Economic and biological benefits of interspecies switching in a simulated chaotic fishery

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SIMULATION D'UNE PÊCHERIE CHAOTIQUE : L'INTÉRÊT ÉCONOMIQUE ET BIOLOGIQUE DU CHANGEMENT DE CIBLES.

RÉSUMÉ

Nous avons simulé un environnement hautement variable et imprévisible dans un modèle bio-économique. Le compartiment biologique du modèle inclut des éléments de chaos et de hasard pour la dynamique des espèces et pour l'écosystème dans son ensemble. Le compartiment économique inclut pour les pêcheurs la possibilité de s'adapter à cet environnement biologique en réorientant leur effort de pêche (par exemple en changeant d'espèce-cible) afin de maximiser le rendement économique. Nous utilisons le modèle pour expliquer deux caractères importants des pêcheries qui ne sont pas abordables par les modèles à l'équilibre: les bénéfices biologiques et économiques du changement de cible; la variabilité accrue des prises, du revenu des stocks et des structures d'âge des populations quand l'effort de pêche augmente.

1. INTRODUCTION

Traditional bioeconomic models used for fisheries management are usually limited in their ability to predict regularly observed processes in fisheries. By and large, such models show «the inevitable tendency towards the overfishing of common resources» and little else. We believe that the limited capability of these models is due to an underlying misrepresentation of the biological environment. These models assume that the fishery, unexploited, is inherently stable, and that populations naturally tend to flow to some fixed, equilibrium values. In fact, observations and recent simulations (French *et al.*, 1989) both support the picture of a biological system with large chaotic or random fluctuations over the long term.

In this paper we report results from a bioeconomic simulator that emphasizes the highly variable characteris-

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tics of ocean fish populations. There are three aspects of the model that we believe are interesting : thoroughly conventional biological ideas are used to generate chaotic populations ; one does not have to introduce exotic assumptions about biological behavior. The model's simulations of highly variable populations are qualitatively consistent with a much broader range of bioeconomic behavior than models that emphasize equilibrium concepts. The model's implications for how we conceptualize the processes of such systems are substantially different from the usual equilibrium models.

Below we describe first the bioeconomic model and then turn to a description of the processes predicted by the model. We discover two basic phenomena that are widely observed in fisheries, but not predictable with sustainability models. There are clear biological and economic benefits derived from fishermen's switching behavior. By switching we mean the tendency to redirect fishing effort from species to species in response to changes in their relative abundance. Variability in catch, stock size, age class distributions and fishermen's revenue tends to increase with increases in overall fishing effort. Finally, we discuss the implications for management contained in our results.

2. THE MODEL

The biological component of the simulator is an age-structured, multiple species fisheries model with conventional spawning, growth and mortality characteristics for five species. The individual dynamics of four of these species approximate typical bottom dwelling ocean fish - cod, haddock, pollock and redfish. The fifth species - "bloom" - is a short lived, very fast growing species such as squid or sand lance. The spawning, growth and other important relationships for each species are set in a very conventional way. To these single-species biological elements, we have added a constraint on the total biomass that the eco-system can support. This constraint creates an interdependence among the species. In a particular year, if the ecosystem's mass grows to exceed this biomass limit, survival of the newly spawned fish is reduced in order to bring the actual mass down to the biomass limit. If the numbers of newly spawned fish are not sufficient to achieve compliance with the biomass constraint, all of the newly spawned fish are eliminated and the system's mass temporarily exceeds the biomass constraint. The frequency and extent of this biomass limit induced mortality of newly spawned fish depends upon the overall growth rate of the system. The system growth rate however, is basically unpredictable (1) since it depends upon an infinite number of possible combinations of age class distributions within each population and overall weight distributions among populations. Consequently, the constraint leads to chaotic variability. In an unexploited model system with significant heterogeneity in the species, the total mass remains relatively stable, fluctuating only slightly around the biomass limit, while individual species populations vary significantly. We stress that this chaotic behavior is a result of the nonlinearity in the system once the biomass constraint is activated, and occurs without any introduced randomness. This source of variability may be viewed as a system-wide density dependent effect.

In a real fishery, there is additional unpredictability in recruitment due to local factors such as climate, current flows and other difficult to quantify and measure influences. We have added this variability to our model by introducing randomness in the spawning function (2) for each species. This randomness makes an occasional strong

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(1) *What we mean by «basically unpredictable» is this : if one were fully knowledgeable of all the relationships, the parameters and the current values of the system, population change from year to year would be predictable. However, a fundamental characteristic of chaotic systems is that even small errors in inputs of current values or inexact specification of parameters or functional relationships would lead to large errors of prediction. In the real world the magnitude of measurement and specification error is likely to greatly exceed the levels necessary for accurate prediction of a system of this sort; consequently, we refer to the system as «basically unpredictable» although it is deterministic unless randomness is added.*

(2) *This is done by replacing the spawning survivor function for each species with a random variable with a Lorentzian distribution at each value of the mature population. The average value reproduces the original function. The distribution is asymmetric so that negative values do not occur.*

year-class possible, even when the mature population of a species is low, although the probability of such an occurrence decreases as the mature population decreases.

Each of these features - the biomass constraint and the random spawning distribution - introduces variability into the age-class distributions of each of the species in our simulations. The biomass constraint is most important when the fishing effort is low, at which time the populations frequently grow large enough to reach the biomass limit. On the other hand, random spawning has its most pronounced effect when the system is heavily fished. It enables a species to escape extinction or a future of depensated population levels, since an occasional strong year-class or two will occur, even with a very low mature population. Figure 1 shows population patterns with light fishing (effort = 0.1) with only the chaotic sources of variability. Figure 2 shows population patterns with light fishing and with both chaotic and random sources of variation.

The economic component of the model is a straightforward adaptation of a production possibilities model. Its purpose is to provide an economic decision rule for determining the dynamic allocation of fishing effort among species, i.e., switching. Depending upon the relative price and abundance of each species, fishermen switch their harvesting effort in such a way as to maximize their returns (Fig. 3).

In the simulations presented in this paper we have simplified the economic model somewhat by assuming that the fishery in question is a small part of a larger market. Consequently, prices are assumed given and constant (3). This simplification eliminates the additional variability that can be introduced into the overall bioeconomic system through the market, but it has the advantage of clearly illustrating the effects of biological variability alone.

