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Recovery  
of  
Three Bering Sea Type  
Fish Populations  
from  
Catastrophic Larval Mortality  
— A Simulation Approach

April 1985

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RECOVERY OF THREE BERING SEA TYPE FISH POPULATIONS  
FROM CATASTROPHIC LARVAL MORTALITY  
- A SIMULATION APPROACH

By

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## ABSTRACT

One approach towards elucidating fish stock and recruitment relationships is to simulate how changes in early stage mortality affect the exploitable stock biomass. Predation, starvation and pollution are known contributors to early larval mortality. This study examines the effects of losses due to oil contamination on recruitment to exploitable biomass. Simulation methods are used to project larval mortalities caused by possible accidental release of oil through time for three commercial Bering Sea fish stocks, Atka mackerel (*Pleurogrammus monopterygius*), walleye pollock (*Theragra chalcogramma*) and Pacific ocean perch (*Sebastes alutus*). Two hypothesized relationships between adult and new recruit biomass are used. Case I models annual recruit biomass (Age 1) as a proportion of the previous year's reproducing adult biomass. Assuming no density dependence, a catastrophic mortality of all Age 1 fish permanently lowers exploitable biomass for all three species. Perch biomass declines the least and mackerel the most, although losses to the latter species are obscured by its high interannual recruitment variation. In Case II, with no spawning stock and recruitment relationship, recruit biomass is a proportion of the long term mean biomass. Under these conditions, populations respond to loss of all Age 1's by first declining, then returning to near pre-oil spill biomass after the year class cycles through. Results of early mortality on each species are discussed in light of life history differences between species. Ideas for further use of the



simulation are also presented.

## INTRODUCTION

"...it seems to me that even though there be governing causes of mortality that may result in a true law of mortality, any group of lives studied is so heterogeneous, due to differences in...climate, race, physical characteristics, etc. that any formula must in practice be considered merely to be a generalization of what is actually happening." (Elston, 1923 p.68)

Current fisheries research continues to tackle the problem of the relationship between spawning stock and subsequent recruits as an important key to effective stock management. Increased understanding of stock and recruit relationships will arise from ongoing studies of larval stage mortality and growth but progress is slow due to high spatial and temporal variability. Meanwhile, model simulation of larval mortality and resulting effects on recruitment can aid in delineating the expected range of response to environmental perturbation.

Early mortality in marine fish has been attributed to consumption by predators (Lebour, 1923; Theilacker and Lasker, 1974; Hunter, 1976; Alvarino, 1980; McGowan and Miller, 1980; Frank and Leggett, 1983; and additional references in Hunter 1981; 1983), starvation (Hunter and Kimbrell, 1980; Beyer and Laurence, 1980) as well as to marine pollution (Nelson-Smith, 1972; Kuhnhold, 1972; Rosenthal and Alderdice, 1976; Kuhnhold et.al., 1978; IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN, 1977; additional references in Bax, 1985). The purpose of this study was to simulate the impact of catastrophic first year mortality due to oil contamination in marine fish, and to project biomass losses to the exploitable stock through time. A stock as used in this

paper refers to a group of fish spawning in the same place and time; no allowance has been made for discrete spawning units. Thus the catastrophic loss applies to all potential recruits to that stock.

#### DESCRIPTION OF THE MODEL

A biomass-based, single species simulation model was programmed to run on a Columbia PC to study the impacts of losses of fish eggs and larvae on subsequent year class strengths. Three commercially important Bering Sea fish species with dissimilar life history patterns (Table 1) were selected to demonstrate potential stock biomass responses to catastrophic first year mortality following an (hypothetical) oil spill. Stable population age structures for Atka mackerel, walleye pollock and Pacific ocean perch corresponding to long-term mean data from Niggol (1982) and Bakkala and Low (1983) were used (Table 2). For convenience, each species was initially ascribed 100 units of biomass. Oil loss effects on exploitable biomass were analyzed by first deriving a general simulation, then running separate simulations with data from each species. Each set of simulations contrasted two hypothesized relationships between recruit and adult biomass. The first case modelled recruit biomass as a proportion of the previous years' spawner biomass; the second assumed no spawner and recruit relationship. Interannual recruitment variability was determined empirically for each

Table 1. Model Inputs: Life history parameters of Bering Sea Pacific ocean perch, Atka mackerel and walleye pollock.

SPECIES	TYPICAL LIFESPAN (years)	EXPLOITABLE AGES	REPRODUCTIVE AGES	SPAWNING MODE	SPAWNING SEASON	COEFFICIENT OF VARIATION (recruits)	HABITAT (adults)	FECUNDITY (eggs)	SOURCES
PACIFIC OCEAN PERCH	20	11-20	6-20	ovoviviparous	Mar.-May	0.23	demersal	27,000 - 180,000	Niggol 1982 Bakkala & Low 1983
WALLEYE POLLOCK	12	3-12	3-12	oviparous	Mar. -June	0.47	semi-demersal	186,000 - 600,000	Niggol 1982 Bakkala & Low 1983
ATKA MACKEREL	7	2-6	3-7	oviparous	June -Aug.	0.95	pelagic	5000 - 43,000	Niggol 1982 Macy et.al. 1978 Bakkala & Low 1983

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Table 2. Model Inputs: Growth coefficients (G), stable age structure in 100 biomass units (B), and mortality coefficients (M) for Pacific ocean perch, Atka mackerel and walleye pollock. (Niggol, 1982).

SPECIES	INPUT	AGE CLASSES																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PACIFIC OCEAN PERCH	B	5.2	6.8	9.7	9.6	9.1	8.5	7.8	7.4	6.7	5.9	4.9	4	3.4	2.8	2.3	2.3	1.6	1.1	0.7	0.4
	G	1.38	0.95	0.512	0.37	0.306	0.258	0.254	0.174	0.153	0.155	0.103	0.084	0.076	0.061	0.054	0.035	0.019	0.004	-0.01	
	M	1.12	0.6	0.52	0.42	0.38	0.34	0.32	0.28	0.28	0.3	0.28	0.25	0.26	0.27	0.28	0.31	0.36	0.44	0.59	
WALLEYE POLLOCK	B	6.6	12	13.6	14.2	13	11.5	9.7	7.6	5.3	3.4	2.1	1								
	G	1.398	0.686	0.554	0.385	0.264	0.144	0.112	0.087	0.077	0.059	0.047									
	M	0.8	0.56	0.513	0.47	0.385	0.322	0.354	0.451	0.513	0.517	0.752									
ATKA MACKEREL	B	29.7	26.5	19	12	7.2	3.8	1.8													
	G	0.569	0.312	0.162	0.107	0.067	0.5														
	M	0.71	0.65	0.62	0.6	0.7	0.78														

species and entered into the model.

#### CHARACTERISTICS OF SELECTED SPECIES

##### Atka mackerel

Atka mackerel are distributed across the North Pacific east of 165 W and north of 44 N (Figure 1). Though primarily pelagic, adult mackerel aged three or four begin moving inshore to spawn during May. Spawning peaks in summer in the straits between the Aleutian Islands, as females deposit sticky egg masses on kelp fronds or on stones. Each female produces three or four batches of eggs at 5-7 day intervals at preferred water temperatures of around 5-8 C. After a 40-45 day incubation period during which they would be especially susceptible to smothering or contamination from oil, newly hatched, planktotrophic larvae are dispersed with currents in the open ocean. They display some vertical migration; more larvae reside in the upper layers of the water column at night than during the day (Macy et.al., 1978).

##### Walleye pollock

Walleye pollock are one of the most abundant north Pacific fish. They are semi-demersal and inhabit deep waters of the north Pacific and Bering Sea to off central California (Figure 2). Walleye pollock prefer slightly colder temperatures than Atka

