). The diet matrix was constructed mainly after Castello (1997 *b*), Santos (1999) and Martins (2000) (Table 2). Values shown represent the weight proportion of each prey in the diet. Data on fisheries landings were obtained from IBAMA's landings report (IBAMA 2000) (Table 3). Biomass and landings data was entered divided by the model area to get the amount by square kilometre.

TABLE 2 – Diet matrix for the groups included in the trophic model.

#	Prey / Predator	2	3	4	5	6	7	8	9	10	11	12
1	Phytoplankton	1.00	0.20	0.20	0.10							
2	Zooplankton		0.20	0.20	0.90	0.37	0.80		0.55			0.20
3	Benthos 1		0.05	0.20			0.20	0.50				
4	Benthos 2					0.20		0.50				
5	Anchoita								0.20	0.38		0.42
6	Loligo					0.07			0.05	0.13	0.11	0.01
7	Juv. benthophagous fish					0.19				0.25		0.14
8	Benthophagous fish										0.17	0.02
9	Juv. nektophagous fish					0.18			0.20	0.25		0.14
10	Nektophagous fish										0.06	
11	Tuna-like											
12	Oceanic squids										0.67	0.07
13	Detritus		0.55	0.40								
	Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 3 – Marine fishery landings in the Rio Grande do Sul state, Southern Brazil, according to the IBAMA's 2000 report (in t/Km^2/year)

Group / Gear	tuna long-line	purse seine	bottom trawl	demersal long-line	gill-nets	Total
Phytoplankton	0	0	0	0	0	0
Zooplankton	0	0	0	0	0	0
Benthos 1	0	0	0	0	0	0
Benthos 1	0	0	0.008	0	0	0.008
Anchoita	0	0	0	0	0	0
Loligo	0	0	0	0	0	0
Juv. benthophagous fish	0	0.001	0.007	0	0.004	0.012
Benthophagous fish	0	0.006	0.036	0	0.021	0.063
Juv. nektophagous fish	0	0	0.008	0	0.002	0.01
Nektophagous fish	0	0	0.04	0.001	0.011	0.052
Tuna-like	0.057	0.002	0	0	0	0.059
Oceanic squids	0	0	0	0	0	0
Detritus	0	0	0	0	0	0
Sum	0.057	0.009	0.099	0.001	0.038	0.204

The model built represents an average annual situation, *i.e.*, we assume a stable situation where the total biomass in the ecosystem shows no accumulation tendencies (BA_i=0), but not a steady state in the sense of the absence of dynamic processes (see Christensen & Walters 2000, Pauly & Christensen 2002). In the same sense, when data came from different databases, we assume no significant inter-annual differences. This is a common and simplifying assumption done in order to allow modelling complex systems (Christensen & Walters 2000). Since these models work with many parameters and their interdependence (according to the biological background within the mathematical functions), any difference should be compensated or minimised in the process of adjustment for mass-balance (tuning).

In the dynamic simulation, the module Ecosim was used. The basics of this module consist of biomass dynamics expressed through a series of coupled differential equations (Walters et al. 1997, Pauly et al. 2000). These equations are derived from Ecopath's master equation (Eq. 1), and take the form:

$$dB_i / dt = g_i \sum_j Q_{ji} - \sum_j Q_{ij} + I_i - \left(M0_i + F_i + e_i\right)B_i \qquad \text{(Equation 2)}$$

where dB_i/dt represents the growth rate during the time interval dt of group (i) in terms of its biomass (B_i), g_i is the net growth efficiency (production/consumption ratio), M_i the non-predation ("other") natural mortality rate, F_i is fishing mortality rate, e_i is emigration rate and I_i is immigration rate.