3. THE BEHAVIOR OF THE MODEL

We describe here the changing bioeconomic patterns that result as effort is increased from a very low level (zero) to a very high level (where 60-70% of the catchable fish are caught each year) under two different regulatory regimes :

Case 1 - Switching. A basically unregulated fishery where four of five species are exploited and in which fish are first vulnerable to capture in the year they reach maturity. Fishermen are free to allocate effort among species according to the economic rule described above.

Case 2 - Non-switching. A fishery similar to the first, except effort allocated to each species is fixed at a constant level by regulation.

The first case comes very close to being an unregulated fishery. We chose this case for purposes of comparison with the usual models of overfishing. Sustainability models tell a compelling but uncomplicated story about the effects of overfishing. As demand for a resource increases, profits rise attracting more fishing effort. Greater effort at first leads to greater catch, but as the ability of the resource to sustain itself declines so do catch and profits. The process ends only when average profits are exhausted and stocks depleted.

In case 1 in our model a similar pattern is observed with certain important differences. At low levels of effort, average catch rises rapidly as a function of effort (4) (Fig. 4) Although each species shows considerable variation (Fig. 5), in any given year two or three strong year classes tend to be present in each population (Fig. 6).

As effort is increased further, total catch tends to rise but with that rise there is an increase in the variability

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(3) *This simplification is not a necessary attribute of the model. Normally the model generates prices endogenously as if the fishery were a closed system.*

(4) *Except where noted, the data in figures and tables are the average for 150 simulated years of fishing, computed after transients due to initial conditions have disappeared.*

Fig. 1 - Catchable weight of cod with light fishing and chaotic sources of variability only

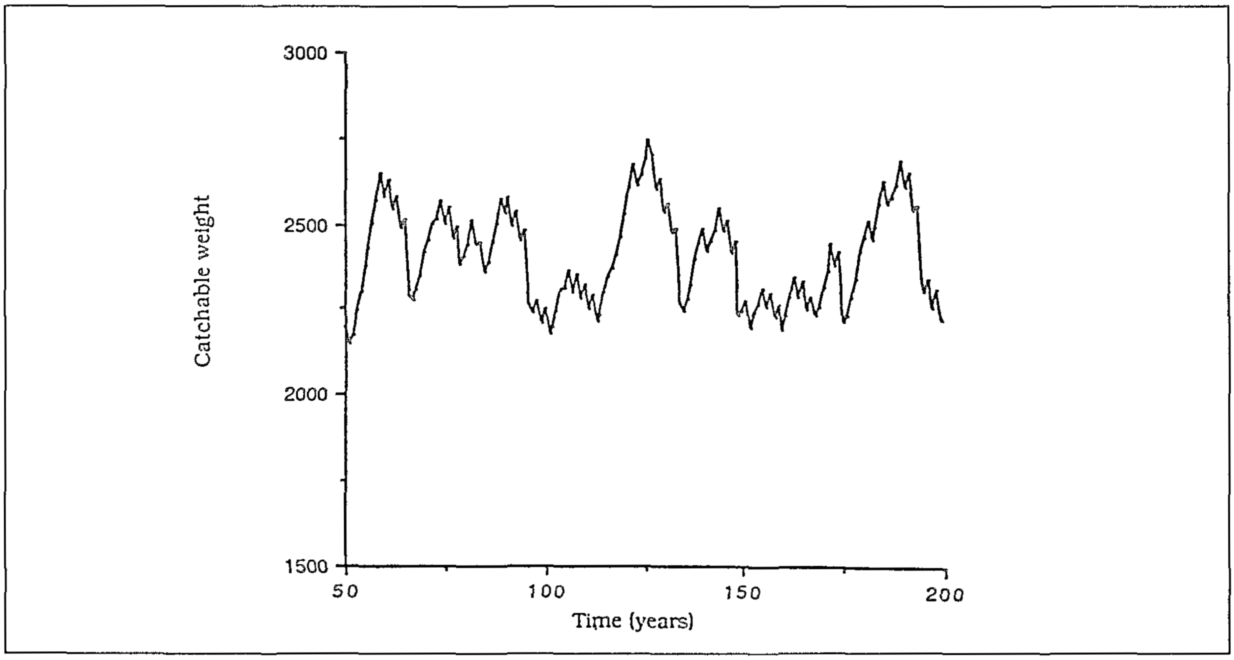


Fig. 2 - Catchable weight of cod with light fishing chaotic and random variability both