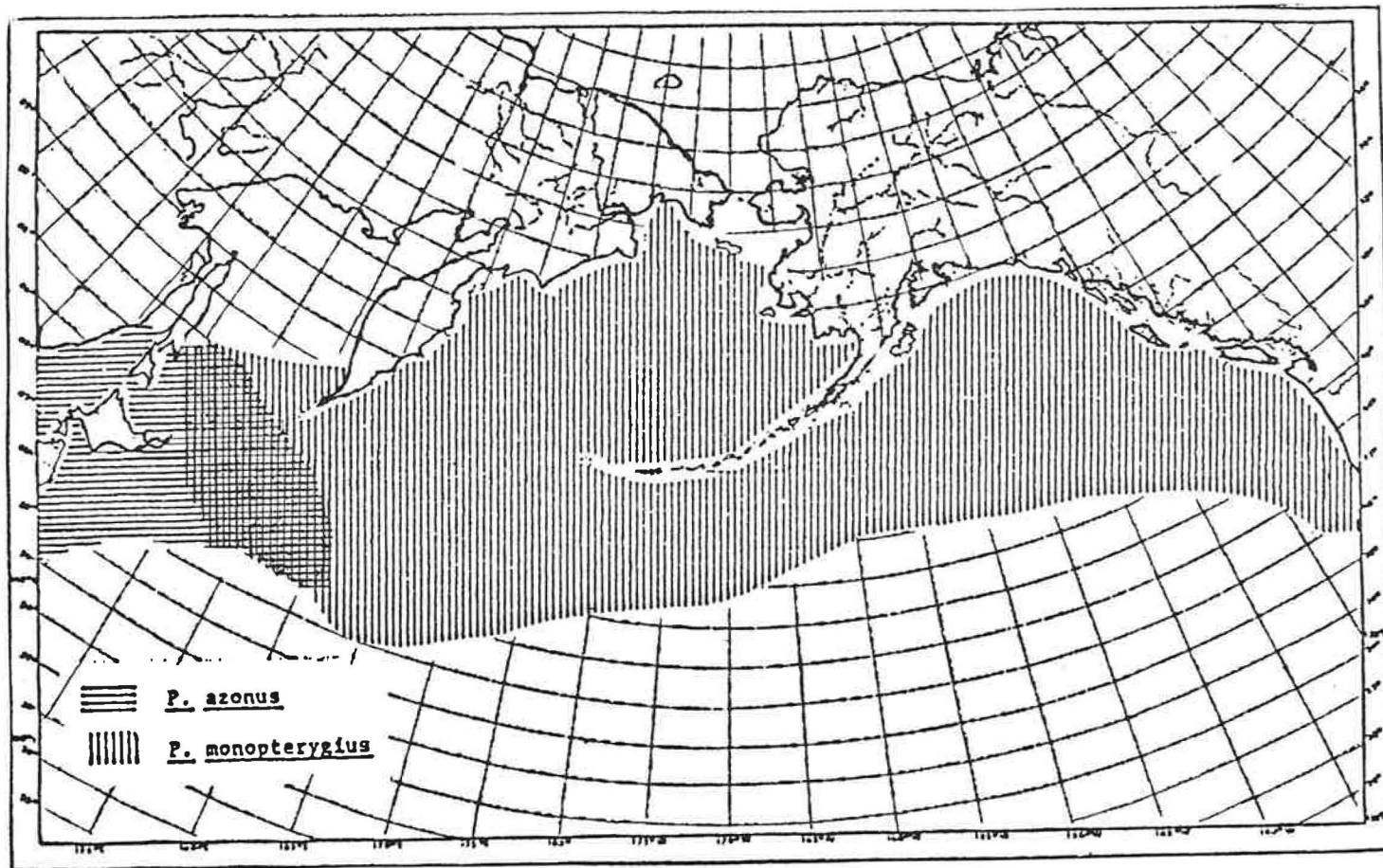


Figure 1. Presumed range of *Pleurogrammus monopterygius* and *P. azonus* in the North Pacific and Bering Sea. Both species are found further inshore than the map indicates (from Macy et.al., 1978).

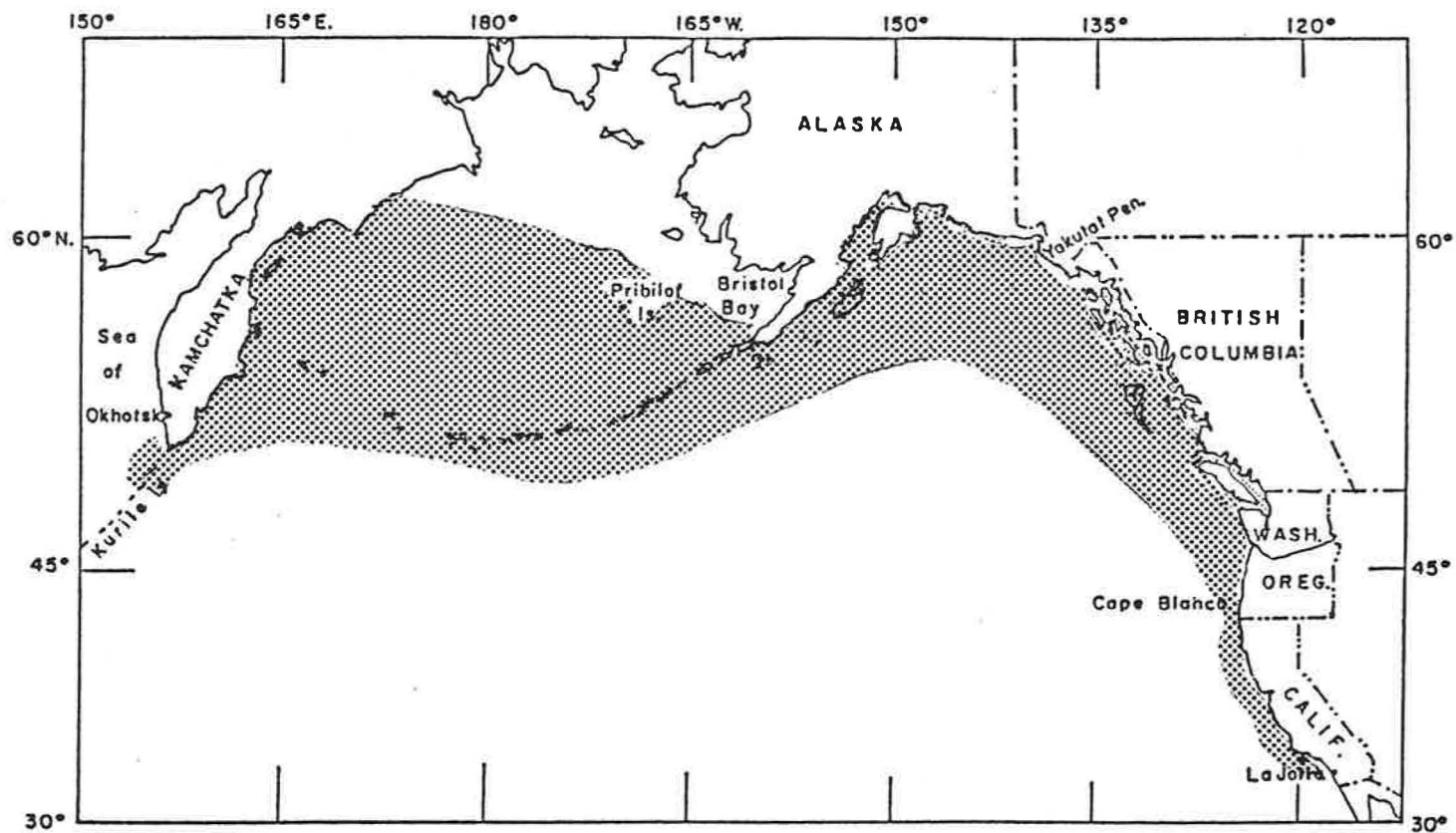


Figure 2. Distribution of walleye pollock, *Theragra chalcogramma* (Smith, 1981), modified.



mackerel, with optima between 2-5 C. Most of the population winters offshore, then migrates to spawning grounds on the southeastern Bering Sea continental slope and Gulf of Alaska shelf west and northwest of Unimak Island between February and May. During the spawning season which peaks in late April, three to four year (+) females release eggs that concentrate in the surface waters and hatch in about twelve days (at 6-7 C). Newly hatched larvae have been observed drifting offshore with local current systems which may promote larval survival. By age 1, walleye pollock achieve their broad oceanic distribution (Kasahara, 1961; Serobaba, 1975; Smith, 1981; Norcross and Shaw, 1984).

#### Pacific ocean perch

Pacific ocean perch were once a dominant ichthyofaunal component in the north Pacific (Major and Shippen, 1970; Gunderson, 1976). However, heavy fishing during the past two decades has reduced their numbers. Their trans-Pacific range (Figure 3) includes open ocean habitat as well as rocky bottomed gullies, caves and submarine depressions along the outer continental shelf and upper slope between 180 to 460 m. Bering Sea stocks of Pacific ocean perch mature at 6-7 years of age. They mate during January and February in Bristol Bay, southwest of the Pribilof Islands and in the Gulf of Alaska. Between March and May, females migrate to deep water (around 400 m) and release

