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Cod and Haddock Recruitment Processes - Integrating Stock and Environmental Effects

Sensitivity of potential recruitment to stock structure in the presence of temporally varying survival.

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Abstract

In this paper we discuss the results of a modelling study which quantifies differences in the number of potential recruits produced from a range of age-structured populations over a spawning season with temporally varying survival rates. We include investigations into the effects that variation in female condition and egg quality (as a function of female characteristics) may have on overall production. We also quantify the effects on production of potential recruits via changes in the overall duration of spawning seasons due to environmental influences. The population stock structure (the proportion of females in different age classes) has the most effect on overall potential recruitment. The effects of egg quality dramatically increases larger fish's output of viable offspring whilst decreasing that of smaller fish. Fish condition has a very large effect on potential recruitment, but the effects are felt by all age classes equally. The present model outputs dealing with the interactions of temporally varying survival vs. stock structure and condition suggest that the middle of the spawning period consistently produces the most potential recruits but that the relative production of recruits over the spawning season is heavily influenced by both condition and stock structure.

Keywords: egg quality, female condition, modelling, recruitment, stock-structure, temporal survival.

Introduction

It is becoming increasingly clear that stock structure, in addition to stock biomass, plays an important role in predicting recruitment (Trippel et al.1997, Mackenzie et al.1998, Marshall et al.1998, Marteinsdottir and Thorarinsson 1998, Scott et al. *in press*). This is not just due to the incorporation of size specific fecundities but may be due to the increases in egg quality with female size (Hislop 1988, Kjesbu 1989, Kjesbu et al. 1991, Trippel 1998, Marteinsdottir and Steinarsson 1998, Scott et al. *in press*, Solemdal et al. 1992). Further, size and age related differences in spawning time and duration may reduce the risk of poor recruitment due to chance temporal variability in early mortality (Wright et al. 1999). This study asks the question "what level of significance do differences in stock structure and female characteristics play when there are temporally varying windows for survival over a spawning season"?

Methods

In order to investigate the sensitivity of the effects of varying temporal survival over a range of stock-structures and female characteristics we created an individually based and temporally explicit model. The model is set up with the assumption that input data will consist only of the length at age of each individual. In this preliminary deterministic exercise an individual is a 'super' individual, meaning that there is only one value for a given age class. Variables that are calculated at the individual level and per age class are weight, condition, actual fecundity, maximum egg size, number of batches and the initial date of spawning (see Fig. 1). Variables that are calculated over time are the number of eggs per batch, the percentage of eggs spawned (PES), the duration time between each batch, egg size and egg survival (see Fig 2). The differences in stock structure are represented by 6 populations with differing proportions of fish in each age class. Potential recruits are quantified daily from each age class within each of the separate populations (see Fig3-6).

The equations for these functions below are based on values for Icelandic or Arctic Norwegian cod (*Gadus morhua* L.) derived from information from the following sources: Anon. 1998, Kjesbu 1989, Kjesbu et al. 1991, Kjesbu et al. 1996, Marteinsdottir and Steinarsson 1998, Marteinsdottir and Thorarinsson 1998, Scott et al. *in press* and Vallin 1999.

Calculations at the Individual level (see Figure 1)

Weight is a function of length.

$$Weight_{(age)} = 0.000547 * length_{(age)}^{3.648} \qquad (1)$$

Condition is a function of weight and length. The variation between good and poor condition fish and any subsequent variable that it effects is derived from increasing or decreasing the weight at each age class by 10%.

$$\text{Condition: expected } K_{(age)} = weight_{(age)} / length_{(age)}^{3} * 100 \qquad (2)$$

$$\text{Good condition: good } K_{(age)} = (weight_{(age)} * 1.10) / length_{(age)}^{3} * 100$$

$$\text{Poor condition: poor } K_{(age)} = (weight_{(age)} * 0.90) / length_{(age)}^{3} * 100$$

The change in condition (CK) is the difference between good / poor condition fish at age and the expected K at age. Therefore CK is positive when fish are in good condition and negative when they are in poor condition.

$$\text{Change in condition: } CK = \text{good or poor } K_{(age)} - \text{expected } K_{(age)} \qquad (3)$$

Actual fecundity takes into account the effects of atresia in the pre-spawning stage.