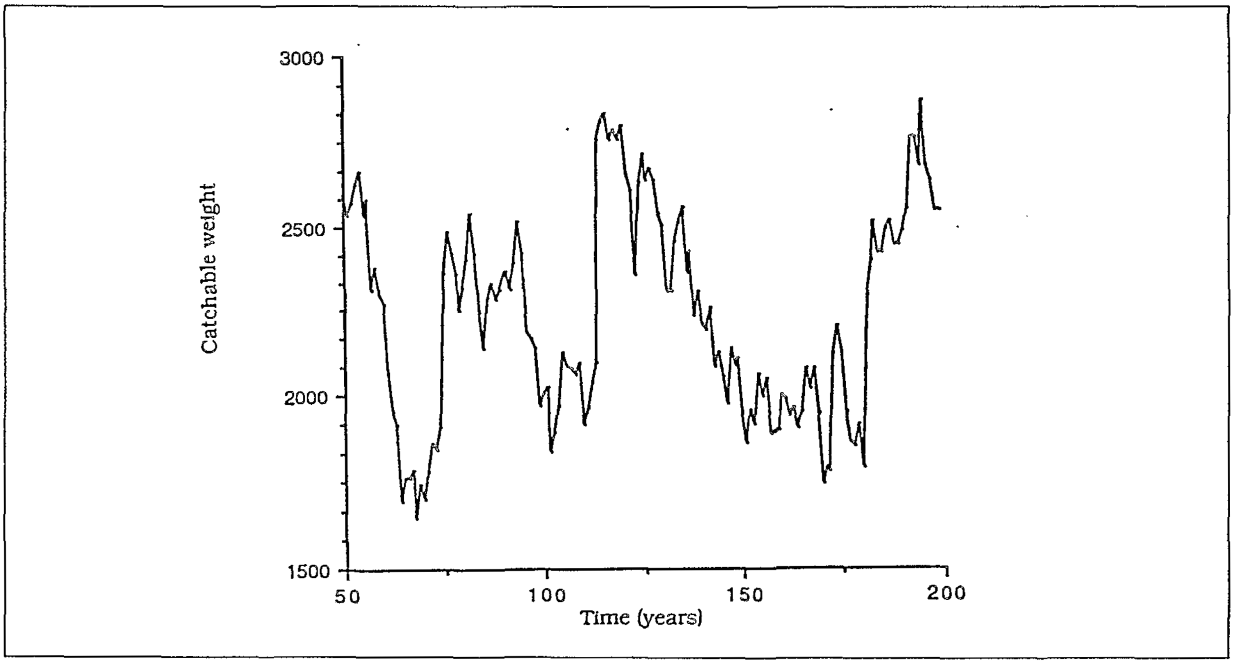


Fig. 3 - The economic submodel

In any given year the allocation of fishing effort is determined by the relative prices of species, assumed constant here, and the production possibilities curve (the sections of ellipses shown). The shape and position of the production possibilities curve is determined by the abundance of each species each year. The ellipse shape shows the diminishing returns fishermen experience over the course of a single year as more and more of a stock is harvested.

The optimal allocation of effort occurs when the returns to harvesting each species are proportional to the relative prices of the species. This is shown as points E1 (for one year) and E2 (for some other year in which the abundance of the two stocks is different) in the diagram. In year 1 harvests of A1 and B1 occur. In the other year harvests of A2 and B2 occur.