We tested a new fishery scenario for the presently virgin stock of the small pelagic and foraging fish anchoita *Engraulis anchoita* (Pisces, Engraulididae). The fishing mortality rate is here represented as the yield/biomass (*Y/B*) ratio. Several scenarios were tested: *Y/B* = 0.2, 0.4, 0.6, 0.8 and 1.0. Default Ecosim settings were used (with no forcing functions and an average value of the vulnerability rate – see Christensen & Walters 2000, Pauly & Christensen 2002) for this preliminary model. The *Y/B* value was increased until when the biomass would show no stabilisation trend. At this point, we should say the stock had collapsed. The goal was not only to estimate the maximum value for this fishing rate but to analyse the effect of this fishery in the other groups during time windows of 20 years. The results in terms of fishing pressure do not represent optimum fishing rates to be applied by the fishery industry but extreme values in order to assess and understand the ecosystem impacts and the trade-offs of this fishery.

RESULTS & DISCUSSION

A balanced model for southern Brazil continental shelf is numerically shown in Table 4. The original parameters were adjusted, when necessary to mass-balance the model, considering the corresponding rates and the requirements to fulfil the trophic web fluxes, under the constraints that the parameter *EE* remains equal or less than one and that respiration terms are positive (Walters et al. 1997, Pauly et al. 2000, Pauly & Christensen 2002).

The flow diagram is shown in Fig. 2 for a graphical interpretation of the biomass amounts and fluxes. In this representation, boxes size are proportional to the log of biomasses and the arrows represent the fluxes (consumption) between different groups.

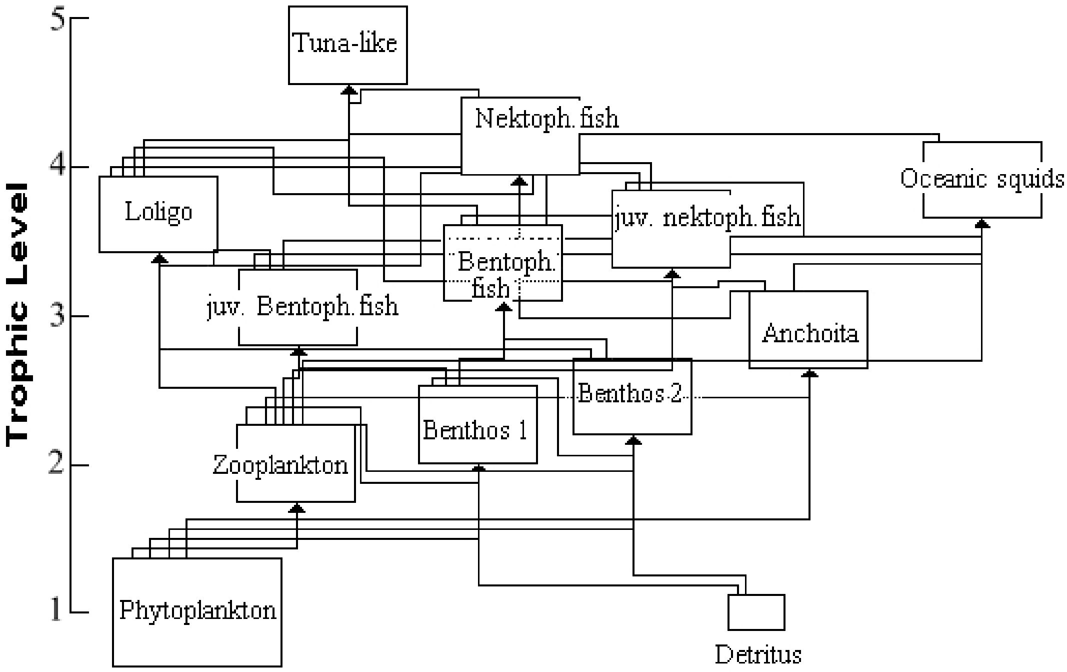

FIGURE 2 – Flux diagram for the continental shelf of southern Brazil's ecotrophic model. Box sizes are proportional to log(*B*)

TABLE 4 – Balanced ecotrophic model of the continental shelf of southern Brazil. Underlined values where estimated by the iterative process.