$$\text{Actual Fecundity: } Afec_{(age)} = 1.66 * weight_{(age)}^{2.739} * length_{(age)}^{-5.318} \qquad (4)$$

Maximum egg size is the maximum diameter value that an individual is able to produce during the spawning season and is needed as input for equation 11 to determine the change in egg size over the spawning season.

$$\text{Maximum Egg size: } Maxegg_{(age)} = 0.67 * weight_{(age)}^{0.0845} \qquad (5)$$

The number of batches that an individual will produce over the spawning season is a function of both length and weight.

$$\text{Batch Numbers: } Bnum_{(age)} = 14805 * weight_{(age)}^{1.6} * length_{(age)}^{-4.72}. \qquad (6)$$

$$\text{Batch Number over time: } Bnum_{(age,\ time)} = \{-Bnum_{(age)} / 2 \text{ to } + Bnum_{(age)} / 2\}$$

The date, from the first of January, that an individual will commence spawning is a function of length. The adaptation of temperature change as a power function to the original formula makes all age classes initial spawning dates relatively closer together in warmer weather and farther apart in cooler weather.

Initial date for spawning $Date_{(age)} = 117.2 - 0.276 * len_{(age)}^{\text{(temperature change)}}$ (7)

Calculations at the Individual level over the spawning season (see Figure 2)

The number of eggs per batch is a function of length and the number of batches:

$Neggs_{(age,time)} = Afec_{(age)} / (2*0.125*length_{(age)}*\pi)^{1/2} * e^{(-1/2*(Bnum(age,time)/0.125*length(age))}$ (8)

The cumulative percentage of eggs spawned over the spawning season:

Percentage eggs spawned: $PES_{(age,\ time)} = (\sum Neggs_{(age,time)}) / Afec_{(age)}$ (9)

Duration of hours between batches. Older fish have longer interbatch intervals with the interval being a function of PES. Therefore as the spawning season continues the interval drops to a minimum of 48 hrs. It also allows the interval to decrease when the fish are in relatively better condition (for their length) and increase when they are in relatively poorer condition.

$Dbatch_{(age,time} = (48 + 0.001*weight_{(age)} - 50*ck_{(age)}) - (0.0008*weight_{(age)}*pes_{(age)})$ (10)

Egg size, as a function of maximum egg size and length, tends to increase slightly and then decrease over the spawning season.

$Esize_{(age,time)} = Maxegg_{(age)} - 0.0025*length_{(age)} * (PES_{(age,\ time)} - PESmax)^2$ (11)

The calculation of egg survival and egg quality follows the same concept that was used in Scott et al. (in press). When egg survival is constant, regardless of the age or condition of the female, the scalar constant is derived by assuming that the standard population (100,000 females) with natural mortality of Z=0.2 has to reproduce it's self and therefore have a total number of *potential recruits* equal to 200,000 (males + females). When egg quality is related to female characteristics, then egg survival is not constant but a function of egg size related to swim bladder frequencies (see Scott et al. in press for more details).

A) Egg survival: assume all eggs are equal.
   $Seql = 0.59072$ (12)

B) Egg survival is a function of egg size related to swim bladder frequencies:
   $Esur_{(age,time)} = -18.278 + 12.866 * Esize_{(age,time)}$
   $Eblad_{(age,time)} = exp(Esur_{(age,time)}) / (1 + exp(Esur_{(age,time)})$
   Egg Quality: $Sqal_{(age,time)} = 0.94184 * Eblad_{(age,time)}$ (13)

Calculations at the Population Level

There are 6 populations, each population has 100,000 females. The proportion in each age class is determined by assuming the total instantaneous mortality (Z) is constant for each age class per population. There are 10 age classes (4-14 years of age). The values of Z range from 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2, for the 6 respective populations. Population 1 (with only natural mortality of 0.2) is the standard against which all quantitative comparisons are made. When fish are in better/poorer condition the percentage at age which are mature increases / decreases by 15% (see table 1 below).

Table 1: Percent of each age class of mature fish under average, good and poor condition.