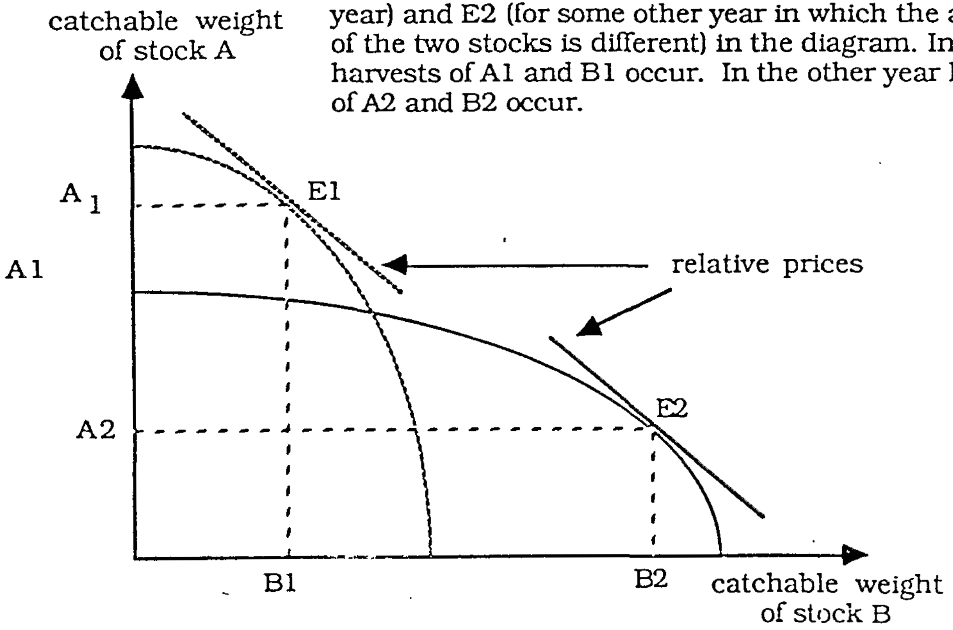


Fig. 4 - Catch vs. effort with switching

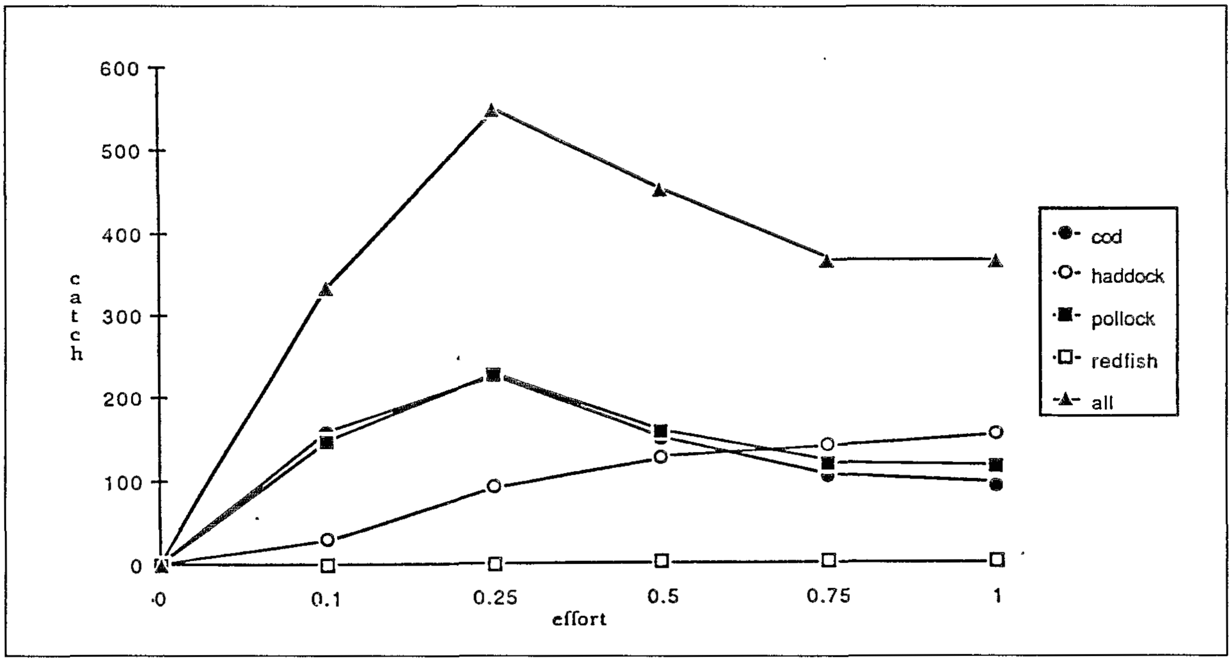


Fig. 5 - Stock variability with switching

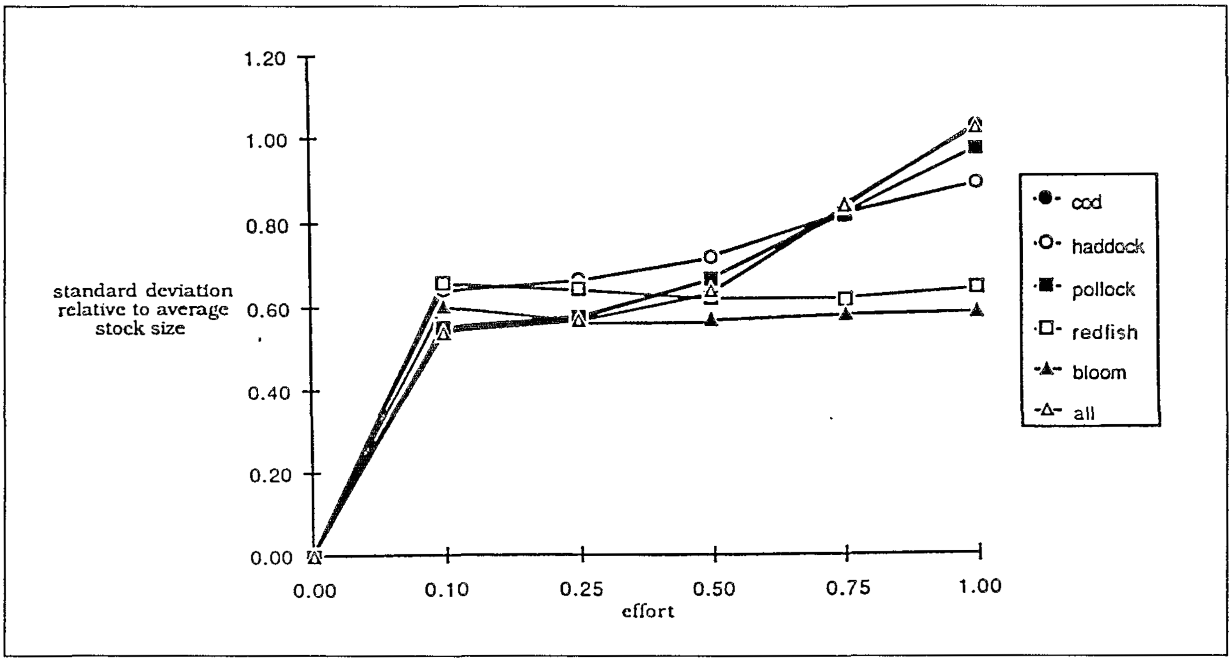


Fig. 6 - Age (year class) distribution for cod with light fishing

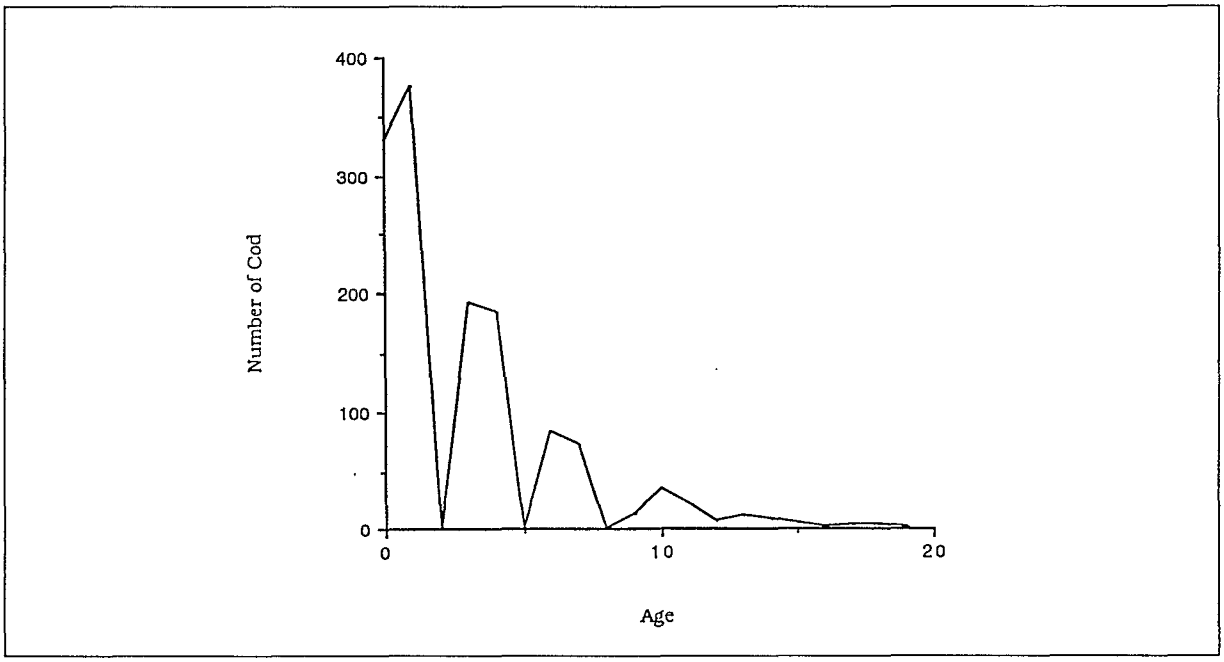
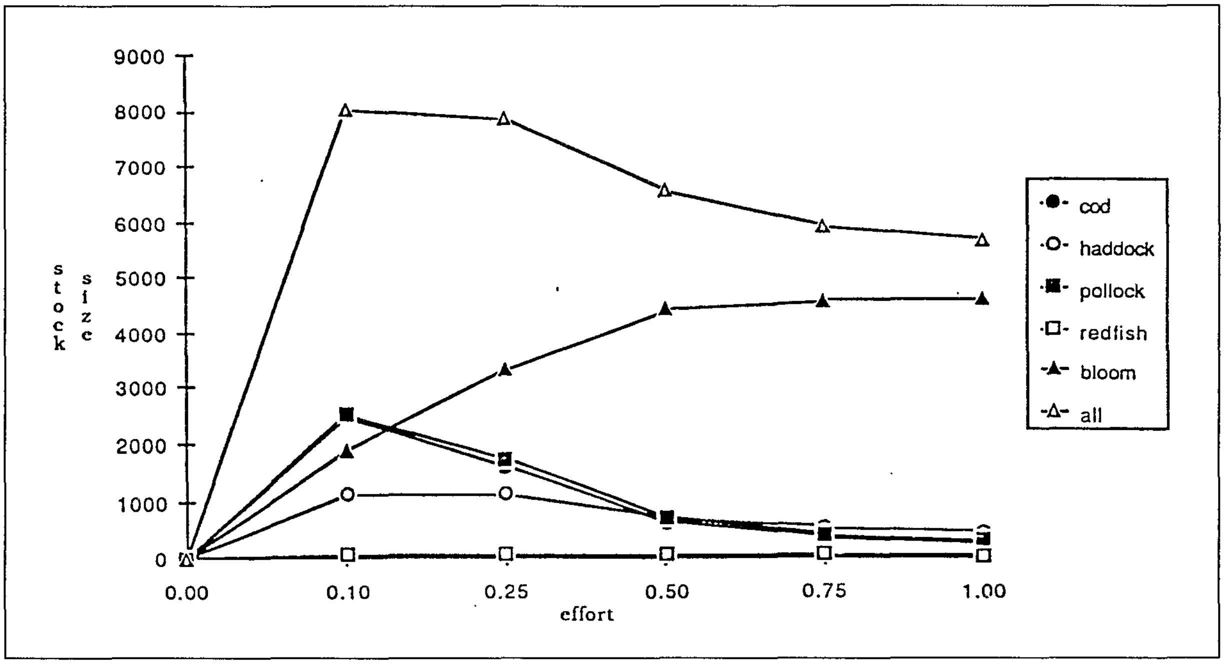


