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Yield Analysis for the Long-finned Squid, *Loligo pealei* (LeSueur)

by

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Abstract

A modified version of yield-per-recruit analysis was used to estimate potential yields in the *Loligo pealei* fishery off the northeastern USA. The model accepts monthly values of growth and fishing, spawning and natural mortality rates and assumes two cohorts per year class, as associated with spawning peaks. Two patterns of exploitation were examined by simulating dominance of the international fishery (offshore, winter fishing coupled with the domestic (inshore summer fishing) and the domestic fishery alone through variation of the monthly pattern of fishing mortality. Parameter estimates were derived from survey catch per tow and commercial catch data.

Simulated yield per recruit was significantly higher from a domestic fishery than from an international fishery under most assumptions of mortality which were examined. Yield per recruit results were coupled with a stock-recruitment function to examine the sensitivity of equilibrium yields associated with various levels of fishing mortality to the degree of compensation. Maximum equilibrium yield, assuming a Beverton and Holt (1957) stock-recruitment relationship with moderate compensation was estimated at 27,900 t for an international fishery and at 33,200 t for a domestic fishery.

INTRODUCTION

The long-finned squid, *Loligo pealei*, is becoming increasingly important to the domestic fishery off the northeastern United States (USA). If this trend continues it will result in a significant change in the seasonal (spatial) pattern of fishing and on subsequent yields from the stock. The historic directed fishery has been centered on the offshore overwintering grounds of *L. pealei* by foreign fleets since the fishery intensified in the early 1970's. The majority of the USA catch has traditionally been taken in the late spring and summer while the stock is

inshore on its spawning grounds. This paper examines the potential effects of changing the exploitation pattern on the stock.

Management of the stock has been based, in part, on yield-per-recruit analysis which assumed the exploitation pattern existing in 1974-75 (Sissenwine and Tibbetts 1977). Estimates of growth, natural, and fishing mortality rates have been revised and understanding of the life cycle has improved since that earlier work. A modified Ricker-type yield-per-recruit model (Lange 1981) was used in this paper to simulate the effects of changing the exploitation pattern on the L. pealei stock. The model was designed to accept monthly inputs of fishing, spawning, and natural mortality and growth rates and to account for variations in year-class structure as defined by peaks in time of spawning.

Natural and fishing mortality rates were estimated from mean catch-per-tow data obtained from bottom trawl surveys conducted by the Northeast Fisheries Center (NEFC) during 1968-81 and mean catch per cohort estimates based on commercial catch and length frequency data (1978-81). Yield estimates based on revised mortality estimates were compared for exploitation patterns reflecting (1) a dominant offshore winter fishery coupled with a relatively small inshore summer fishery as had existed since the early 1970's (hereafter referred to as the international fishery) and (2) a dominant inshore summer fishery similar to that traditionally prosecuted by the USA, with no offshore winter fishery (hereafter referred to as the domestic fishery).

The Beverton and Holt (1957) stock-recruitment model was used with results from the yield per recruit analysis to determine a total yield function which would account for the relationship between spawning biomass and subsequent recruitment. Equilibrium recruitment for a range of fishing mortality rates was calculated from Beverton-Holt stock-recruitment model and used to examine sensitivity of

yield-per-recruit to the degree of compensation, as described by Shepherd (1982).

YIELD-PER-RECRUIT-ANALYSIS

The Model

A modified Ricker yield-per-recruit model (Lange 1981) was used to simulate the effects of various fishing patterns on the L. pealei stock. This stock spawns during April-September with peaks generally occurring in late spring and early autumn resulting in two cohorts each year. The model was designed to accept monthly rates of natural (M) and fishing (F) mortality and growth (g) for each of these two cohorts throughout their life span beginning at 6 months of age. Relative size of the two cohorts, expressed in proportion (in number) to the year-class total (N₀) at 6 months (PN_i), and mean weights (W₀) of each cohort at that age were also input. All individuals are assumed to die after spawning, as reported for other squid species. This component of natural mortality affects only that portion of the stock which has reached maturity and was, therefore, considered separately (S) in the simulations. A constant natural mortality rate (M) was used throughout the period of the life cycle used in the model (over 6 months of age, or about 6 cm and greater) since the data were not adequate to estimate M with finer temporal resolution. Average annual instantaneous fishing mortality (F) was apportioned throughout the year according to the monthly pattern of exploitation.

For each cohort during any time period (t), N is the number of squid in the cohort, W is the average weight of an individual in that cohort, YN is the catch in numbers and Y the catch in weight for the cohort. Then

$$N_0 = N_0 PN_i \quad (1)$$

$$N_t = N_0 \exp-(F+M+S)t \quad (2)$$

$$W_t = W_0 \exp gt \quad (3)$$

$$YN = [FN_0 / (F+M+S)] [1 - \exp-(F+M+S)t] \quad (4)$$

$$Y = [FN_0 W_0 / (F+M+S-g)] [1 - \exp-(F+M+S-g)t]. \quad (5)$$

N_0 and W_0 are initial conditions for the given time period for the cohort.

Data

Data used in this analysis included mean numbers at length per tow from the NEFC spring and autumn bottom trawl surveys (1968-81) and USA commercial and distant-water-fleet length frequencies and total catch (t) by month (1978-81). Figure 1 presents a flow chart of the development of these data for input to the yield-per-recruit analysis, as described below.

Stratified mean numbers at length per tow, pooled separately over the southern New England and Mid-Atlantic areas, were subjected to modal length analysis (Tomlinson 1971) to determine percent composition and mean number per cohort by area. Modal analysis, using the program NORMSEP, provides a method of separating length frequencies into representative normal distributions approximating age classes. This is a subjective technique which relies on determination by the user of the number of age groups and their respective (overlapping) cutoff points represented in the length distribution. It also assumes that lengths are normally distributed within an age class.

Only day tows (0800-1600 hours) were used in this analysis since vulnerability of Loligo to the survey trawl is considerably less during dawn (0400-0800), dusk (1600-2000, Lange 1980), and night (2000-0400, Sissenwine and Bowman 1978), and size compositions from night tows were obviously different from those observed during the day.

Loligo caught during surveys in the Mid-Atlantic area were consistently smaller than those from the southern New England area. These slight differences in estimated mean length per cohort by area were assumed to be due to the timing of the seasonal surveys in each area. Mid-Atlantic

stations generally occurred 2-3 weeks prior to those in southern New England waters (Figure 2). Observed length frequencies from spring and autumn surveys (pooled over 1968-81) in the southern New England area and corresponding estimated numbers at length per cohort from modal analysis are presented in Figure 3, to illustrate this aging method. Percent composition and mean numbers per cohort per tow from the two areas were, therefore, calculated separately (differences in length frequencies would have prevented separation of cohorts by modal analysis) and averaged (weighted by area) to produce a single estimate of mean number (and percent) per cohort.

Total abundance of recruits was estimated by areal expansion of stratified mean numbers per tow (day tows only) from the autumn (for the spring cohort) and spring (for the autumn cohort) surveys. Several assumptions of trawl catchability were applied to these estimates and resulted in four different estimates of abundance.

Total catch in numbers per cohort was estimated by first pooling length-frequency sample data from the 1978-81 distant-water-fishery over each month, weighted by the total foreign catch for that month, and then conducting modal analysis on the resultant expanded frequency. Similarly, length frequency expansion and modal analysis was done for the USA catches, based on monthly domestic length-frequency and catch data for the 1978-81 fisheries. Total catches per cohort per month were then determined by combining the estimates for the two fisheries.