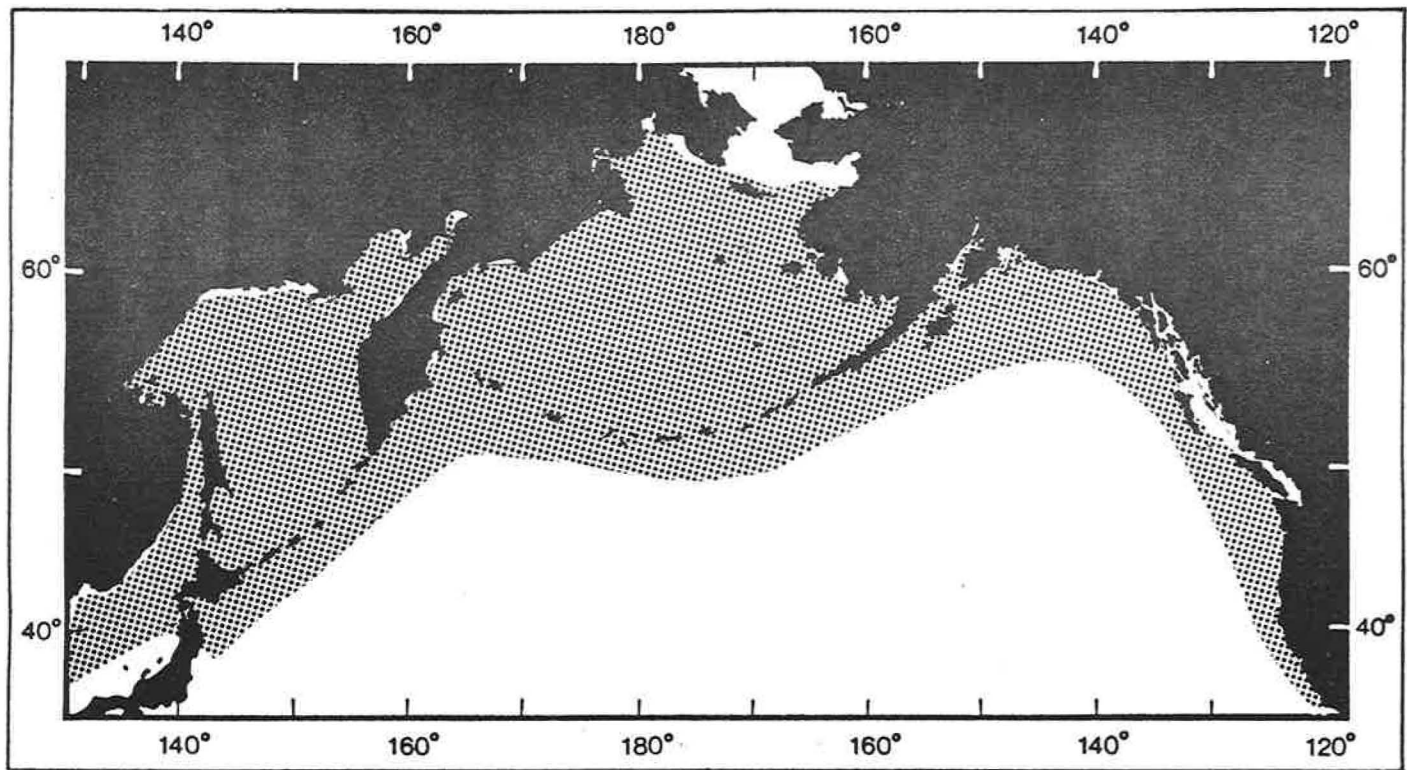


Figure 3. Distribution of Pacific ocean perch, *Sebastes alutus* (Major and Shippen, 1970), modified.

pelagic larvae in spawning episodes lasting three or four hours. Emergent larvae, 6-8 mm in length, remain pelagic for up to five years and feed on copepods and other crustaceans (Laevastu, pers. comm.). After two years, they develop demersal habits.

#### COMPUTATIONS

Yearly biomass changes in the stocks were simulated as follows:

$$B_{i+1,t+1} = B_{i,t} e^{G_i (B_{i,0} / B_{i,t}) - M_i} \quad (1)$$

where

- i - year class; i = (1,20) for Pacific ocean perch  
(1,7) for Atka mackerel  
(1,12) for Walleye pollock
- t - time (year); t = 0 at start of simulation
- B - biomass units; initially 100 units in population
- G - empirical growth coefficient
- M - mortality coefficient (natural + fishing mortality)
- e - natural constant (2.71828...)

Since the mortality schedule relating recruits to prior adult biomass is poorly known for most species (Cushing, 1971; Hunter, 1976; Gunderson, 1976), recruitment was simulated for both maximum effect and minimum effect cases under the assumption that actual population responses would lie somewhere between the two. In Case I, the maximum effect of oil losses on subsequent years' exploitable stock biomass was simulated assuming direct linear proportionality between stock and recruits (ages 0-1) biomass. Thus in years following the oil spill, the affected year class contributed zero biomass towards the exploitable stock. Case II assumed that recruited biomass was independent of parental

biomass, representing the control of recruit biomass via an environmental "window" that allowed only a prescribed number of larvae to successfully recruit no matter how many were spawned in a given year (Hempel, 1965). Recruit biomass was determined as the proportion of the equilibrium spawner biomass necessary to sustain that equilibrium biomass. Recruit biomass for year (t+1) was computed in year (t) for each case as follows:

Case I: Maximum effect of oil losses possible

$$R_{t+1} = S_{.t} * p \quad (2)$$

Case II: Minimum effect (environmental window)

$$R_{t+1} = S_{.0} * p \quad (3)$$

where

t, t+1 - time (years), and 0 denotes equilibrium year

. - denotes summation over mature age classes unique to each species: Pacific ocean perch = 11- 20  
Atka mackerel = 3- 7  
Walleye pollock = 3- 12

R - biomass recruited, based on a starting population biomass of 100 units

S - reproductive stock (no. of units) in a given age class, during a given year, (t)

p - species specific, empirically determined proportionality constant relating equilibrium population biomass to recruit biomass

Using empirical growth, mortality and biomass distribution data (Table 1), equations (1) and either (2) or (3) were computed for each species in one hundred year time series. Growth and mortality coefficients were adjusted slightly, if necessary,

until each population maintained a stable biomass over successive years. Justification for using a stable biomass model was presented in Laevastu and Larkins (1981, p.98). In year 1 of the study, each fish population had an age and biomass structure that totaled 100 units. Later age and biomass structures do not necessarily sum to 100.

Once the equilibrium population structure was obtained, early mortality due to an oil spill was simulated by setting first year fish biomass in year fifteen ( $R(15,1)$ ) equal to zero. Population responses to oil contamination losses were graphed both for individual year classes within species and for total exploitable biomass between species.

Annual recruitment variability due to unexplained fluctuations in the environment, predator and prey populations, adult fertility and other changing factors was included in the second set of simulations using a random number generator. For each species, a normally distributed, interannual coefficient of variation of recruits was matched to that obtained from available data (Bakkala and Low, 1983; Chikuni, 1975). Total exploitable biomass responses to 100% recruitment failure in year fifteen were then graphed for each species using Case I and Case II recruitment regimes. Density-dependent growth and mortality were omitted from the simulations for simplicity and because few relevant empirical data exist to support their inclusion (Gunderson, 1976).

## RESULTS

### Individual Year Class Effects

Responses of representative year classes to catastrophic loss of recruits under Case I and prior to inclusion of interannual recruitment variability, are illustrated in Figures 4-7. The first simulation (Figures 4-6) shows different between species responses: Atka mackerel declined the most, and Pacific ocean perch the least. An example of individual year class responses to 100% mortality of recruits and Age 2's (Figure 7) was included for comparison with Figures 4-6. For Atka mackerel, the effect of losing all of the two youngest year classes in one year was much greater than losing just one year class.

### Total Exploitable Biomass Effects

Total exploitable biomasses, the percent of each species utilized by commercial fisheries, were computed and their responses to 100% mortality of Age 0-1's were compared (Figure 8) prior to inclusion of interannual recruitment variability in the simulations. Atka mackerel biomass fell the most within a year of the oil kill, yet the population increased slightly before stabilizing. Pacific ocean perch declined the least, and showed no change until nearly a decade after the catastrophic event. Walleye pollock biomass fell nearly as rapidly as mackerel and