Fig. 7 - Stock size vs. effort with switching



of catch and stock sizes. In addition, the stock of each of the exploited populations tends to decline at a fractional rate faster than catch (Fig. 7 and Tab. 1a) while the population of the unexploited bloom species increases. Further increases in effort lead to a decline in the catch and stock of the exploited species and a very pronounced increase in the variability. At these very high levels of effort the fishery is characterized by occasional strong year classes which (if they occur in one of the exploited species) are very rapidly fished down (Fig. 8).

In short, our model shows the same basic effects as a sustainability model except it predicts, in addition, the typically observed increasing variability of catch and stocks with heavy fishing. For purposes of management this is not a trivial difference as we will discuss below.

Case 2,in which a constant level of effort is assigned to each species, was designed to provide a "control" against which the biological and economic effects of fishermen's switching behavior could be evaluated. Switching is a well documented phenomenon, not only in fisheries but also in other renewable resource based activities. James Acheson (1988) for example, thoroughly describes the switching of Maine fishermen in response to seasonal changes in the abundance of various species. Brush (1980), describes similar behavior among Peruvian potato farmers in response to unpredictable variations in climate and yield at different altitudes. Almost all the examples in the literature are of switching in response to unpredictable seasonal variations in the environment. Our model does not contain seasonal effects, but it does exhibit longer term variability that is qualitatively similar. The rationality of switching is intuitively obvious if one perceives the environment to be highly variable. Switching behavior may be costly to the fisherman in that it requires learning about a much broader spectrum of the environment and usually means the acquisition of more specialized gear than would otherwise be required. If the alternative is to starve or be subject to wide fluctuations in income, such costs may be very acceptable.

To generate the control case (2) the model was modified to remove the economic allocation rule described above. In effect, the simulator now represents a situation where fishermen were not capable (for regulatory or other reasons) of switching. For each level of effort described in the switching case above, a strictly comparable long run average catch rate (by weight) was calculated for the non-switching case. The non-switching model was then run at these comparable levels of effort.

When the results for the non-switching model for all levels of effort are compared with the switching model, the overall trends are very much the same, especially at low levels of effort (Fig. 9). The catch of each species rises rapidly at low levels of effort and is very close to the catch realized with switching. Variability also rises but less rapidly than catch (Fig. 10). At higher levels of effort, as in the switching case, catch declines and variability continues to rise. However, significant differences in catch occur at the highest level of effort. With switching the catch of the three major species (cod, haddock and pollock) tends to be seven to eleven percent higher than without switching (Tab. 1a and 1b). This higher catch with switching is very interesting because it points out a surprising biological effect of switching. First, catch can only be higher with switching because there are larger populations, since catch rates are identical with and without switching. These higher population levels (about four to six percent for the three major populations) arise from the fact that with switching, fishing effort tends to be allocated away from (towards) a species as that species population declines (rises). The biological impact of these allocation effects is stronger at low population levels because it is at low populations that small differences in spawning populations become important.

From the fisherman's perspective the rationality of switching is strongly confirmed by the model. For a fisherman who is free to switch among the various species in the environment, high levels of population variability mean that when one population is low, effort can be redirected towards more abundant populations. Table 1a and 1b show that for each species at all levels of effort, the variability of catch tends to be higher with switching than it is without switching; but the variability of the weight or size of each population tends to be about the same or lower with switching. In effect, because the economic decision rule causes fishermen to favor more abundant species, switching causes the catch of each species to vary to a greater extent than population.