Parameter Estimation

Monthly estimates of population parameters are presented in Table 1. Each cohort is assumed to be fully recruited to the first NEFC survey conducted about 6 months following hatching (the autumn survey for the spring cohort and the following spring survey for the autumn cohort) and simulation is begun based on abundance at age 6 months. Mortality and growth rates prior to that time are, not

included. Age selectivity (by month) to the fishery based on mesh selectivity information for Loligo sp. in the eastern Central Atlantic (Ikeda, Far Seas Fisheries Laboratory, Shimizu, Japan, personal communication, 1973) was assumed to be 25%, 50%, 75%, and 100% at 6, 7, 8, and 9 months and older, respectively, for the spring cohort and 75% and 100% at 6 and 7 months and older, respectively, for the autumn cohort based on mean length at age estimates (Lange 1981) and differences in spatial availability of each cohort to the fishery. Initial individual weights were calculated from mean lengths at the time of the autumn and spring surveys for the spring and autumn cohorts, respectively, using a length-weight relationship presented in Lange and Johnson (1981). Growth rates were based on weight-at-age estimates calculated from growth functions developed previously (Lange 1981).

To estimate total mortality (Z) per cohort, mean number per tow from the 1968-81 pooled survey data from the appropriate cohort was compared to mean number per tow from the same cohort one year later using:

$$Z_k = -\ln(X_{i+1}/X_i) \quad (6)$$

where Z_k = total mortality for cohort k and X_i = mean catch per tow in year i.

Fishing mortality (F) was estimated for each cohort based on solution of the catch equation:

$$C = (NF/Z)(1-e^{-Z}) \quad (7)$$

where C = catch in numbers per cohort over the same 12 months used in calculating Z, Z = the estimate of annual total mortality for each cohort, and N = the average annual abundance (1968-81) of the cohort at 6 months of age.

Differences in trawl efficiency between spring and autumn surveys, due partly to differences in seasonal distribution of this species, prevent comparisons of catch-per-tow data between seasons; therefore, annual differences were used.

Annual fishing mortality was initially apportioned to

months according to observed monthly exploitation patterns (1978-81) assuming that catch in numbers was directly proportional to fishing mortality. The use of proportional F values implies a constant population size, which is not true, but was necessary to initiate the estimation procedure. Simulations were run, therefore, varying the proportional F values until the simulated monthly yield in number for all cohorts approximated the observed monthly catches in number (1978-81 average). The resulting monthly F vector was used for all simulations of the offshore/ inshore exploitation pattern. A second fishing mortality vector was calculated for the inshore fishery concentrated primarily during the spring and summer and based on the 1978-81 USA fishery. Monthly F values were calculated as the ratio of monthly USA to monthly international catch in number. These monthly ratios were then converted to proportions of their total so they would sum to 1, accounting for all of the annual fishing mortality.

The autumn cohort is generally not available to the inshore fishery during its first spring. The average percent composition of the autumn cohort in the 1978-81 US fishery in April-May was 89% below the average foreign composition in March of the same years. This difference was accounted for in the model by reducing relative fishing mortality on the autumn cohort by 89% in April and May of its first spring.

Abundance estimates based on areal expansion of survey catch-per-tow data assume that all Loligo in the path of the survey trawl are caught (which is probably not true) and, therefore, represent minimum estimates of actual abundance. Catchability coefficients, if known, can be used to adjust abundance estimates to account for individuals which escape capture. Since estimates of survey catchability are not available for Loligo, catchability coefficients calculated for haddock (Clark et al. 1982) were applied to the minimum abundance estimate for Loligo to

provide an estimate of abundance presumably closer to actual abundance. The average catchability coefficient for haddock is 0.45 indicating that 45% of the haddock, on average, in the path of the trawl were caught. Catchability of haddock with the survey gear is assumed to be high therefore this may be considered a conservative estimate for squid.

Natural mortality (M) was considered to be the difference between the total and fishing mortality estimates for each cohort. However, individuals from the spring cohort begin spawning during the summer of their second year prior to the autumn survey, while the autumn cohort is considered to spawn in its second spring after the spring survey. The difference in natural mortality estimates between the two cohorts was assumed, therefore, to be associated with spawning by the spring cohort. Since the spring cohort is assumed to spawn during August-September of its second summer at 16-17 months of age, the annual estimate of spawning mortality was divided by 2 to obtain a monthly estimate. This mortality rate was applied to the spring cohort during the 2 months in which it was assumed to spawn during its first spawning season (Table 1). The spring cohort also survives to spawn during April-July of the following year, and the annual rate was apportioned equally to those four months as well.

The autumn cohort does not begin spawning until its second spring at about 18 months of age. Total mortality (Z) for the autumn cohort between 18 and 30 months of age was calculated from the mean numbers per tow for that cohort from spring surveys conducted during its second and third spring. Annual fishing and natural mortality were assumed to be the same as during 6-18 months but with no adjustment for partial recruitment, and spawning mortality for the autumn cohort was estimated as the difference between Z (during 18-30 months) and the sum of F plus M. Since the autumn cohort spawns over a 6-month period (April-September), the annual estimate of spawning mortality was

divided by 6 to obtain a monthly estimate. This mortality was applied to the autumn cohort during each month that it was assumed to spawn (Table 1). Natural mortality was assumed to be the same for each cohort and equivalent to that calculated for the autumn cohort.

The proportion of the year class belonging to each of the two cohorts at 6 months of age was calculated from mean number-per-tow data for each cohort from the autumn or spring surveys (spring and autumn cohorts, respectively), pooled over 1968-81.

Simulations

Simulations were run for each exploitation pattern using estimated numbers of recruits apportioned into spring and autumn cohorts and natural (M), spawning (S), and fishing (F) mortality rates based on 1968-81 pooled survey data. Four sets of M and current F vector (monthly) were calculated, as described above, under different assumptions of the catchability of the survey trawl. These resulted in varying levels of estimated abundance and subsequent rates of fishing and natural mortality producing a range of potential yields. Five additional scaler multipliers of the F vector values were used with each value of M.

Sensitivity of the model to differences in spawning mortality (S) was also tested by simulating yields with monthly spawning mortality rates of approximately 0.5 and 2 times the average estimated level. Output from all simulations included estimates of yield in number and weight per 1,000 individuals recruited at 6 months of age, and mean weight of the Loligo taken in the fishery. Total weight and number of spawners was also estimated to provide an indication of the impact of the various levels of fishing and natural mortality rates on spawning.

EXAMINATION OF SUSTAINABLE YIELD

Methods

Results from the yield per recruit analysis may be combined with a stock recruitment relationship to obtain estimates of total yield using a method described by Shepherd (1982) and demonstrated by Sissenwine et al. (1984). This technique uses the reciprocal of spawning biomass per recruit values to produce lines of constant recruitment per spawning biomass. The intersection of these lines, with the stock recruitment function for various fishing mortality rates determines the equilibrium recruitment level for that F. Equilibrium yield is then obtained for each F by multiplying the equilibrium recruitment by the appropriate yield per recruit.

The Stock-Recruitment Relationship

Sissenwine and Tibbetts (1977), in simulating the effects of fishing on Loligo pealei, assumed the relationship between spawning stock and recruitment to be described by the Beverton and Holt model (1957):

$$R' = P' / (1 + A(P' - 1)) \quad (8)$$

where R' = the size of the year class when it enters the exploited phase of the life cycle relative to the number of recruits to the unexploited population, P' = the weight that spawn relative to the weight spawning in the unexploited population, and A = a parameter ranging from 0 (where recruitment is linearly related to spawning stock size) to 1 (where recruitment is independent of spawning stock size). This stock recruitment relationship (Figure 5) was used to demonstrate the uncertainty in sustainable yield relative to stock recruitment.

Total Yield Estimation

Virgin spawning biomass per 1,000 recruits was estimated by simulating conditions with no fishing mortality

but with all other parameters as calculated for the yield-per-recruit analysis, with $N = 2.0$ billion recruits. The ratio of spawning biomass per recruit for the current level of F (0.41) from the international fishery (Table 4), to that with $F = 0$ (48.8 kg per 1,000 recruits) indicates that spawning biomass per recruit has been reduced to about 65 % of the virgin level. Estimates of virgin recruitment were determined for each level of A (0.4, 0.8, and 1.0) for the current level of F (0.41), using the following equation derived algebraically from equation 8:

$$R_v = (B/R)'RA/(A+(B/R)'\cdot 1) \quad (9)$$

where R_v = virgin recruitment, $(B/R)'$ = the ratio of current spawning biomass per recruit, R = current recruitment (2.0 billion), and A = the level of density dependence as described above. Virgin spawning biomass (B_v) was then estimated by multiplying current spawning biomass per recruit (B/R) by R_v and dividing by $(B/R)'$. The ratio of current to virgin recruitment ($R' = R/R_v$) was used to determine the ratio of current to virgin spawning biomass by $P' = (B/R)'\cdot R'$, for level of A , and this ratio was used to calculate current spawning biomass ($B = B_v P'$).