Group name	Trophic level	Biomass (t/Km²)	P/B (/year)	Q/B (/year)	EE	P/Q
Phytoplankton	*1.00*	160.000	100.000	-	*0.085*	-
Zooplankton	*2.00*	*4.066*	64.000	324.000	0.600	*0.198*
Benthos 1	*2.26*	*5.900*	5.000	23.000	0.900	*0.217*
Benthos 1	*2.45*	*4.518*	4.000	15.000	0.600	*0.267*
Anchoita	*2.90*	12.000	*1.177*	6.000	0.600	*0.196*
Loligo	*3.68*	1.800	3.000	*23.153*	0.900	*0.130*
Juv. benthophagous fish	*3.05*	*4.637*	2.000	4.000	0.900	*0.500*
Benthophagous fish	*3.36*	2.000	0.600	2.500	*0.140*	*0.240*
Juv. nektophagous fish	*3.58*	*5.656*	3.200	6.500	0.900	*0.492*
Nektophagous fish	*4.21*	0.800	0.640	2.500	*0.159*	*0.256*
Tuna-like	*4.82*	*0.170*	0.500	3.000	0.700	*0.167*
Oceanic squids	*3.90*	*0.149*	3.000	6.000	0.900	*0.500*
Detritus	*1.00*	-	-	-	*0.007*	-

Biomasses estimated from the provided parameters seem realistic according to available information (see Haimovici et al. 1997, Vasconcellos & Gasalla 2001). Considering the estimated *P/Q* ratios, the juveniles of the nektophagous and benthophagous fishes and the oceanic squids were the most efficient groups in transforming the consumed biomass into its own biomass. This is expected since both juvenile fishes and squids have high growth rates (Pauly 1998). For the coastal squid *Loligo sanpaulensis*, however, due to the high estimated value of *Q/B*, *P/Q* was not as high as expected.

It was already stated that the main biomass flux in this ecosystem takes place both through the benthic fauna (Haimovici et al. 1997, Odebrecht & Castello 2001) and through the anchoita trophic sub-web (Schwingel & Castello 1994, Castello 1997 *a*, *b*), what is not uncommon in neritic ecosystems (Mann & Lazier 1991). Several of the most abundant fishes -that are also fishery resources- feed mainly on benthic organisms, such as the scienid fishes whitemouth croaker *Micropogonias furnieri*, the argentine croaker *Umbrina canosai* and other less abundant fishes like the black-drum *Pogonias cromis* and the coastal *Menticirrhus* spp. Other important fishery resources are nektophagous, feeding on fishes like the anchoita itself and squids, like the striped weakfish *Cynoscion guatucupa*, the king-weakfish *Macrodon ancylodon* (Haimovici 1997*a*, *b*, Martins 2000) and others, as it does the Argentinean hake *Merluccius hubbsi* in the southernmost Brazilian outer continental shelf, under strong influence of the sub-antarctic waters (Haimovici et al. 1993, Martins *op. cit*.).

According to the present model, the higher fishing pressure that *Engraulis anchoita* seems to stand without collapsing (*i.e*., showing no biomass stabilisation in the time window tested) is a ratio *Y/B* = 0.8, where the biomass shows a stabilisation around 46% of the original (virginal) biomass after 7.5 years of exploitation (Fig. 3). This exploitation pattern would mean an extraction of almost 54% of the stock, i.e., around 640,000 t per year.