Fig. 8 - Age class distribution of cod at fishing effort of 1.0

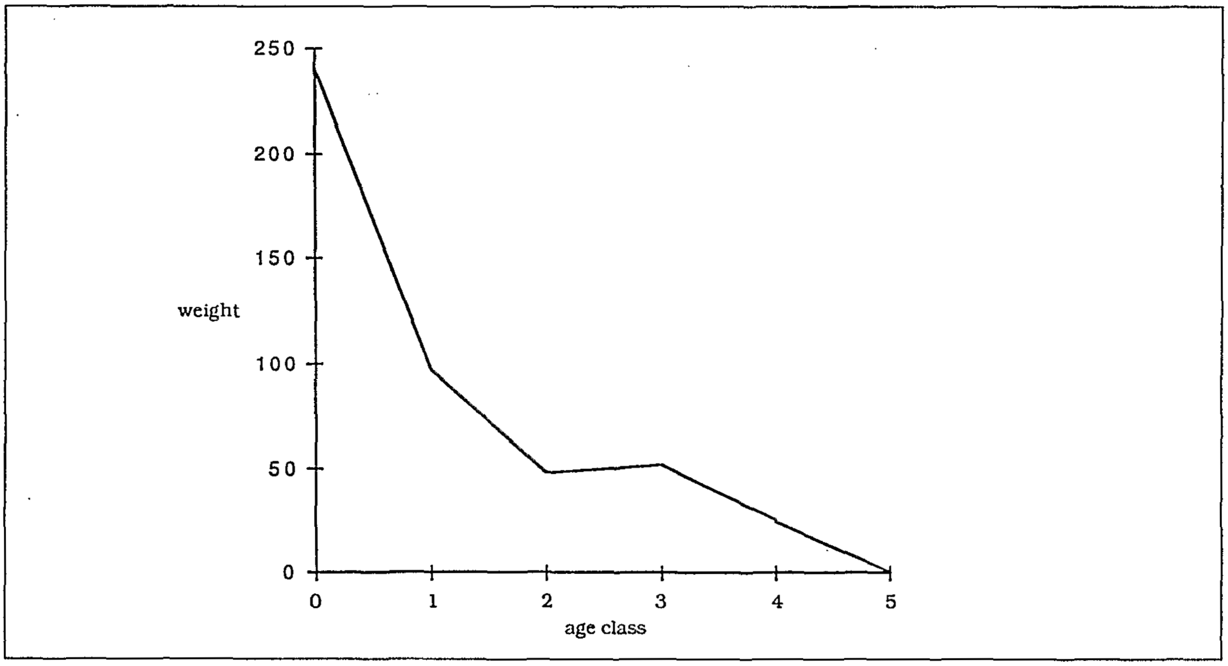


Fig. 9 - Catch vs. effort without switching

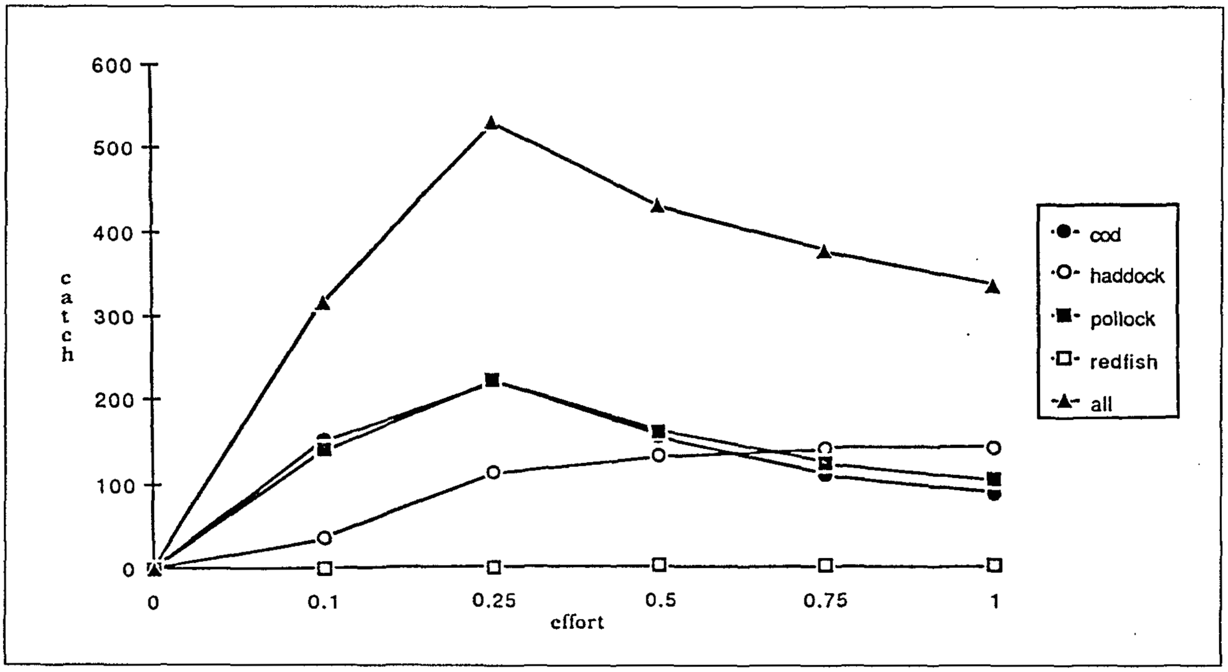


Fig. 10 - Variability of catch at various levels of effort without switching

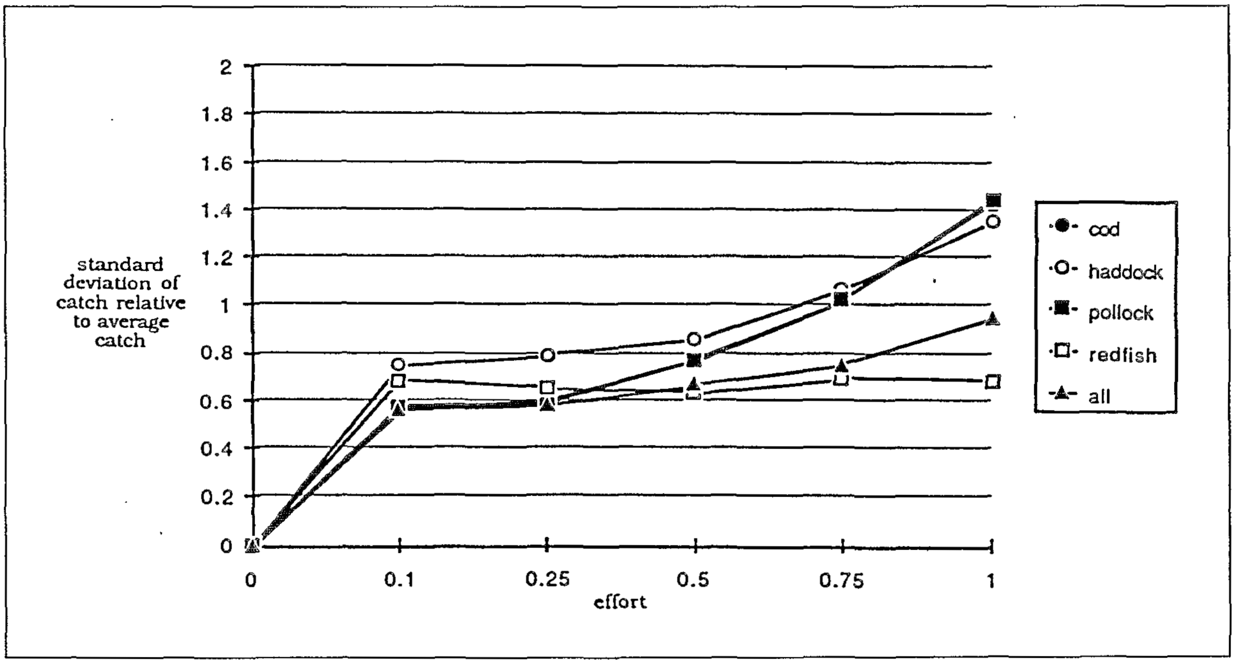
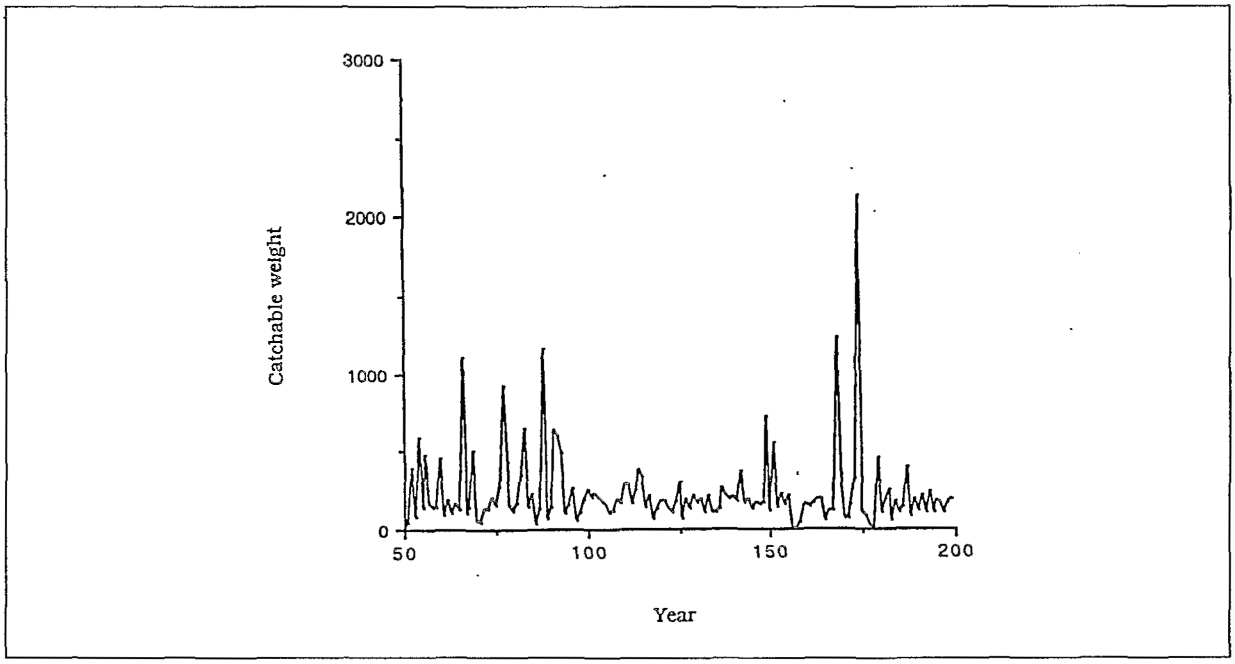


Fig. 11 - Catchable weight of haddock with heavy fishing



By far the most important effect of switching, from the fisherman's perspective, is that it dramatically reduces the variability of revenue. For the fisherman who switches the relevant variability is the variability in the combined catch of all four exploited species. For the non-switching fisherman, the relevant variability is the variability in the catch of each species. Again, inspection of tables 1a and 1b shows that this benefit of switching is most apparent at high levels of fishing effort, where the variability of total revenue for switching fishermen is generally in the range of 35-45 % lower for switching. At the very lowest levels of effort, switching tends to reduce the variability of revenue but by only about 5-20 %, still significant but generally less than half of the difference that occurs with heavy fishing. Since catch with switching is generally close to or above catch without switching, the reduction in the variability of income that arises with switching constitutes a significant economic benefit that is attained by adaptive fishermen. In this way, the model confirms the often observed advantages of non-specialization in a highly variable environment.

4. DISCUSSION

As we note above, a view of the biological environment that emphasizes its highly variable or chaotic characteristics leads to a perspective on some of the basic processes at work in fisheries that is different from that provided by equilibrium models. In the switching example just discussed, the implications of this different perspective are relatively straightforward ; namely, the often observed switching behavior of fishermen appears to have both biological and economic benefits. These benefits arise only because of the variability in the system. If one views the fishery as if