The reciprocal of each of the spawning biomass per recruit (B/R) values (Table 4) represents the slope of the line of constant recruitment per unit spawning biomass associated with a given F . These lines are plotted with the stock-recruitment functions (Figure 5). The intersection of each line with the stock-recruitment function determines the equilibrium recruitment level (Shepherd 1982). These points were calculated for each F , as the product of the current spawning biomass and the recruitment per unit spawning biomass ratio ($R_E = B(R/B)$). Equilibrium yield was then estimated by multiplying equilibrium recruitment by the appropriate yield per recruit.

RESULTS

Total mean numbers of Loligo per tow averaged 679.8 in the autumn surveys and 130.4 in the spring surveys (1968-81). Breakdown of those catches to cohort and age was as follows:

Survey	Cohort			
	Autumn		Spring	
	No./tow	Approx. age (months)	No./tow	Approx. age (months)
Autumn	228.64	0+	287.98	6
Spring	59.70	6	38.37	12
Autumn	151.21	12	11.22	18
Spring	14.06	18	18.06	24
Autumn	0.74	24	-	-
Spring	0.17	30	-	-

A relatively high average number of individuals from the spring cohort was observed in its second spring survey (18.06) compared to the number in the previous autumn (11.22). This apparent discrepancy may be the result of increased availability of the spring cohort at that age in some years as it moves inshore to spawn. The greater number per tow of the autumn cohort in its second autumn (151.21) compared to its first spring (59.70) survey may be accounted for by the greater availability of that cohort in the survey area during autumn. The spring survey is conducted prior to onshore movement of immature Loligo, and the autumn cohort does not mature until after its second spring survey.

Total mortality between 6 and 18 months of age was estimated from equation (7) to be 3.245 for the spring cohort and 1.446 for the autumn cohort. Total mortality between 18 and 30 months was estimated to be 4.415 for the autumn cohort. However, relatively small errors in determining composition by cohort using modal analysis, especially in the older age groups, could dramatically alter the calculated Z values. Alternative techniques for determining age structure of a population from length frequencies (modal analysis) are being investigated. The estimated average minimum abundance of each cohort based on

survey catches at 6 months of age was 0.729 billion individuals for the spring cohort and 0.151 billion for the autumn cohort for a total of 0.880 billion for the entire year class. The spring cohort accounted for 82.8% of this total, although this may be partly an artifact of the differences in catchability between spring and autumn surveys. Applying a trawl catchability coefficient of 0.45, as applicable to haddock, to this minimum estimate resulted in an estimated abundance of about 2 billion individuals at 6 months of age. Estimates of fishing, natural, and spawning mortality rates were made assuming that level of average abundance. Mean weights at 6 months of age were calculated as 13.3 g for spring and 12.6 g for autumn-spawned cohorts.

The average annual (1978-81) international catch in numbers between 6 and 18 months of age was 0.201 billion for the spring cohort and 0.066 billion for the autumn cohort, based on expanded length frequencies and modal analysis. Estimates of annual fishing mortality determined from equation (8) based on the average catch and abundance of 2 billion individuals (1.656 billion - spring cohort and 0.344 billion - autumn cohort), were 0.410 for the spring and 0.363 for the autumn cohorts. Natural mortality was estimated as 1.083 per year (1.446 minus 0.363) or 0.090 per month based on the autumn cohort. This estimate of M was used for both cohorts. Spawning mortality was estimated to be 1.752 per year for the spring cohort (3.245 minus 0.410 minus 1.083) or 0.876 per month in its first spawning season (2 months) and 0.438 per month when partitioned over the 4 months of its second spawning season. Spawning mortality for the autumn cohort was estimated to be 2.969 per year (4.415 minus 0.363 minus 1.083) or 0.495 per month for each of the months that it spawns.

Three additional levels of year-class abundance were determined by assuming catchability coefficients of 100% (0.88 billion individuals), 60% (1.5 billion), and 30% (3.0 billion). Fishing, natural, and spawning mortality rates were recalculated for each assumption of year-class abundance. Annual estimates of mortality rate for each level of abundance were as follows:

Abundance	F		M	S	
	Spring	Autumn		Spring	Autumn
0.88	0.931	0.827	0.619	1.695	2.969
1.50	0.546	0.487	0.962	1.738	2.969
2.00	0.410	0.363	1.083	1.752	2.969
3.00	0.273	0.242	1.204	1.768	2.969

The international fishery for Loligo has been predominantly an offshore fishery, with a minor inshore component primarily in the spring and summer, over the time period considered in this analysis (1968-81). Simulations assuming this exploitation pattern revealed that maximum yield (kg) per 1,000 recruits (about 26.7 kg) would be expected at an annual F of about 3.0 assuming a monthly M of 0.09 (based on an abundance at 2 billion individuals) and would result in harvesting about 66% of the initial recruits (Table 2). Yield would be greatest at a higher F if M was higher (at an F of 4.0-5.0 for M = 0.15).

Under all simulated levels of F and M, greater yields in terms of weight would be expected from a domestic fishery than an international fishery (Table 2). The international fishery relies on the capture of great numbers of immature squid during the time when growth is significantly greater than natural mortality. By delaying harvest, as in a domestic fishery, the squid are larger and fewer need be taken for the same yield. Maximum yield per 1,000 recruits of 33.4 kg from a domestic fishery with M = 0.09 would result from an annual F of 4.0, which would harvest 60% of the initial recruits at an average size of 36.0 g compared with a harvest of 66% of the recruits at an average size of

40.7 g in the international fishery.

Sensitivity analysis indicates that the effect of an error in the estimation of spawning mortality is much less critical than the effect of errors in estimating natural mortality (Table 3). Simulated yield per recruit for each exploitation pattern assuming the calculated levels of monthly spawning mortality (0.876 and 0.495) were, for the simulated range in F values, 12-14% less than when spawning mortality was reduced to 0.43 for the spring cohort and 0.25 for the autumn cohort, and 7-8% greater than when spawning mortality was increased to 1.74 for the spring and 1.0 for the autumn cohort (for $M = 0.09$). Similar variations in natural mortality (0.5 - 2.0 times) resulted in an average 25% increase in yield (kg) when M was reduced from 0.09 to 0.052 (43% decrease) and an average 26% decrease in simulated yield when M was increased from 0.09 to 0.15 (67% increase). This is primarily because the spring cohort, which comprises 83% of an average year class, has been reduced during simulation by 10 months of natural and fishing mortality prior to the occurrence of spawning mortality. Spawning does not occur until after growth has substantially slowed, whereas natural mortality is continually reducing abundance of the year class throughout its life, including the peak growth period, thus producing a greater impact on the available biomass.

Estimates of potential spawning biomass (and abundance) per 1,000 recruits (at 6 months of age) are presented in Table 4 for each set of mortality (F, M, and S) estimates and for each exploitation pattern. These are estimates of total biomass suffering spawning mortality per 1,000 recruits and, since all individuals are assumed to die after spawning, represent the number and weight of all spawners (not the spawning product). Spawning was greater under a domestic than an international fishery for all levels of F, M, and S which were simulated. Spawning decreased with increases in natural or fishing mortality. Assuming natural

mortality was 0.09, as estimated for an abundance of 2.0 billion individuals, spawning biomass would increase 16% (14% for a domestic fishery) if fishing mortality was lowered from 0.41 (as calculated) to 0.27 and would decrease 92% (90% for a domestic fishery) if F was increased to the level needed to produce maximum yield ($F = 3.0$). The relationships of yield and spawning biomass to changes in fishing mortality are presented in Figure 4 for the international and the domestic fisheries, assuming an abundance of 2.0 billion recruits.