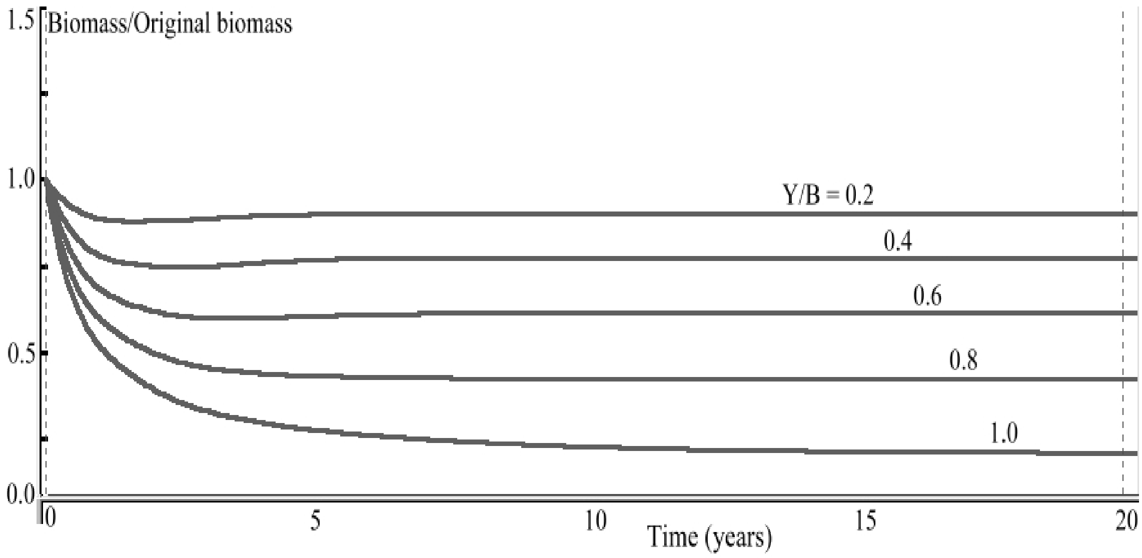

FIGURE 3 – *Engraulis anchoita'*s biomass change over time under constant exploitation rates as shown: *Y/B* = 0.2, 0.4, 0.6, 0.8 and 1.0 ($year^{-1}$).

This simulated fishery showed impacts on other groups' biomasses and their recovery time. Particularly, nektophagous fishes (juveniles and adults groups), the group "tunas" and oceanic squids were affected negatively by the anchoita's biomass decrease. These last two groups however, showed some recovering after 10 – 12 years, but neither did the anchoita itself nor the nektophagous fishes (Fig. 4), if that fishing pressure was kept constant over time.

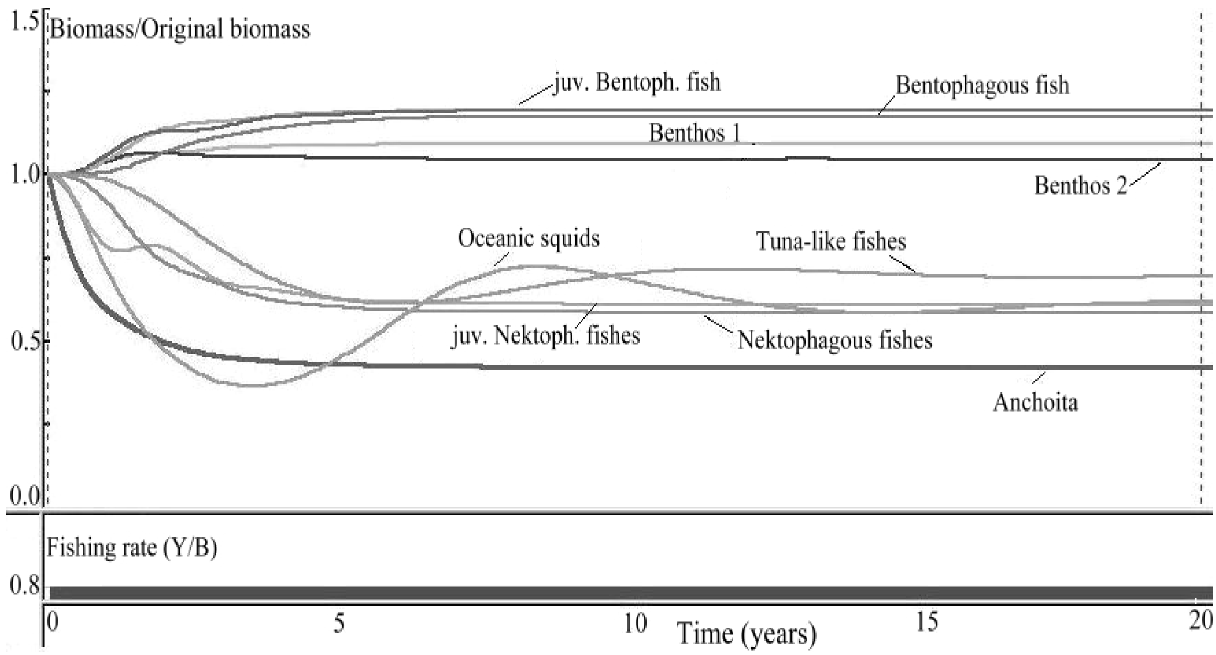

FIGURE 4 – Graphic representation of the different groups' biomass evolution over 20 years, facing the new fishing rate on Anchoita (*Y/B*=0.8 year^{-1}). Biomass/Original biomass in the Y axis (a value of 1 means no change over time).