it were an equilibrium system, the benefits of switching would simply not be apparent. From this latter perspective, species-specific schemes that attempt to stabilize effort and catch are entirely reasonable. In fact, it is entirely possible that a person or agency with this perspective might tend to view the increasing variability of catch caused by switching as an undesirable source of instability in the fishery. However, if one perceives the environment as highly variable, one tends to view regulatory attempts to stabilize species-specific fisheries as socially and economically costly and unlikely to succeed. In short, in this regard our model suggests a fundamentally different perspective on the processes and regulatory possibilities inherent in fisheries.

Another significant difference between our model and the usual equilibrium model concerns the relationship between effort and variability. In our model as effort is increased stock sizes decline and, in contrast to the usual models, there is a marked increase in the variability of catch, stock size and other measures of the state of the fishery. In a very heavily fished state, relatively strong year classes occasionally appear (Fig. 11). These strong year classes attract a high level of effort and, thus, are quickly fished out.

This pattern suggests an entry process in heavily exploited fisheries that would not be anticipated with a sustainability model. For example, it is typically the case that the relatively certain knowledge available to a potential investor is the immediate and very near term state of the fishery (that knowledge being determined by the juvenile and catchable age year classes currently in the fishery) and the long term average yield of the fishery. In a heavily fished fishery, investments timed to the occurrence of the occasional strong year class could be profitable, even though the long term average yield from the fishery might be insufficient to sustain profitable investment. An entry process like this leads to an upward effort even in a very heavily fished fishery. A pattern of this sort is qualitatively very similar to those observed in the heavily harvested fisheries of Georges Bank.