Virgin spawning biomass was estimated to be 112,970 t based on a current recruitment level of 2.0 billion individuals and assuming $F = 0.41$ and $A = 0.8$. Equilibrium recruitment (R_E) for each fishing mortality rate are presented in Table 5 along with yield per recruit and equilibrium yield (Y_E) values for each exploitation pattern.

In the case of a moderate density dependent relationship between spawning biomass and recruitment ($A = 0.8$) maximum equilibrium yields were determined for F levels slightly greater than those calculated for the present fishery situation.

For the international fishery, the maximum F for which there is equilibrium recruitment is about 0.93. The maximum equilibrium yield of 27,900 t (Figure 6) occurs at $F = 0.70$ and a spawning biomass of about 38,400 t. If F is increased to 0.93 equilibrium yield declines to about 92% of maximum (25,700 t). If F increases beyond 0.93, yield is not sustainable.

For the domestic fishery, the maximum F at which equilibrium yield can occur is also about 0.93. The maximum equilibrium yield of 33,200 t (Figure 6) occurs at $F = 0.80$ and a spawning biomass of about 36,200 t. Increases in F beyond 0.93 result in dramatic declines in equilibrium yield. Yields at only about 7% of maximum are sustainable at $F = 1.2$, but yield is not sustainable when $F > 1.2$.

If recruitment was constant over the entire range of spawning biomass (in fact, complete compensation, $A = 1.0$) equilibrium yield could continue to increase to about 53,400 t at $F = 3.00$ for the international fishery and to 66,800 t at $F = 4.00$ for the domestic fishery. However, if there were only a weak compensatory relationship between spawning biomass and recruitment ($A = 0.4$), yields beyond about 1,400 t at $F = 0.27$, would not be sustainable.

CONCLUSIONS

Simulations based on an international fishery, as has existed since the early 1970's, and applying natural and spawning mortality rates as calculated from NEFC bottom trawl survey data, indicate that maximum yield per recruit of Loligo would occur at an annual F of about 3.0 if recruitment is independent of spawning biomass. This level of fishing mortality would produce an average annual yield of 53,400 t if annual abundance at 6 months of age was 2.0 billion individuals, the average level estimated from survey catches during 1968-81 assuming a catchability coefficient of 45% to the survey trawl. Maximum equilibrium yields determined by coupling the results of the yield-per-recruit analysis with a stock-recruitment function and assuming moderate density dependence would occur at an annual F of about 0.70 and would be about 27,900 t. This is somewhat below the level of catch since the mid-1970's, and may reflect the 35% reduction from virgin spawning biomass per recruit.

As the USA catch of Loligo increases and the fishery continues to be conducted primarily inshore during the summer, a greater yield from the stock should occur than from an international (primarily winter) fishery. Simulated maximum yield estimates from a domestic fishery (66,800 t at $F = 4.0$) were 25% greater than from a combined international fishery. Incorporating a stock-recruitment function which assumed a moderate relationship between spawning biomass and

recruitment with the yield-per-recruit analysis resulted in a maximum equilibrium yield for a domestic fishery of 33,200 t at an annual F of about 0.80.

At the average level of F estimated for the fishery during 1968-81 ($F = 0.41$), assuming 2.0 billion recruits per year equilibrium yield is about 13% greater for the domestic fishery than for the international fishery. Maximum equilibrium yield (incorporating a moderate stock-recruitment relationship) for the domestic fishery (at $F = 0.80$) is about 19% greater than for the international fishery (at $F = 0.70$). However, an improved understanding of the stock-recruitment relationship is necessary before more definitive conclusions can be reached. If this relationship is stronger than assumed here (i.e. $A < 0.8$), sustainable yields will be less than the present estimates. Other studies have shown, however, that the total ecosystem is relatively 'tight' and it is probably not realistic to assume that virgin spawning biomass and recruitment would have been over five times the present level, as indicated for $A = 0.4$.

Environmental factors, which were not explicitly considered in the present analysis, likely play a significant role in the relationship between spawning biomass and subsequent recruitment. The results should therefore, be considered to be typical of the situation that has been observed in recent years (last 10-15) rather than applying to any particular year.

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Table 1. Monthly estimates of: fishing mortality (F), selectivity (Sel), natural (M) and spawning (S) mortality, and growth (G) rates for two cohorts of L. pealei under two exploitation patterns, assuming abundance of 2.0 billion individuals at 6 months of age. (Each cohort enters simulations at 6 months of age)

Month	Relative F		Spring Cohort				Autumn Cohort			
	Fa ¹	Fb ²	Sel	M	S	G	Sel	M	S	G
Oct	.013	.066	0.25	.09	0.000	0.360	-	-	-	-
Nov	.038	.028	0.50	.09	0.000	0.309	-	-	-	-
Dec	.130	.019	0.75	.09	0.000	0.270	-	-	-	-
Jan	.350	.009	1.00	.09	0.000	0.216	-	-	-	-
Feb	.210	.019	1.00	.09	0.000	0.196	-	-	-	-
Mar	.180	.019	1.00	.09	0.000	0.180	-	-	-	-
Apr	.010	.085	1.00	.09	0.000	0.166	0.75	.09	0.000	0.278
May	.050	.575	1.00	.09	0.000	0.154	1.00	.09	0.000	0.246
Jun	.010	.094	1.00	.09	0.000	0.144	1.00	.09	0.000	0.221
Jul	.003	.028	1.00	.09	0.000	0.135	1.00	.09	0.000	0.200
Aug	.002	.019	1.00	.09	0.876	0.127	1.00	.09	0.000	0.183
Sep	.004	.038	1.00	.09	0.876	0.120	1.00	.09	0.000	0.169
Oct	.013	.066	1.00	.09	0.000	0.113	1.00	.09	0.000	0.157
Nov	.038	.028	1.00	.09	0.000	0.108	1.00	.09	0.000	0.146
Dec	.130	.019	1.00	.09	0.000	0.103	1.00	.09	0.000	0.137
Jan	.350	.009	1.00	.09	0.000	0.098	1.00	.09	0.000	0.128
Feb	.210	.019	1.00	.09	0.000	0.094	1.00	.09	0.000	0.121
Mar	.180	.019	1.00	.09	0.000	0.090	1.00	.09	0.000	0.115
Apr	.010	.085	1.00	.09	0.438	0.086	1.00	.09	0.495	0.109
May	.050	.575	1.00	.09	0.438	0.083	1.00	.09	0.495	0.104
Jun	.010	.094	1.00	.09	0.438	0.080	1.00	.09	0.495	0.099
Jul	.003	.028	1.00	.09	0.438	0.077	1.00	.09	0.495	0.095
Aug	.002	.019	1.00	.09	(3)	0.074	1.00	.09	0.495	0.091
Sep	.004	.035	-	-	-	-	1.00	.09	0.495	0.087
Oct	.013	.066	-	-	-	-	1.00	.09	0.000	0.084
Nov	.038	.028	-	-	-	-	1.00	.09	0.000	0.080
Dec	.130	.019	-	-	-	-	1.00	.09	0.000	0.078
Jan	.350	.009	-	-	-	-	1.00	.09	0.000	0.075
Feb	.210	.019	-	-	-	-	1.00	.09	0.000	0.072
Mar	.180	.019	-	-	-	-	1.00	.09	0.000	0.070
Apr	.010	.085	-	-	-	-	1.00	.09	0.495	0.068
May	.050	.575	-	-	-	-	1.00	.09	(3)	0.066

1 Fa - Monthly fishing mortality ratio assuming the traditional offshore/inshore fishery (1978-81 pattern).
 2 Fb - Monthly fishing mortality ratio assuming a dominant inshore fishery (1978-81 US pattern).
 3 - infinity, no individuals remain.