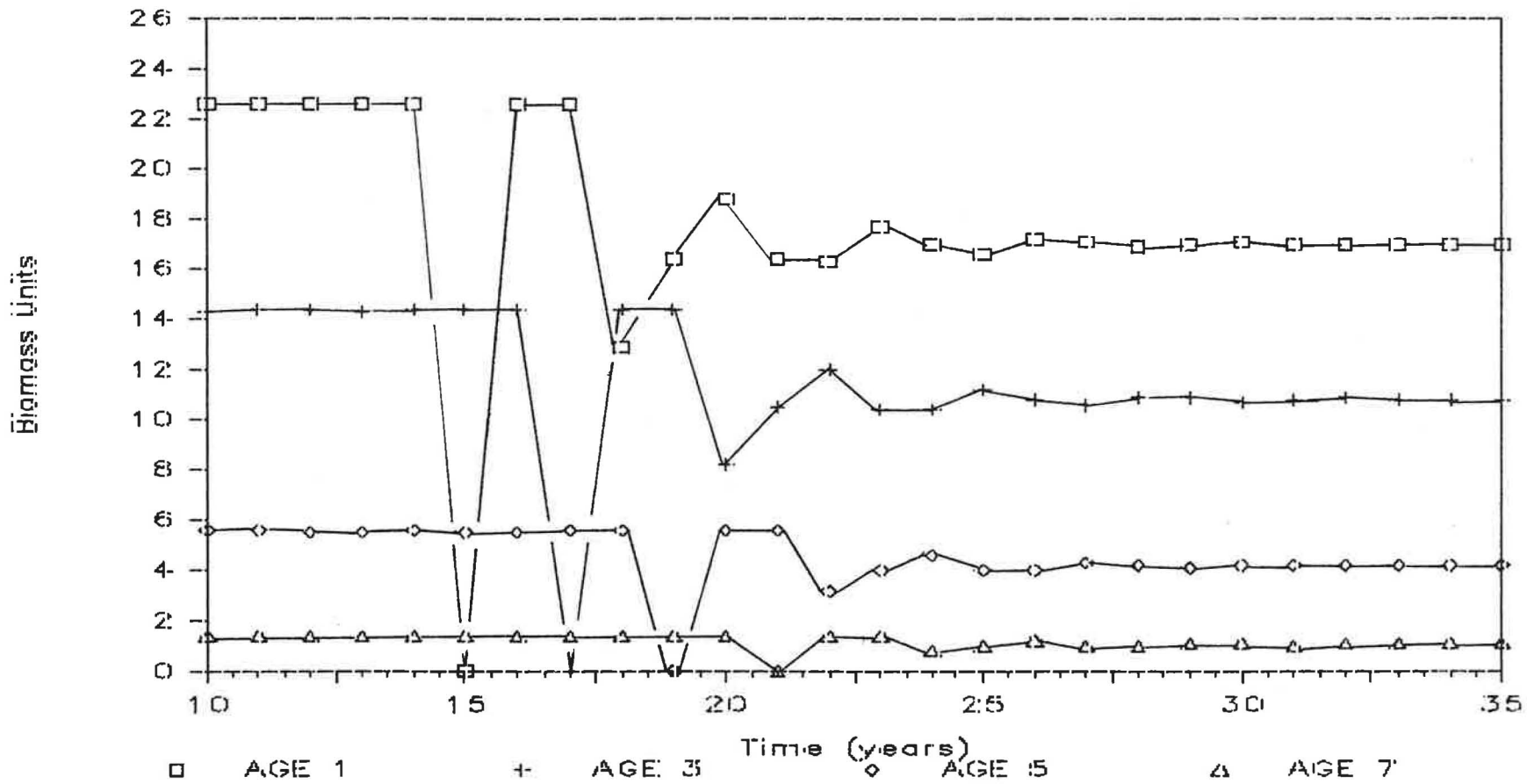


Figure 4. Effect of 100% mortality of Age 1 (0-1 year old) Atka mackerel in one year on the equilibrium biomass of selected year classes over time.

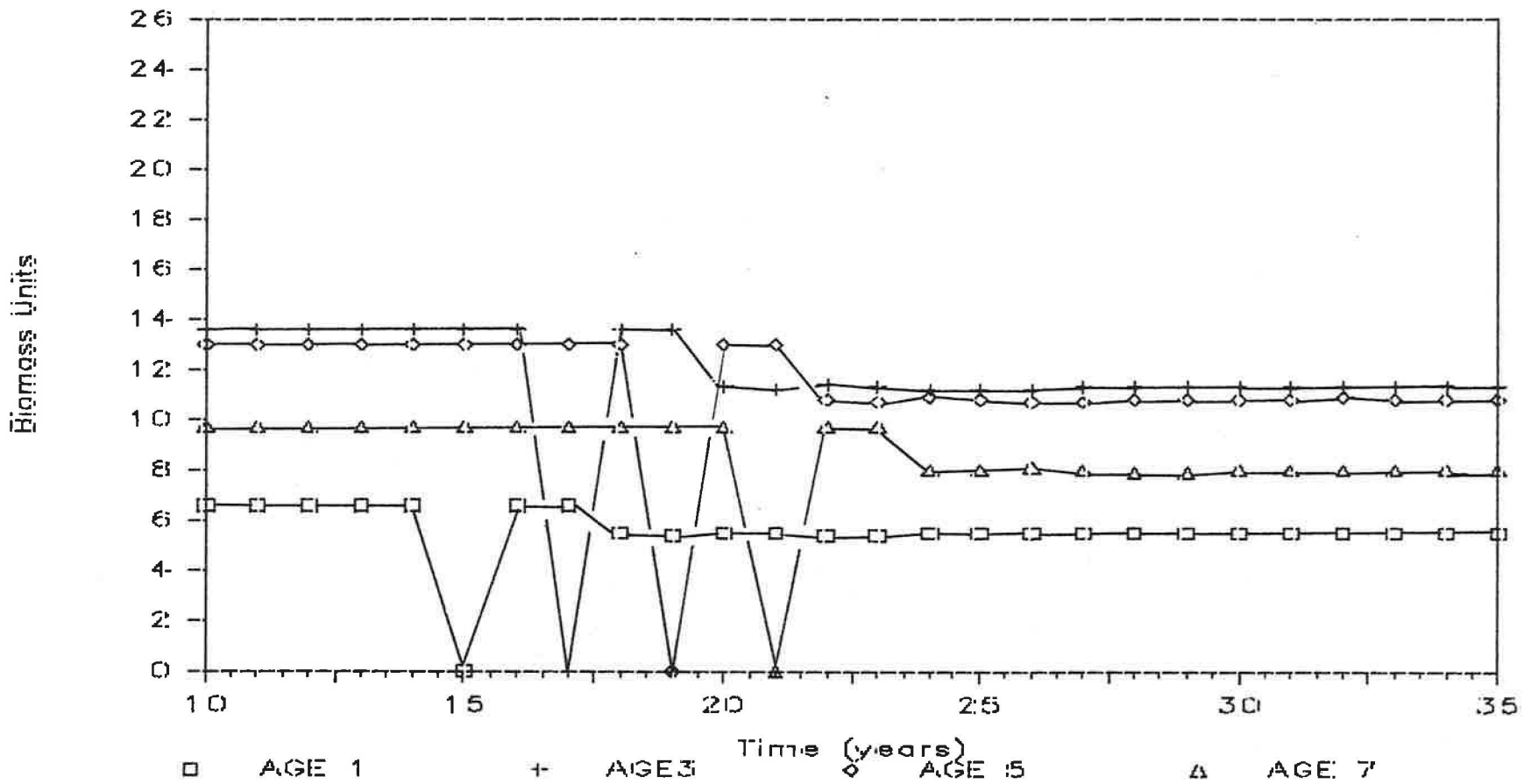


Figure 5. Effect of 100% mortality of Age 1 (0-1 year old) walleye pollock during one year on the equilibrium biomass of selected year classes.



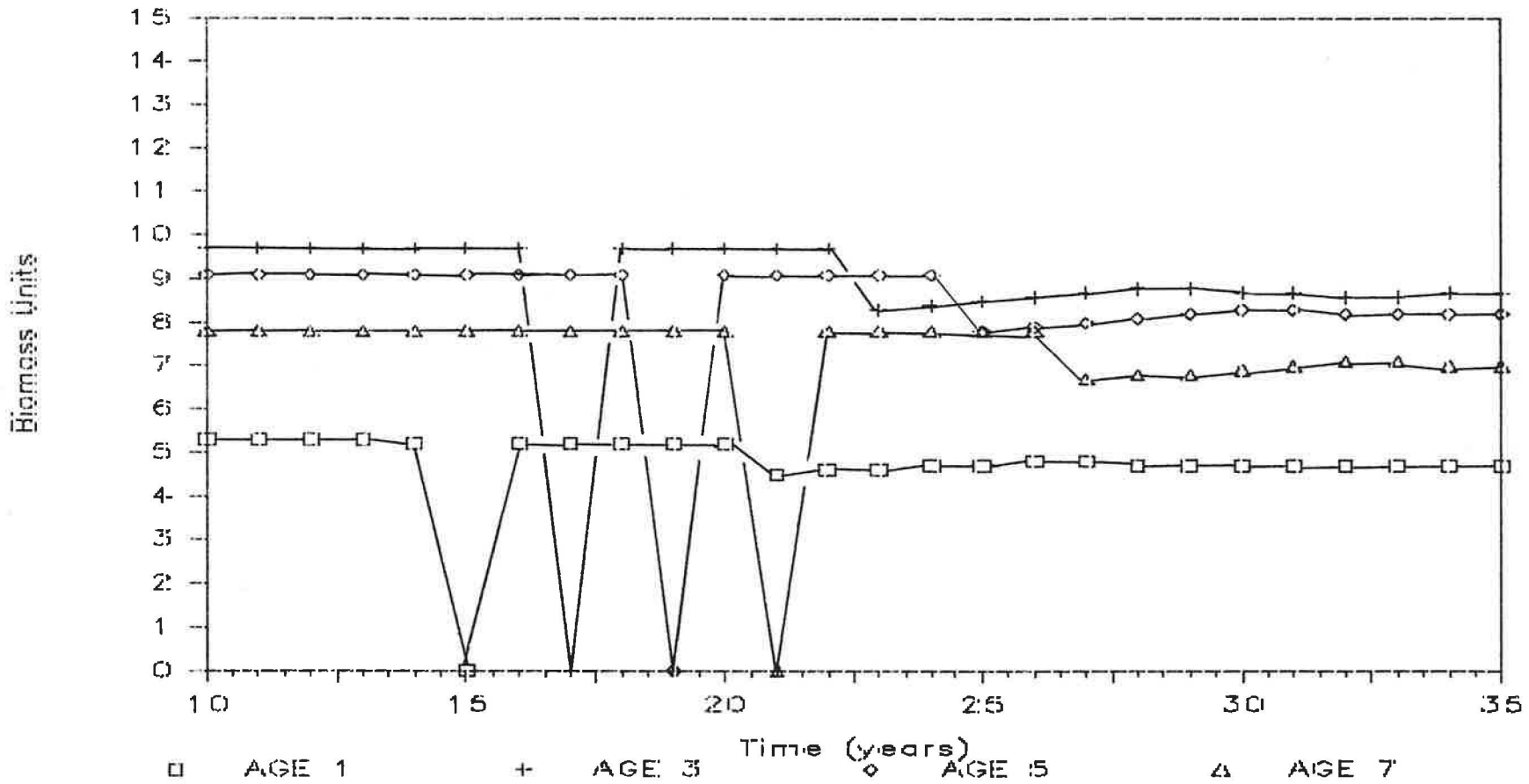


Figure 6. Effect of 100% mortality of Age 1 (0-1 year old) Pacific ocean perch in one year on the equilibrium biomass of selected year classes.