This suggests that the observed entry in real fisheries is likely to be much greater than one might predict with equilibrium models. It also suggests, unlike an equilibrium model, that reductions in effort might be achieved simply by imposing a required delay on the entry of new effort - i.e., a delay long enough to remove the certainty of the knowledge about the state of the fishery at the time a new boat enters. Under these conditions, rational investment could not take advantage of the certainty of near term knowledge of the fishery and would cease at a total level of effort much lower than observed. An equilibrium model, on the other hand, suggests only much more draconian and, generally unsuccessful, direct regulatory reductions in effort.

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Table 1a - Case 1 - Fishing in a nearly unregulated (switching) environment
Age of first capture at maturity - Price fixed

		Level of fishing effort					
		0.00	0.10	0.25	0.50	0.75	1.00
cod	average total weight	3045	2469	1605	630	338	245
	standard deviation	1716	1370	929	421	279	251
	Stand. dev. / average	0.56	0.55	0.58	0.67	0.83	1.02
	average catch (revenue)*	2	158	228	150	104	93
	standard deviation	1	94	145	129	143	184
	Stand. dev. / average	n/a	0.59	0.64	0.86	1.38	1.97
	avg. share of total biomass	0.38	0.31	0.20	0.10	0.06	0.04
haddock	average total weight	932	1114	1123	703	536	467
	standard deviation	667	714	746	505	437	414
	Stand. dev. / average	0.72	0.64	0.66	0.72	0.82	0.89
	average catch (revenue)*	0	29	92	127	140	155
	standard deviation	0	29	91	143	200	261
	Stand. dev. / average	n/a	1.00	0.99	1.13	1.43	1.69
	avg. share of total biomass	0.12	0.14	0.14	0.11	0.09	0.08
pollock	average total weight	2643	2515	1729	710	410	314
	standard deviation	1485	1382	991	473	334	306
	Stand. dev. / average	0.56	0.55	0.57	0.67	0.81	0.97
	average catch (revenue)*	2	147	229	158	119	114
	standard deviation	1	86	143	139	164	213
	Stand. dev. / average	n/a	0.59	0.62	0.88	1.38	1.86
	avg. share of total biomass	0.33	0.31	0.22	0.11	0.07	0.06
redfish	average total weight	31	50	66	63	52	42
	standard deviation	23	33	42	39	32	27
	Stand. dev. / average	0.72	0.66	0.64	0.62	0.62	0.64
	average catch (revenue)*	0	0	0	1	1	2
	standard deviation	0	0	0	1	1	2
	Stand. dev. / average	n/a	1.00	0.97	0.97	1.09	1.31
	avg. share of total biomass	0.00	0.01	0.01	0.01	0.01	0.01
bloom	average total weight	1408	1880	3332	4435	4582	4617
	standard deviation	874	1130	1875	2514	2654	2701
	Stand. dev. / average	0.62	0.60	0.56	0.57	0.58	0.59
	average catch (revenue)*	0	0	0	0	0	0
	standard deviation	0	0	0	0	0	0
	Stand. dev. / average	n/a	n/a	n/a	n/a	n/a	n/a
	avg. share of total biomass	0.17	0.23	0.42	0.68	0.77	0.81
total	ave. total weight	8059	8028	7855	6541	5918	5685
	ave s.d. of total weight	4765	4629	4583	3952	3736	3699
	tot. ave. catch (revenue)*	n/a	334	548	452	364	364
	standard deviation		181	312	287	303	371
	Stand. dev. / average		0.54	0.57	0.64	0.83	1.02

* With prices fixed (as assumed) catch and revenue are proportional

Table 1b - Case 2 - Fishing in a non switching environment
Age of first capture at maturity - Price fixed

		Level of fishing effort					
		0.00	0.10	0.25	0.50	0.75	1.00
cod	average total weight	2980	2358	1546	643	356	235
	standard deviation	1689	1348	907	472	315	255
	Stand. dev. / average	0.57	0.57	0.59	0.73	0.88	1.09
	average catch (revenue)*	2	151	220	154	109	87
	standard deviation	1	87	130	119	111	124
	Stand. dev. / average	n/a	0.58	0.59	0.77	1.02	1.43
	avg. share of total biomass	0.37	0.29	0.20	0.10	0.06	0.04
haddock	average total weight	915	1395	1356	723	538	448
	standard deviation	600	1039	1050	548	446	406
	Stand. dev. / average	0.66	0.74	0.77	0.76	0.83	0.91
	average catch (revenue)*	0	36	111	131	141	141
	standard deviation	0	27	88	112	150	191
	Stand. dev. / average	n/a	0.75	0.79	0.85	1.06	1.35
	avg. share of total biomass	0.11	0.17	0.17	0.11	0.09	0.08
pollock	average total weight	2689	2381	1677	723	423	296
	standard deviation	1520	1355	987	519	363	307
	Stand. dev. / average	0.57	0.57	0.59	0.72	0.86	1.04
	average catch (revenue)*	0	139	222	161	123	103
	standard deviation	0	79	133	124	126	149
	Stand. dev. / average	n/a	0.57	0.60	0.77	1.02	1.45
	avg. share of total biomass	0.33	0.30	0.21	0.11	0.07	0.05
redfish	average total weight	32	51	65	65	55	44
	standard deviation	25	34	41	41	35	28
	Stand. dev. / average	0.79	0.67	0.63	0.63	0.64	0.64
	average catch (revenue)*	0	0	0	1	1	2
	standard deviation	0	0	0	0	1	1
	Stand. dev. / average	n/a	0.68	0.65	0.63	0.70	0.68
	avg. share of total biomass	0.00	0.01	0.01	0.01	0.01	0.01
bloom	average total weight	1450	1849	3222	4428	4577	4617
	standard deviation	890	1094	1868	2512	2643	2700
	Stand. dev. / average	0.61	0.59	0.58	0.57	0.58	0.58
	average catch (revenue)*	0	0	0	0	0	0
	standard deviation	0	0	0	0	0	0
	Stand. dev. / average	n/a	n/a	n/a	n/a	n/a	n/a
	avg. share of total biomass	0.18	0.23	0.41	0.67	0.77	0.82
total	ave. total weight	8066	8034	7866	6582	5949	5640
	ave s.d. of total weight	4724	4870	4853	4092	3802	3696
	tot. ave. catch (revenue)*	n/a	317	530	427	374	333
	standard deviation		177	308	285	282	316
	Stand. dev. / average		0.56	0.58	0.67	0.75	0.95

* With prices fixed (as assumed) catch and revenue are proportional