Although the small pelagic fish *Engraulis anchoita* is exploited in the southern range of its distribution (Argentinean waters), in Brazilian waters is considered a virgin stock, however with a high variable biomass (Castello 1997*b*). Because of its abundance, it is considered as a potential fishery resource for high quality fish-meal production and for the canned industry. Ecologically, as a secondary consumer, this species is one of the most important links in the neritic trophic web, transferring plankton's production to higher consumers (Castello 1997 *a*, *b*).

The small diet overlapping between the juvenile benthophagous and nektophagous fishes seemed to be enough to allow an increase in the first group's biomass when the second was affected by the reduction in one of the most important preys (the anchoita) availability. Consequently, an increase in the benthophagous fishes biomass would cause a decrease in the "Benthos 2" group (shrimps) biomass through predation. This, on the other hand, would have economical implications since the later group is exploited.

This effects are not surprising at all and have been observed in other regions of the world where the predator-prey interactions and the fisheries have important cascade effects on the ecosystem structure causing huge ecological and economic impacts. This was the case, for instance, of the Atlantic cod (*Gadus morhua*) and the northern shrimp (*Pandalus borealis*) interactions in the North Atlantic. The heavy fishing on the cod led to an increase first in the shrimp biomass and later on it's fishery, what prevented the cod, a heavy carcinophagous species, to recover (Worm & Myers 2003).

Vasconcellos & Gasalla (2001) estimated that in the southern region of the Brazilian continental shelf a high proportion of the primary production was already appropriated by the fishery, which utilises a large proportion of the marine shelf ecosystem carrying capacity.

Our simulations showed that in southern Brazil, a new fishery on the anchoita would force the ecosystem to evolve to a new equilibrium level in the best case, with low anchoita abundance and shifted groups dominance (Fig. 4). The impacts on other economically important groups, however, must be analysed and the trade-offs should be taken into account. We believe that ecotrophic models of this type will be useful tools in that sense, since they reveal indirect effects of fishing on any given target species.

A more detailed model of our study area should help confirm these tendencies more accurately, as individual species instead of groups are taken into account. In the future, different models may be built following the present one and taking it as the first step in a progressively complex analysis.

CONCLUSIONS AND RECOMMENDATIONS

It is undeniable today that any kind of fishery on one particular resource has impacts on almost all the ecosystem components. Public concern arises when the affected groups are also economically important or play a fundamental ecological role. In all cases, some kind of conservative approach is desirable (Pitcher 2001).

The development of a new fishery targeting the anchoita should have an impact in this ecosystem, affecting negatively the fishery of other important fishes like weakfish and hake and probably the Argentinean squid, as well as the important macrobenthic resources (coastal shrimps). As these groups are currently fully exploited (Haimovici et al. 1997), a management action is recommended to protect these stocks. The Argentinean squid is not yet exploited commercially in southern Brazil but due to its biologic characteristics and the migration pattern of the species (Haimovici 1997 *b*), management actions have yet to be analysed.

For the fish groups and even for the anchoita itself, effort restriction and/or protected areas or seasons may be implemented to assure sustainable exploitation. Measures to protect the juvenile portion of the stocks, for instance, may lead to higher recruitment and adult biomass. Even though this kind of regulations (effort reduction) is hard to implement in the real world, experience tells us sometimes is the only way to avoid stocks depletion (Pitcher et al. 2000, Walters 2000, Pitcher 2001).

More detailed ecotrophic models would lead us to find specific fishing policies for the targeted groups so as sustainable yields can be assured. Nevertheless, it is evident that a precautory policy must be applied, since the system is already heavily exploited (Haimovici et al. 1997, Vasconcellos & Gasalla 2001). Anchoita should be exploited lightly, at the beginning, and the effects on the other resources should be monitored.

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