Table 2. Simulated yield per recruit of *Loligo pealei* for two exploitation patterns (offshore/inshore and inshore fisheries) assuming ranges of annual fishing (F) and monthly natural (M) and spawning (S) mortality rates based on NEFC surveys, pooled over 1968-81, and four levels of average annual abundance. The underlined values represent simulated yield per recruit estimates at the level of fishing mortality estimated to have produced the 1978-81 average landings assuming the indicated level of abundance.

M	S ¹	F	Offshore/Inshore Fishery			Inshore Fishery		
			Yield/1000 No.	Wt(kg)	Mean wt(g)	Yield/1000 No.	Wt(kg)	Mean wt(g)
<u>N = 0.88 billion</u>								
0.052	0.848	0.27	185.7	11.7	62.9	151.6	13.2	87.2
	0.495	0.41	263.5	16.0	60.8	216.6	18.5	85.2
		0.55	331.0	19.5	58.8	273.9	22.9	83.4
		0.93	473.5	25.8	54.4	398.2	31.5	79.1
		1.50	610.6	30.3	49.5	523.7	38.6	73.7
		2.00	684.5	31.8	46.4	595.5	41.6	69.9
		3.00	764.0	32.3	42.2	680.4	43.3	63.7
		4.00	800.4	31.6	39.5	725.9	42.7	58.9
		5.00	818.8	30.8	37.6	753.5	41.4	55.0
<u>N = 1.50 billion</u>								
0.080	0.869	0.27	159.3	9.2	58.0	123.2	10.2	82.5
	0.495	0.41	226.8	12.8	56.3	176.6	14.3	80.8
		0.55	285.9	15.7	54.8	224.1	17.8	79.3
		0.93	412.5	21.1	51.3	328.6	24.8	75.6
		1.50	537.3	25.4	47.3	437.0	31.0	70.9
		2.00	606.3	27.1	44.7	501.2	33.7	67.2
		3.00	683.6	28.1	41.0	581.1	35.7	61.4
		4.00	721.3	27.8	38.6	627.5	35.6	56.8
		5.00	741.9	27.3	36.9	658.2	34.9	53.0
<u>N = 2.00 billion</u>								
0.09	0.876	0.27	151.2	8.5	56.5	114.7	9.3	81.0
	0.495	0.41	215.5	11.8	55.0	164.6	13.1	79.5
		0.55	272.0	14.6	53.5	209.1	16.3	78.0
		0.93	393.4	19.8	50.3	307.4	22.9	74.4
		1.50	514.0	23.9	46.6	410.4	28.6	69.8
		2.00	581.3	25.7	44.2	472.0	31.3	66.4
		3.00	657.7	26.7	40.7	550.1	33.3	60.6
		4.00	695.6	26.6	38.3	596.5	33.4	56.0
		5.00	716.8	26.2	36.6	628.0	32.8	52.3
<u>N = 3.00 billion</u>								
0.100	0.884	0.27	143.6	7.9	55.1	106.8	8.5	79.6
	0.495	0.41	205.0	11.0	53.7	153.5	12.0	78.1
		0.55	259.0	13.6	52.4	195.2	15.0	76.7
		0.93	375.5	18.6	49.4	287.8	21.1	73.3
		1.50	492.1	22.6	45.9	385.7	26.5	68.8
		2.00	557.7	24.3	43.6	444.9	29.1	65.5
		3.00	633.0	25.5	40.3	521.1	31.2	59.8
		4.00	671.0	25.5	38.0	567.5	31.4	55.3
		5.00	692.8	25.2	36.3	599.6	30.9	51.5

1 - Upper values are monthly spawning mortalities for the spring cohort in its first spawning season (applied to two months, S would be one half this value during each of the four months in the second spawning season), lower values are monthly S for the autumn cohort.

Table 3. Sensitivity analysis of simulated *Loligo* yield per recruit assuming two levels of monthly spawning (S) mortality and a range of monthly natural mortality (M) and annual fishing mortality (F) rates.

S ¹	Offshore/inshore Fishery					Inshore Fishery		
	M	F	Yield/1000		Mean	Yield/1000		Mean
			No.	Wt(kg)		wt(g)	No.	
0.43 0.25	0.05	0.27	205.8	16.3	79.2	171.1	18.0	105.3
		0.41	288.9	21.7	75.4	241.8	24.5	101.5
		0.55	359.5	25.9	76.9	302.9	29.7	98.0
		0.93	503.7	32.2	64.0	430.9	38.7	89.9
		2.00	704.3	35.3	50.1	621.2	46.2	74.4
	0.09	4.00	808.9	32.5	40.1	739.0	44.2	59.9
		0.27	160.9	10.9	67.9	123.7	11.6	93.6
		0.41	227.8	14.8	65.1	176.3	16.0	90.7
		0.55	285.6	17.9	62.5	222.4	19.6	88.0
		0.93	407.4	23.1	56.7	322.1	26.3	81.7
	0.15	2.00	589.0	27.4	46.5	482.2	33.4	69.3
		4.00	697.0	26.9	38.7	599.7	39.4	56.6
		0.27	116.8	6.6	56.4	79.8	6.4	80.8
		0.41	166.7	9.1	54.7	114.7	9.0	78.8
		0.55	210.8	11.2	53.1	146.0	11.2	76.9
1.74 1.00	0.05	0.93	306.5	15.2	49.4	216.0	15.6	72.4
		2.00	459.9	19.7	42.8	339.4	21.3	62.8
		4.00	564.5	20.8	36.9	448.7	23.3	51.9
		0.27	176.7	9.2	51.9	143.1	11.0	77.2
		0.41	252.5	12.9	51.1	205.7	15.7	76.3
	0.09	0.55	319.1	16.1	50.4	261.5	19.7	75.4
		0.93	462.6	22.4	48.5	385.0	28.2	73.2
		2.00	681.9	30.2	44.3	588.7	39.6	67.3
		4.00	804.8	31.6	39.3	728.2	42.5	58.4
		0.27	145.6	7.2	49.5	109.1	8.1	74.4
	0.15	0.41	208.6	10.2	48.8	157.3	11.6	73.6
		0.55	264.3	12.7	48.2	200.5	14.6	72.7
		0.93	385.5	17.9	46.5	297.5	21.0	70.4
		2.00	576.9	24.7	42.8	464.2	30.0	64.6
		4.00	694.7	26.5	38.1	593.4	33.0	55.6
0.05	0.27	110.8	5.2	46.7	74.0	5.2	70.2	
	0.41	159.3	7.3	46.1	107.2	7.4	69.3	
	0.55	202.5	9.2	45.6	137.3	9.4	68.4	
	0.93	297.9	13.2	44.2	206.1	13.6	66.1	
	2.00	455.1	18.6	40.9	331.8	20.0	60.1	
0.05	4.00	563.6	20.6	36.6	446.0	22.9	51.2	

1 - Upper values are monthly spawning mortalities for the spring cohort in its first spawning season (applied to two months, S would be one half this value during each of the four months in the second spawning season), lower values are monthly S for the autumn cohort.

Table 4. Simulated spawning biomass (and number) per 1,000 recruits at 6 months of age, for an offshore/inshore and inshore fishery, and assuming a range of monthly natural (M), spawning (S), and annual fishing (F) mortality rates.