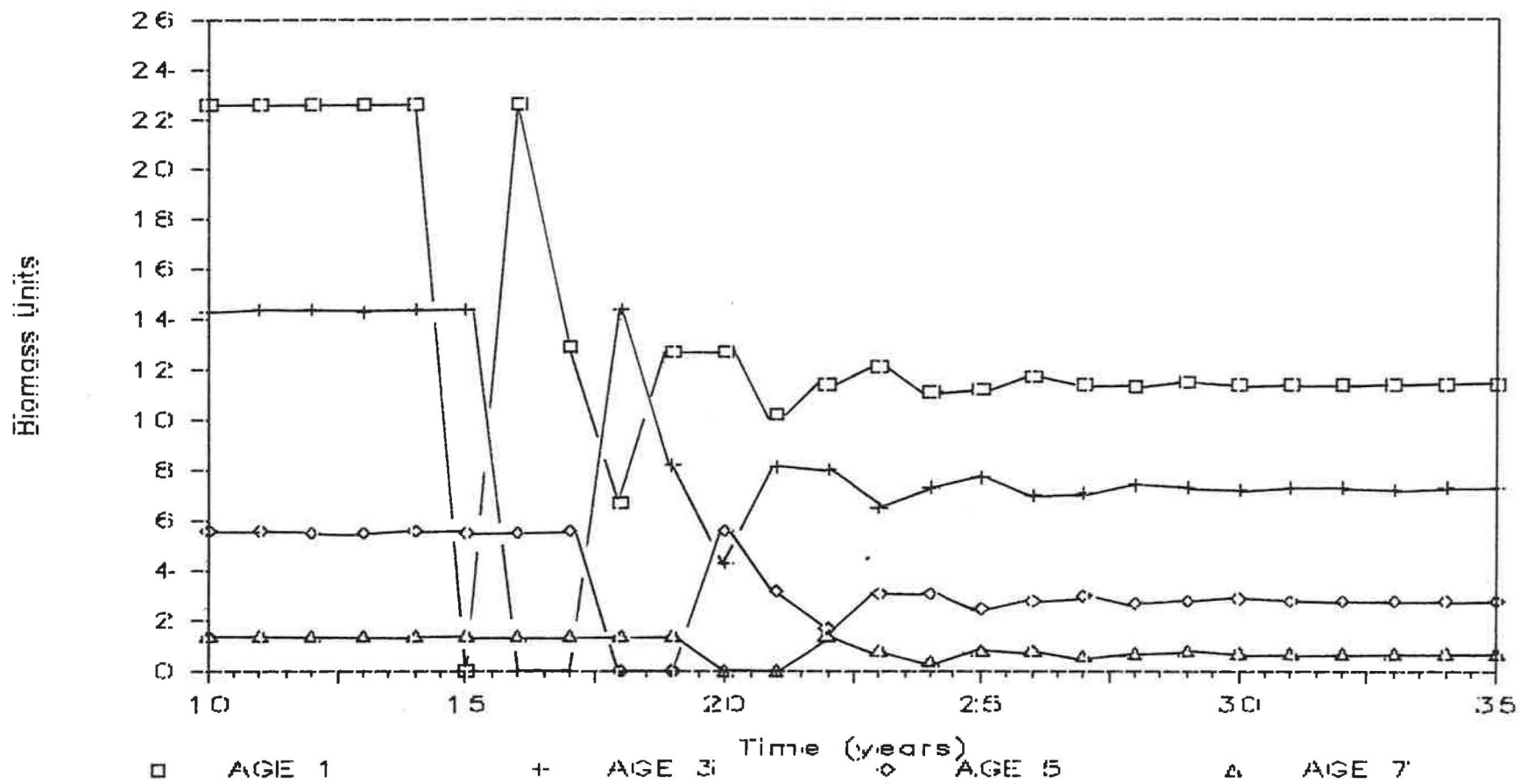


Figure 7. Population responses of Atka mackerel to catastrophic oil induced losses of Age 1 and Age 2 (1-2 year old) fish in a single year.

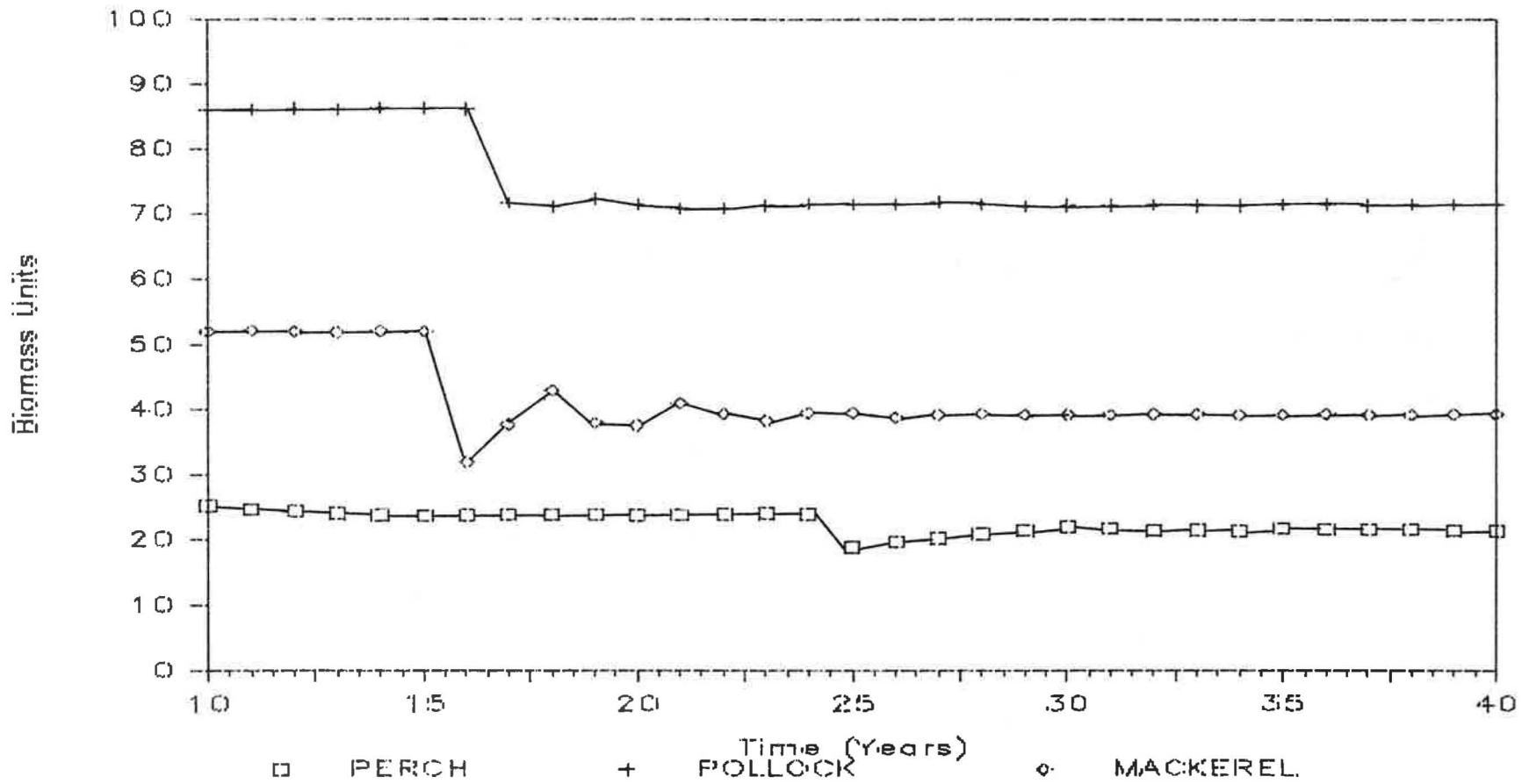


Figure 8. Total exploitable biomass responses of perch, pollock and mackerel to 100% loss of Age 1's in year 15.

did not rebound at all during successive years.

The two final sets of simulations included a normally distributed interannual random component of recruitment computed from recent fisheries data for each species. Results for Case I with linear dependence of recruitment on parent stock size are shown in Figures 9-11. Seed random numbers were used two times-- with and without a simulated oil spill--for each species. Figure 9 shows that losses due to oil in year 15 do not affect the exploitable perch biomass until ten years later (year 25), and that the total percent biomass affected is low. Pollock respond more quickly to oil losses and display a periodic biomass curve. Mackerel show a reduced biomass from oil losses that is somewhat masked by the amplitude of its normally high interannual recruitment fluctuations (Figure 11).