M	S ¹	F	Offshore/inshore		Inshore	
			Spawning /1,000 No.	Wt(kg)	Spawning /1,000 No.	Wt(kg)
N = 0.88 billion						
0.052	0.848	0.27	390.1	58.4	402.2	60.6
	0.495	0.41	338.7	50.1	354.7	53.0
		0.55	294.7	43.1	313.1	46.4
		0.93	202.5	28.9	224.2	32.5
		3.00	27.8	3.8	40.2	5.4
N = 1.50 billion						
0.080	0.869	0.27	282.7	41.3	290.9	42.7
	0.495	0.41	246.0	35.6	256.9	37.5
		0.55	214.3	30.8	227.0	32.9
		0.93	148.0	20.8	163.0	23.2
		3.00	20.6	2.8	29.3	3.9
N = 2.00 billion						
0.090	0.876	0.27	252.3	36.6	259.4	37.8
	0.495	0.41	219.8	31.6	229.2	33.2
		0.55	191.5	27.3	202.6	29.2
		0.93	132.4	18.6	145.6	20.6
		3.00	18.9	2.5	26.2	3.5
N = 3.00 billion						
0.100	0.884	0.27	225.5	32.4	231.6	33.5
	0.495	0.41	196.5	28.1	204.7	29.4
		0.55	171.2	24.3	181.0	25.9
		0.93	118.5	16.5	130.1	18.3
		3.00	16.6	2.2	23.4	3.1

1 - Upper values are monthly spawning mortalities for the spring cohort in its first spawning season (applied to two months, S would be one half this value during each of the four months in the second spawning season), lower values are monthly S for the autumn cohort.

Table 5. Equilibrium recruitment in billions (R_E), equilibrium spawning biomass in thousands of tons (B_E), yield (kg) per 1,000 recruits and equilibrium yield in thousands of tons (Y_E), for two exploitation patterns (international and domestic) and for three levels of density dependence for the stock-recruitment relationship ($A=1.0, 0.8, \text{ and } 0.4$), assuming a current recruitment level of 2.0 billion.

F	International				Domestic			
	R_E	B_E	YPR	Y_E	R_E	B_E	YPR	Y_E
A=1.0								
0.27	2.0	72.2	8.5	17,000	2.0	74.2	9.3	18,600
0.41	2.0	62.5	11.8	23,600	2.0	64.4	13.1	26,200
0.55	2.0	53.7	14.6	29,200	2.0	56.6	16.3	32,600
0.70	2.0	45.9	16.9	33,800	2.0	48.8	19.0	38,000
0.80	2.0	42.0	18.3	36,600	2.0	44.9	20.6	41,200
0.93	2.0	37.1	19.8	39,600	2.0	40.0	22.9	45,800
1.20	2.0	28.3	22.2	44,400	2.0	31.2	25.5	51,000
1.30	2.0	25.4	22.8	45,600	2.0	28.3	26.4	52,800
3.00	2.0	23.4	26.7	53,400	2.0	26.4	33.3	66,600
4.00	2.0	21.5	26.6	53,200	2.0	23.4	33.4	66,800
A=0.8								
0.27	2.09	75.7	8.5	17,800	2.12	64.6	9.3	20,000
0.41	1.97	62.1	11.8	23,200	2.01	52.6	13.1	26,300
0.55	1.83	49.7	14.6	26,700	1.87	42.1	16.3	30,500
0.70	1.65	38.4	16.9	27,900	1.73	30.0	19.0	32,900
0.80	1.51	31.6	18.3	27,600	1.61	24.0	20.6	33,200
0.93	1.30	23.7	19.8	25,700	1.42	16.5	22.9	32,500
1.2	Not sustainable				Not sustainable			
A=0.40								
0.27	0.16	5.3	8.5	1,360	0.16	5.3	8.5	1,360
0.41	Not sustainable				Not sustainable			

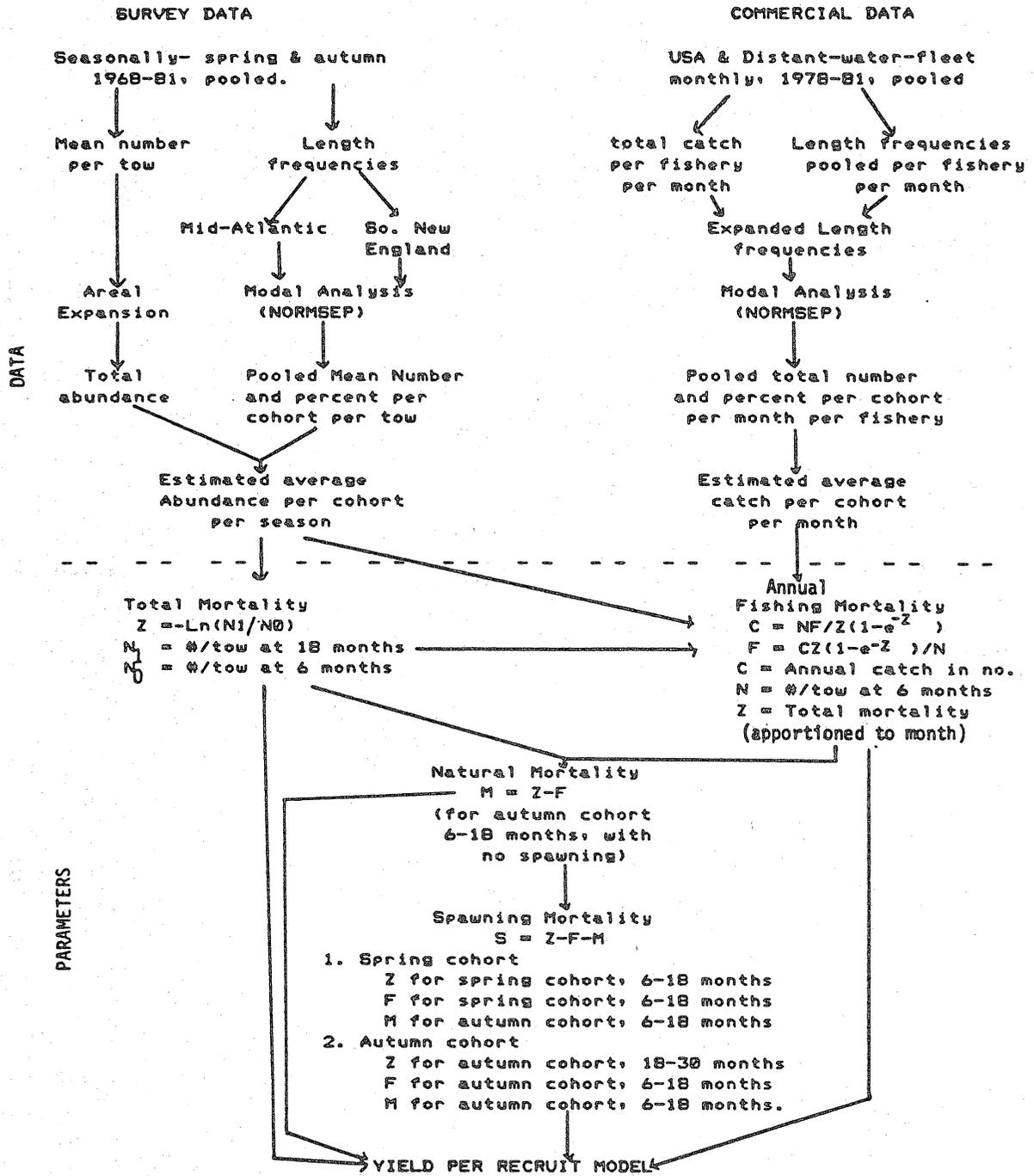


Figure 1. Flow chart showing development of input (data and parameter estimation) to the yield-per-recruit analysis.