Results from Case II simulations with recruitment based on the equilibrium stock showed that effects of oil losses appeared with the first year class exploited by the fishery and diminished as a function of the longevity of the species involved (Figures 12-14).

#### DISCUSSION AND CONCLUSIONS

Predation, starvation, natural environmental and man-made factors leading to early mortality in marine fish populations still require extensive investigation. As mentioned, literature

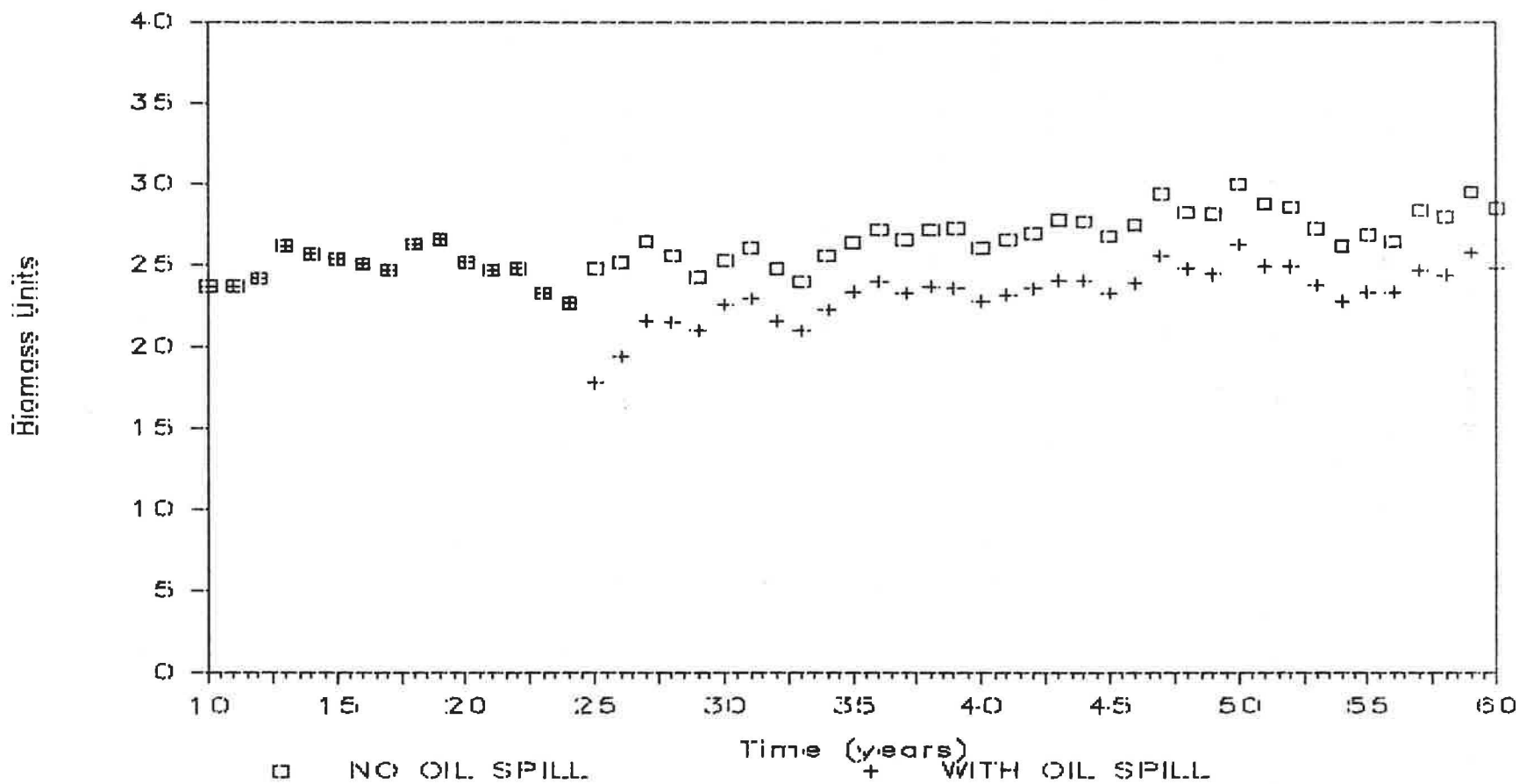


Figure 9. Pacific ocean perch--total exploitable biomass responses, including interannual recruitment variability, to losses due to oil in year 15. Case I (see text): linear relationship between spawning stock and recruits.

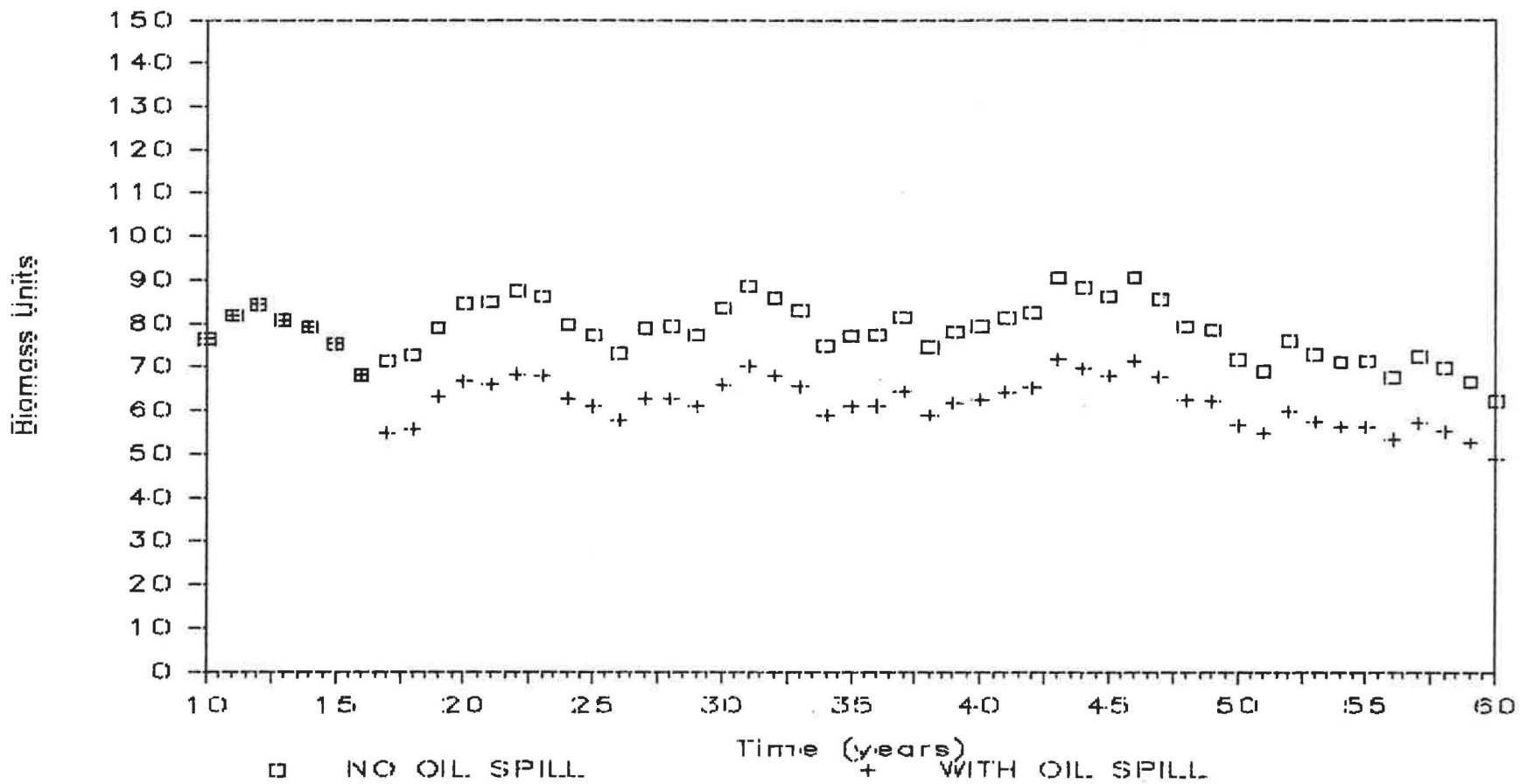


Figure 10. Walleye pollock--total exploitable biomass responses, including interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case I (see text): Linear relationship between spawning stock and recruits.