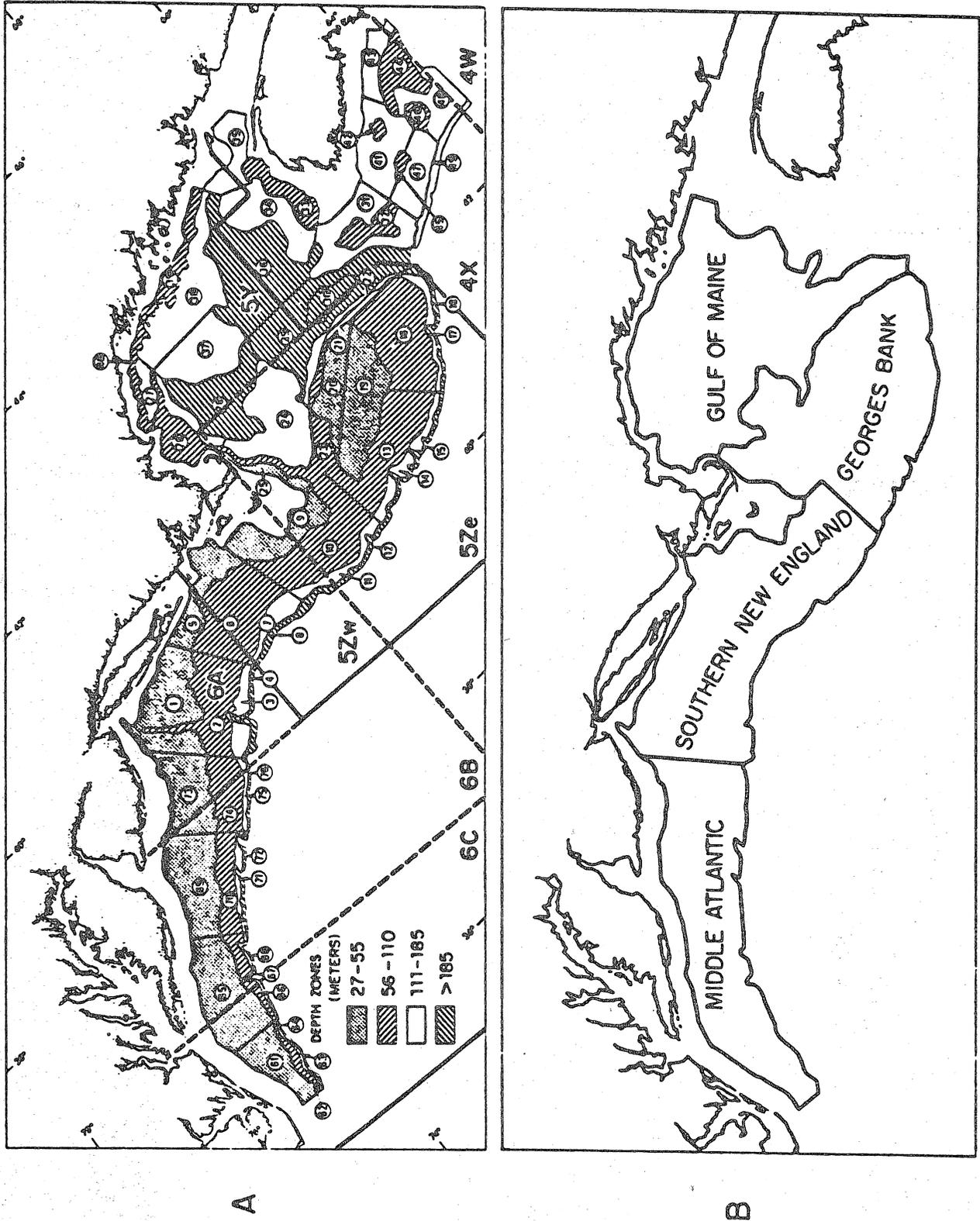
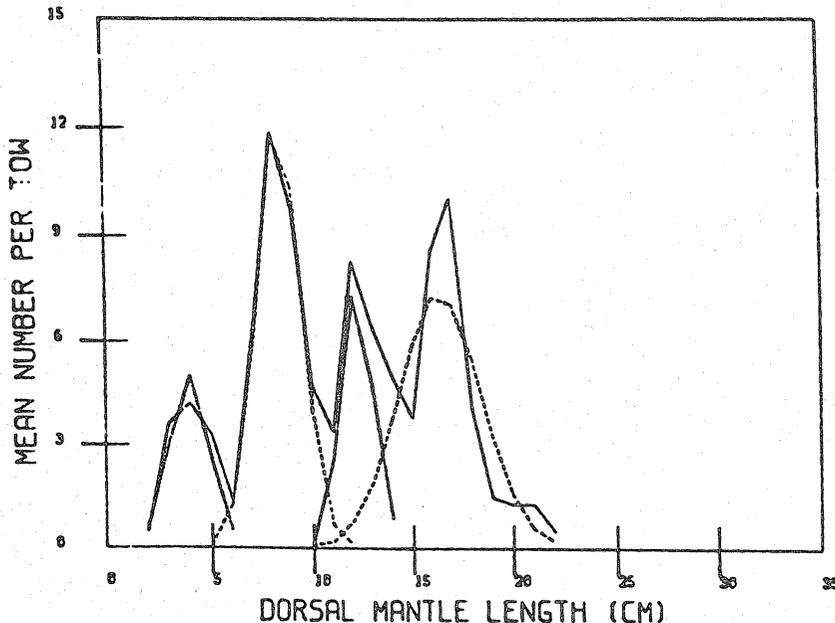


Figure 2. A. USA bottom trawl survey strata and NAFO Subareas 4-6.
B. Geographical areas off the northeast coast of the United States.

LOLIGO LENGTH FREQUENCIES - SPRING



LOLIGO LENGTH FREQUENCIES - AUTUMN

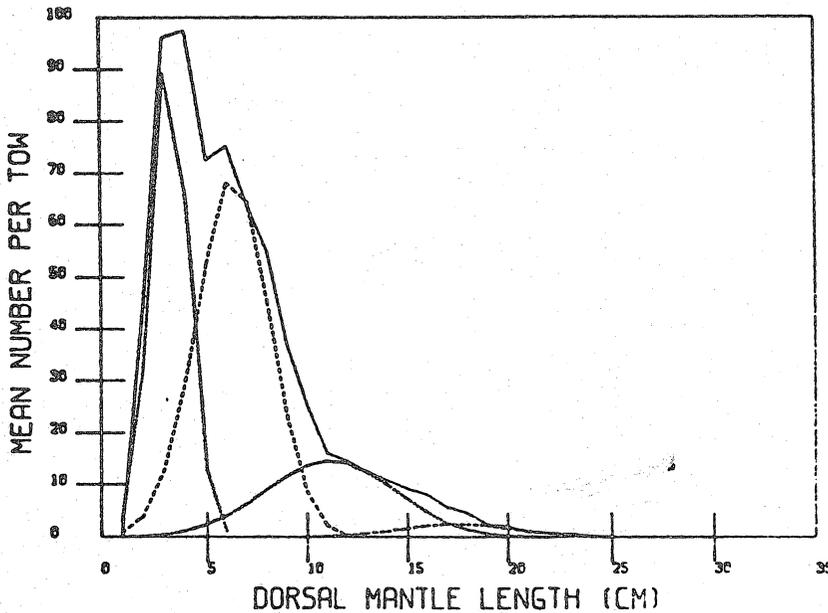


Figure 3. Length frequency distributions from the southern New England area and corresponding composition by cohort from modal analysis from spring and autumn surveys (1968-81 pooled data).

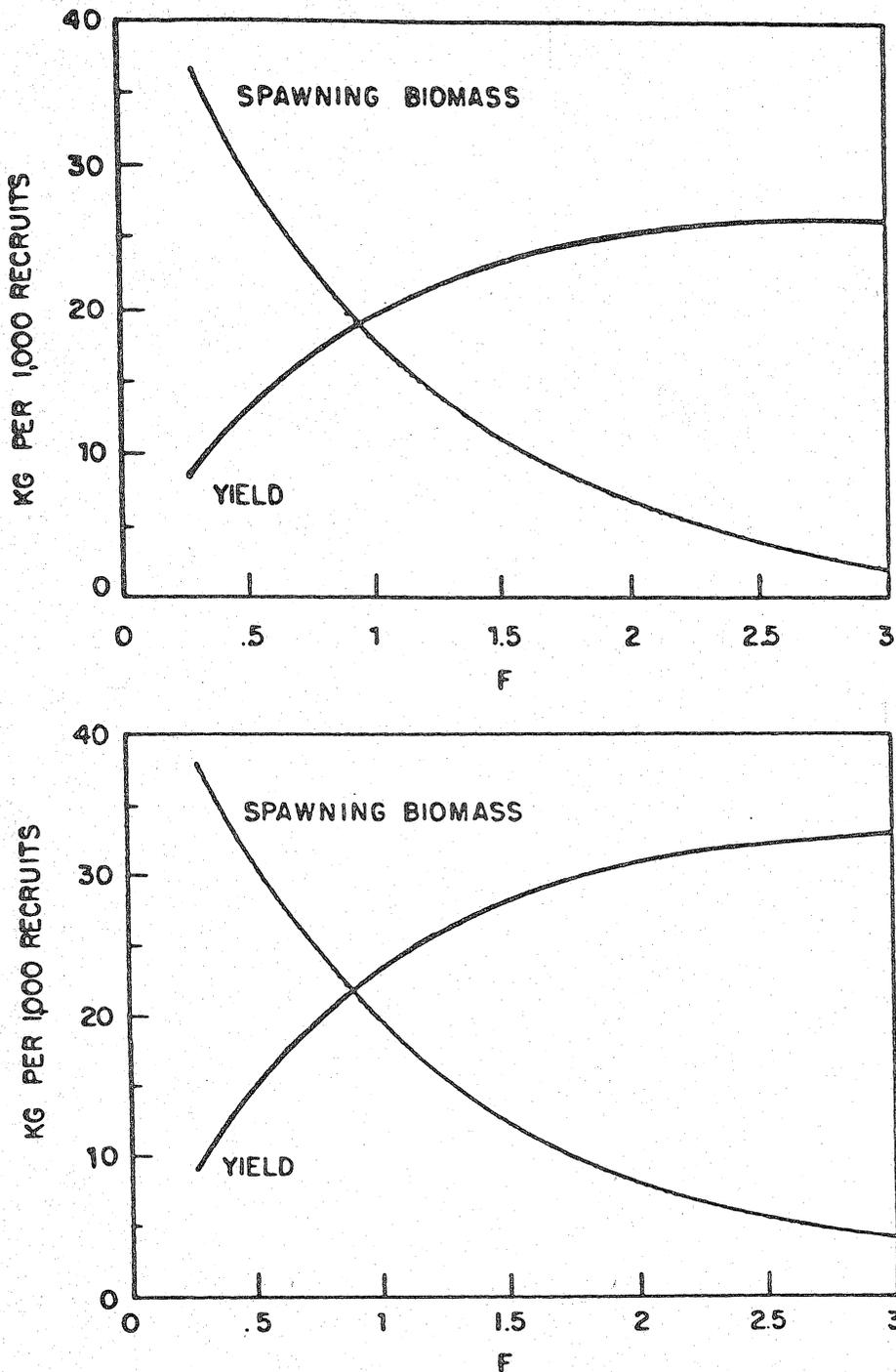


Figure 4. Yield (kg) and spawning biomass (kg) per 1000 Loligo recruits at 6 months of age, assuming natural and spawning mortality rates as calculated for an abundance of 2.0 billion recruits (monthly $M=0.09$, annual $S=1.752$ for the spring and 2.969 for the autumn cohorts), for the offshore/inshore (A) and the inshore (B) fisheries.

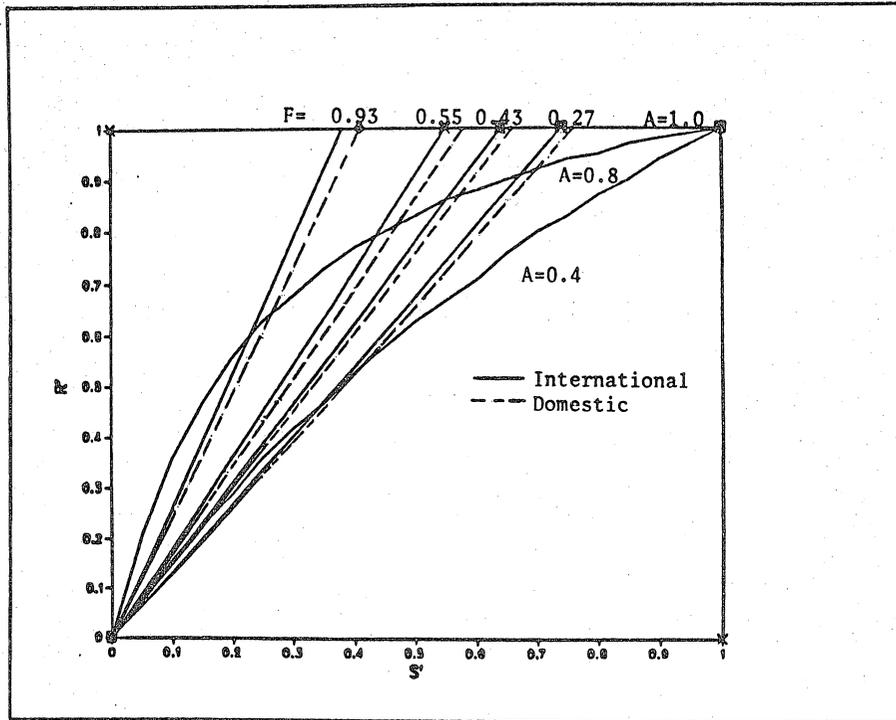


Figure 5. Stock-recruitment relationships as a proportion of virgin spawning biomass ($S_v = 532,000$ t; $112,700$ t; and $97,600$ t) and recruitment ($R_v = 10.9$; 2.32 ; and 2.0 billion individuals), for *Loligo pealei*, with strong ($A=0.4$), moderate ($A=0.8$), and no ($A=1.0$) density dependence, respectively. Lines indicate constant recruitment to spawner ratios for $F=0.27$, 0.41 , 0.55 , and 0.93 and for the international and the domestic fisheries. Equilibrium recruitment is determined as the point of intersection of these lines with the stock-recruitment curves.

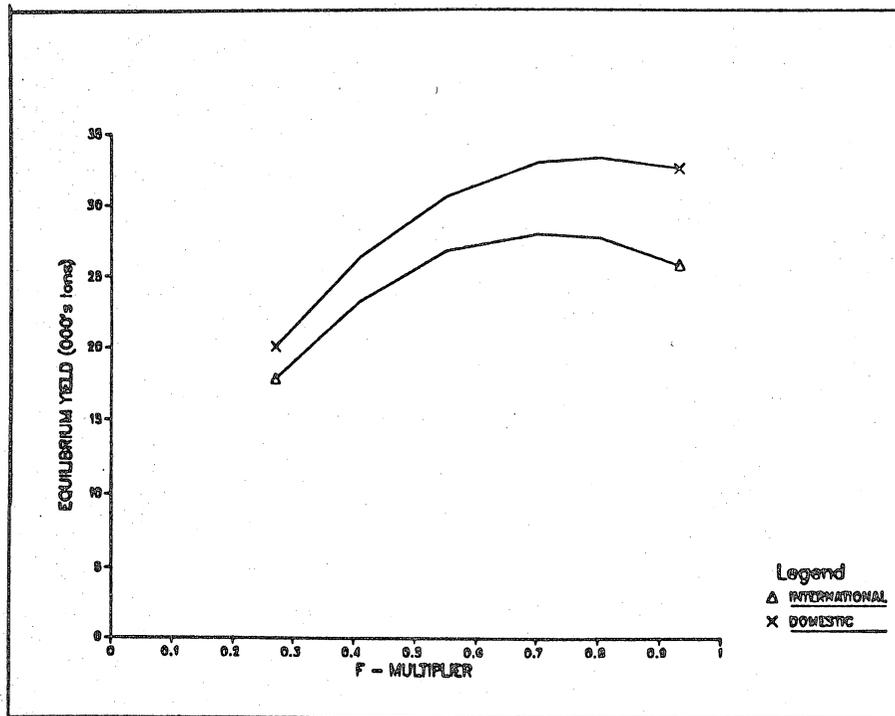


Figure 6. Equilibrium yield (1000's of tons) of *Loligo pealei* as a function of fishing mortality (F-Multiplier), for the international and the domestic fisheries, assuming a Beverton-Holt (1957) stock recruitment relationship with moderate density dependence ($A=0.8$).