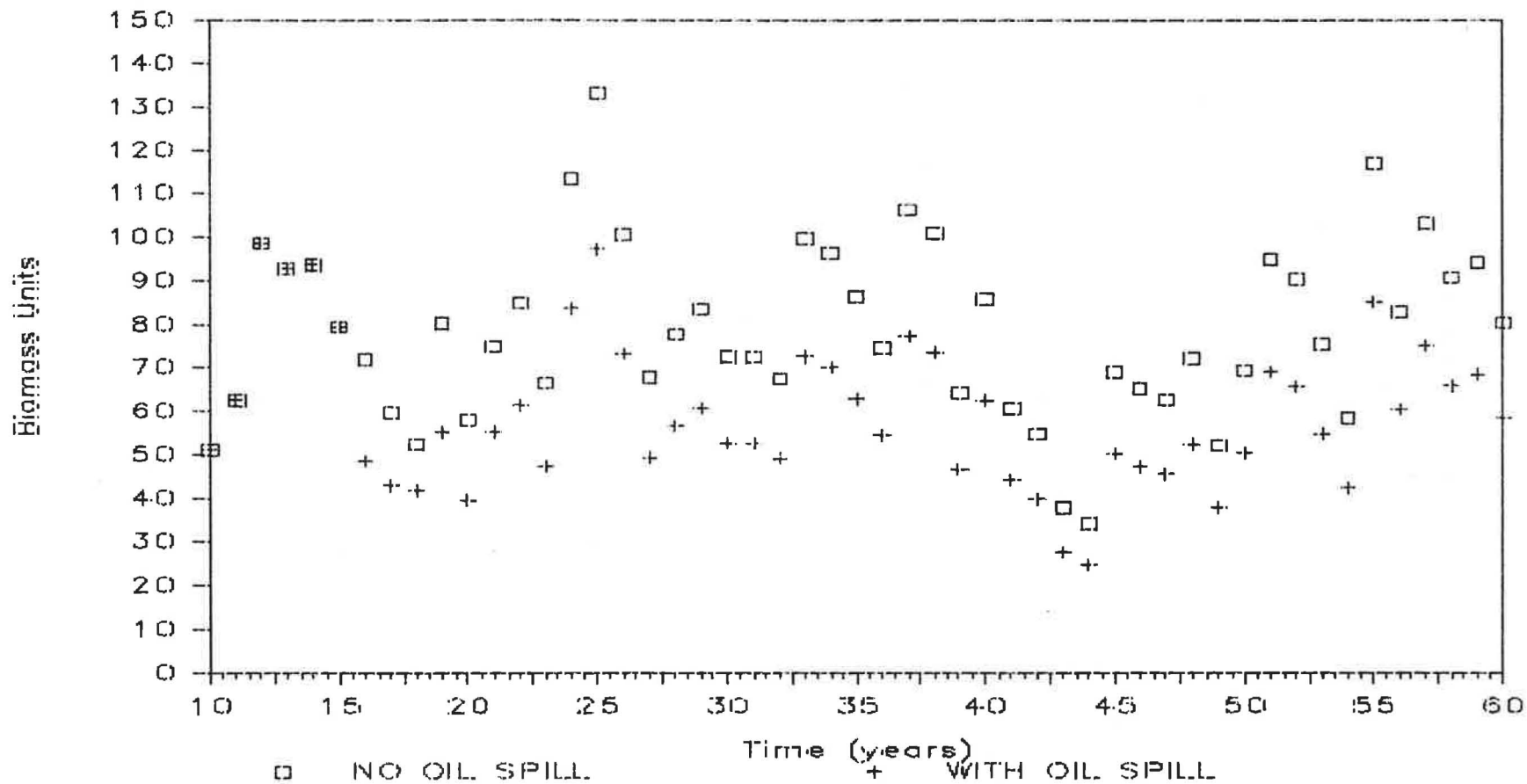


Figure 11. Atka mackerel--total exploitable biomass responses, including interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case I (see text): Linear relationship between spawning stock and recruits.

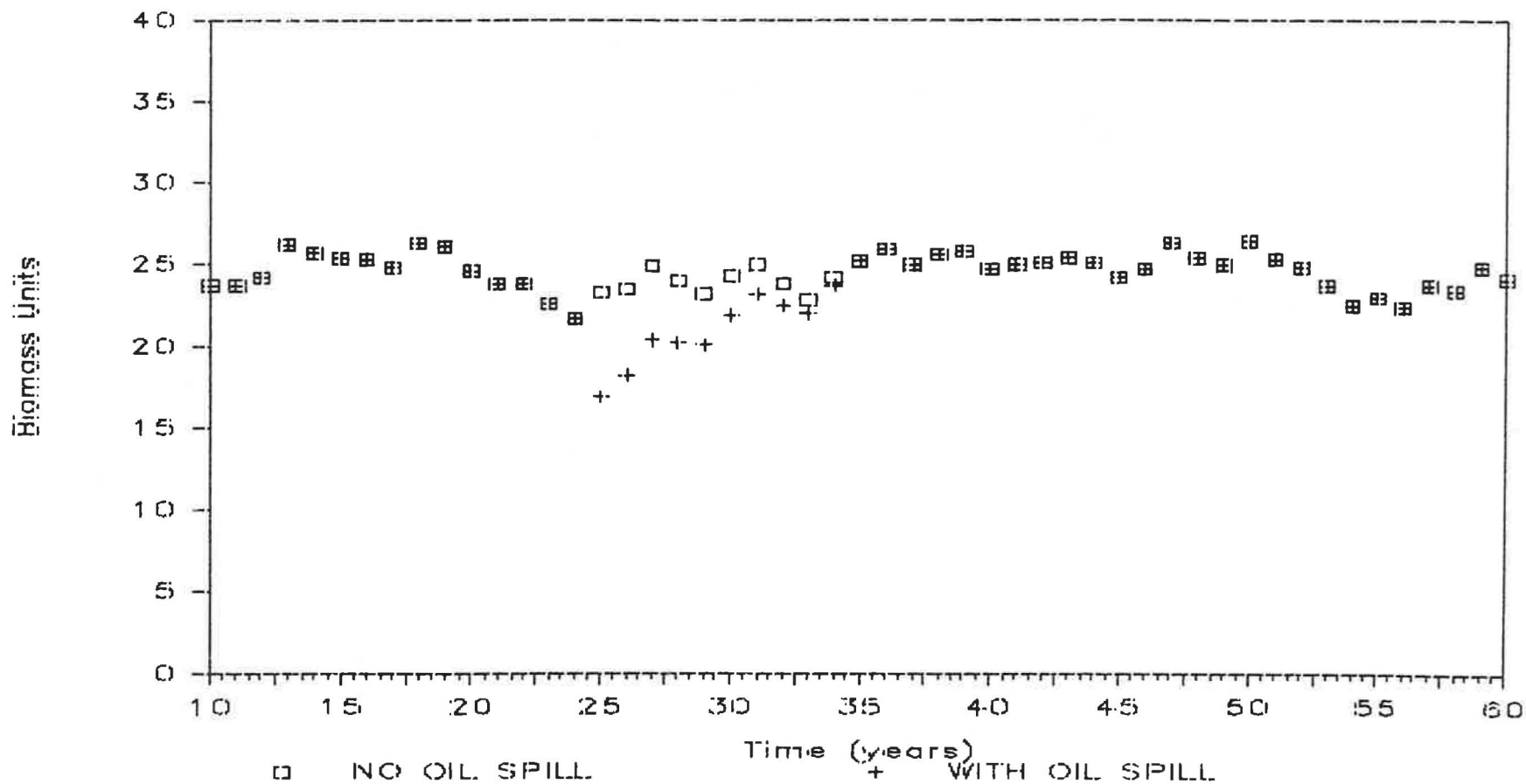


Figure 12. Pacific ocean perch--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.



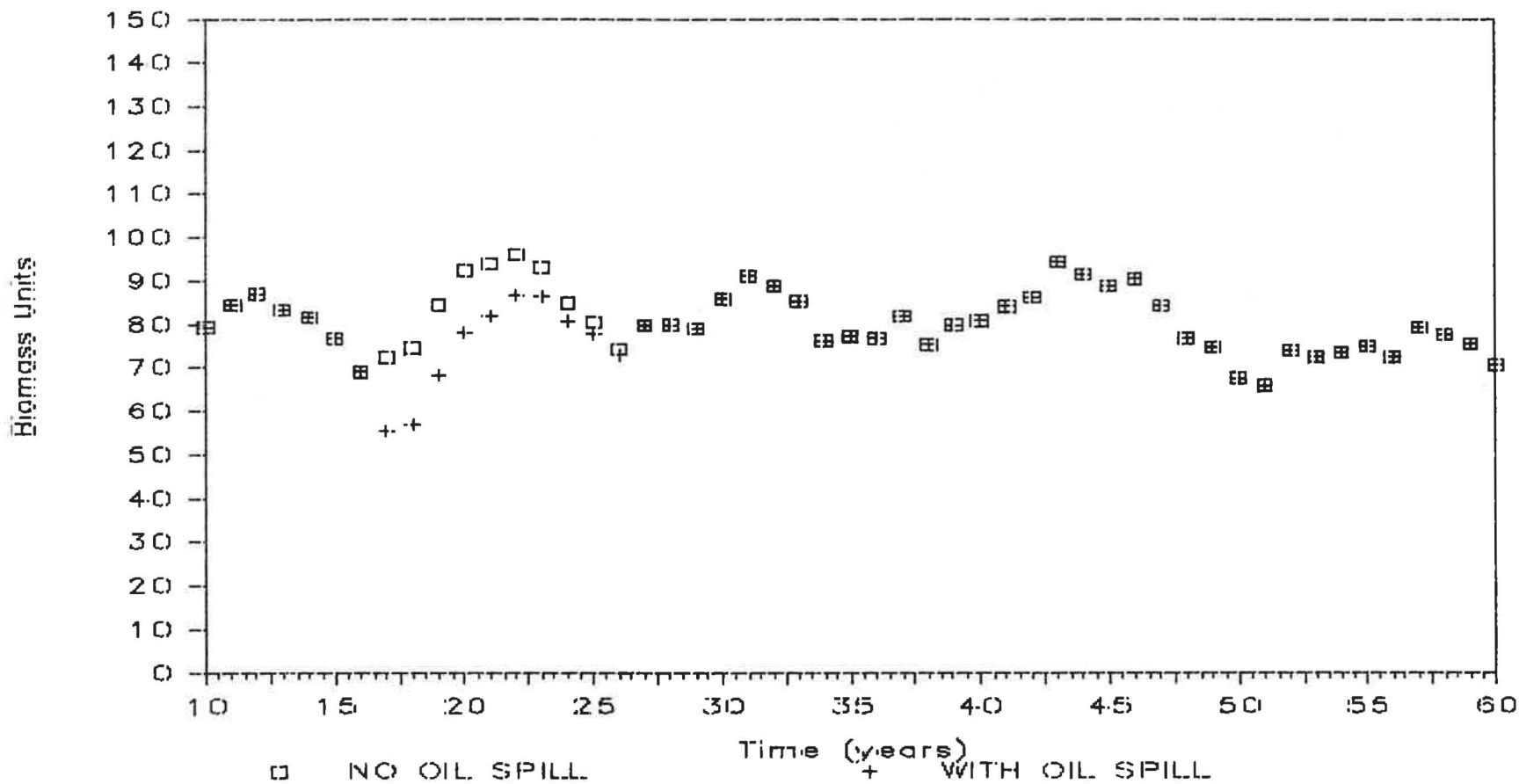


Figure 13. Walleye pollock--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

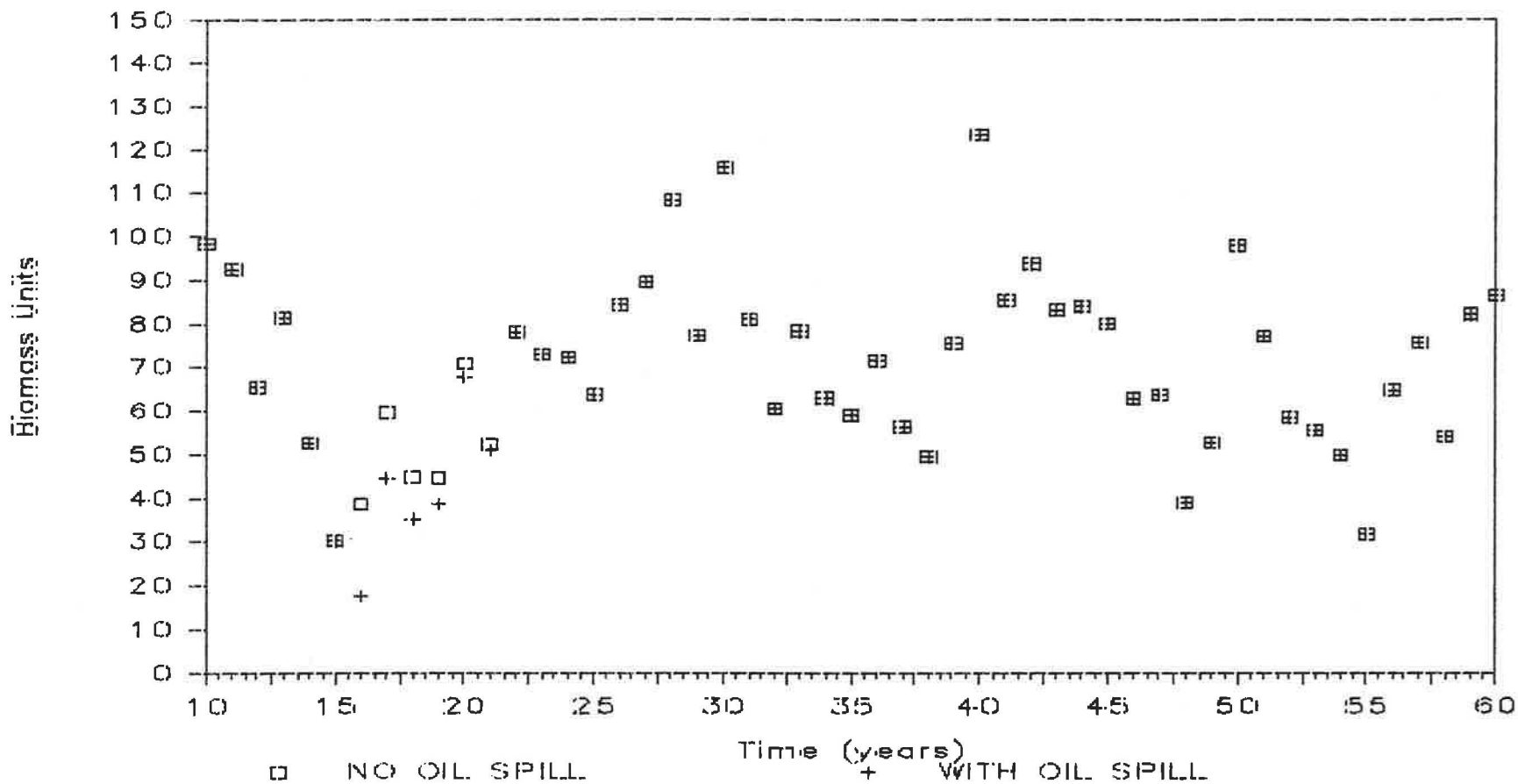


Figure 14. Atka mackerel--total exploitable biomass responses, with interannual recruitment variability, to oil induced loss of Age 1's in year 15. Case II (see text): "environmental window" effect.

currently available quantifying relative importance of these mortality factors is sparse. Rather than attempting to model first year mortality processes per se, this study assumes a mechanism for early mortality (oil contamination), computes recruit biomass that is sensitive (Case I) and non-sensitive (Case II) to previous-year adult biomass, and tracks the impact of low-biomass year classes through time. It is instructive in estimating different species' responses to catastrophic population phenomena other than fishing mortality.

Previous work on population dynamics of marine fish populations has emphasized individual year class fluctuations. Combining year classes from a particular stock into total exploitable biomass damps out individual responses, distributing effects of perturbations through time (Laevastu and Larkins, 1981). In this study, the effects of oil induced losses of recruits to important commercial Bering Sea fish stocks were considered from the total exploitable biomass point of view with the following assumptions: (1) death of Age 0-1's was modelled, as oil contact potential would be highest during the pelagic phases of perch and pollock larvae and during oceanward transport of mackerel larvae (Kasahara, 1961; Gunderson, 1976) and (2) the worst case scenario of 100% mortality (catastrophic) was modelled, as true oil-related mortality after contact is poorly known for any species (Samuels and Ladino, 1984). Actual mortality would be considerably less than 100%, and would more likely range from 1 to 10%, even in a major oil spill (Laevastu, pers. comm.).

Simulated pollock, mackerel and perch populations with twelve, seven and twenty year classes, respectively, responded differently to catastrophic oil losses. These results are attributable to differences in life history characteristics among the three species.

Pacific ocean perch embody two inherently stabilizing traits, longevity and adult demersality (Nikol'skii, 1962; Laevastu and Larkins, 1981). Fecundity and interannual recruitment variability are low, and the number of recruits may be sensitive to stock size (Gunderson, 1976). Thus in nature, this stock probably behaves more like a Case I (see Figure 9, this report) simulation than Case II. The absolute percent biomass loss to the population would be damped by numerous year classes. However, some form of compensatory growth (density-dependent) would be required to elevate the population back to its pre-oil spill biomass.

Walleye pollock biomass, when perturbed by catastrophic oil losses, fluctuated moderately. A cyclical pattern became evident in runs with different seed random numbers (Figure 10). This corresponded well to Laevastu and Larkins' results (1981) which they attributed to cannibalism among the older pollock year classes. Not enough information existed to categorize pollock as either Case I or Case II fish. In the former simulation, recovery of the stock would require compensatory growth. If they behave as in Case II (Figure 13) recovery would occur in about ten years.

The relatively short-lived, pelagic Atka mackerel undergo large interannual recruitment variability (Macy et.al.1978; Ronholt, 1983). They most likely behave as in the Case II simulation (Figure 14). Since interannual recruitment fluctuations are on the same scale as fluctuations due to oil losses, the long-term average mackerel population biomass would appear little changed after oil-caused deaths occurred. In the short term, however, because Age 1's and 2's make up such a large proportion of the total biomass, losses would be swift and acute. Recovery under a Case II scenario would take five to six years.

Some similar responses among the three populations were also noted. In Case I simulations, all three species stabilized at lower exploitable biomass levels that, without inclusion of compensatory density-dependence in the simulation, never returned to original levels. When recruitment was made independent of parent stock size (Case II) exploitable biomass always returned to original levels after a number of years equivalent to the number of different exploitable cohorts in the stock.

Finally, with the inclusion of density-dependent growth and/or mortality (Samuels and Ladino,1984), the simulations presented here could be used to model other mortality factors affecting fish larvae in the ocean such as predation, starvation and anomalous environmental conditions once more data on larval fish biology and distribution become available.

ACKNOWLEDGEMENTS

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