Age	average	high	low
4	25%	40%	10%
5	50%	65%	35%
6	75%	90%	60%
7	100%	100%	85%

The number of potential recruits is the sum of all potential recruits, per population, either daily or as a total over the entire spawning season. The number of potential recruits (NPR) are calculated using equations 14 and 15. For an explanation of what is a potential recruit see details within the paragraph on egg survival.

$$NPR_{(age,\ time,\ pop)} = \sum number_{(age,\ pop)} * number\ of\ eggs_{(age,\ time,\ pop)} * egg\ survival_{(age,\ time,\ pop)}$$

$$Total\ NPR_{(pop)} = \sum NPR_{(age,\ time,\ pop)} \qquad (14, 15)$$

<u>*Calculating the Temporally varying survival rates: Early, middle, late*</u>

The duration of the spawning season in the exercise is generally around 60 days, therefore to mimic the effects of only some periods of the spawning season successfully producing potential recruits we selected the first 20 days as *early*, middle 20 days as *middle* and last 20 days as *late*. Only potential recruits produced during those periods are summed up and compared to Population 1 under standard conditions.

Preliminary Results

Foremost, before we go on to discuss the results we wish to stress that these are preliminary results. There has not yet been a thorough testing of the effects of the potential range of parameter values, nor indeed have all the variables used to date been proven to be the most appropriate.

The effect of Egg quality on potential recruits is presented in Figure 3. There is a large difference in the relative importance of age class production of potential recruits between the scenarios where egg survival is a constant and egg survival is a function of quality related to female characteristics. When egg survival is constant the younger, more abundant age classes play a major role in potential recruit production. However, when the quality of the egg and hence it's survival depends on female characteristics then the relative contribution of younger age classes to the production of viable offspring decreases and that of the older age classes increase despite their decreasing in abundance.

The effect of Condition on potential recruits is presented in Figure 4. Between the range of poor and good condition fish (representing $\pm$ 10% change in weight at length from the average) the number of potential recruits is doubled under standard conditions in Population 1.

The effect of Population Stock Structure on potential recruits is presented in Figure 5. It is obvious from the few scenarios that we have run that stock structure is the most important factor influencing overall potential recruit production. As the older age classes are reduced in abundance with increasing total mortality (Z) there are drastic reductions in potential recruit production. The difference between Z of 0.2 and Z of 0.6 leads to a 68% reduction in overall production.

The effect of temporally varying survival over the spawning season on potential recruits is presented in Figure 6. Using the output of populations 1, 3 and 5 (Z values of 0.2,0.6 and 1.0 respectively) shows that the middle 20 days of the spawning season are the most productive, with the early 20 days being second most productive and the last 20 days being the least productive for all populations. This pattern is more pronounced with the populations that have higher abundance in the older age classes. Population 5 with only 5 % of the population composed of 7 years and older age classes, shows little difference in production in the 3 time windows. The selection for the midseason is seen regardless of fish condition, but there are major shifts in the relative production between the 3 time windows. The early window does relatively much better than the later window when the fish are in good condition, whereas in poor condition the early and late windows are almost equivalent.

Discussion and Conclusions

Due to the uncertainty in some of the underlying equations and parameter values in this model we have only presented a small amount of the potential output possible. Investigations are currently underway in improving this model in an ongoing EU project. Nevertheless it is evident from the output present that if egg quality is a function of female size then age class structure must be taken into account when predicting recruitment as egg quality substantially increases the recruitment potential of the larger fish. It is also obvious that fish condition has a very large effect on potential recruitment, and that the effects are felt by all age classes equally. Truncated age structures via the effects of fishing mortality have the largest effect on potential production. Interactions between population structure, fish condition and temporal windows of selection also show that using the 'individual based' approach can yield results and insights which are not obvious outside of the realm of modelling.

Acknowledgements

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Figure Legends

Fig. 1. The mean values at each age class (4-14) and the derived $\pm$ change in the variable via the $\pm$ 10% change in weight at length for each of the following variables: weight, condition, actual fecundity, maximum egg size and number of batches. For the variable 'date of initial spawning' the maximum and minimum lines represent $\pm$ 1^0C change in the water temperature.

Fig. 2. The values of the variables (egg size, egg quality, duration between batches and potential recruits) at each age class (4-14) that are functions of the percentage of eggs spawned by that 'individual' at any point in time during the 'individuals' spawning season. (Please note that 'individual' here refers to one value for each age class).

Fig. 3. The two panels represent only the contrasting effects of egg quality. The top figure shows the number of potential recruits over time for each age class for Population 1 under average condition with egg survival being a constant across all females (see equation 12). The bottom figure shows the number of potential recruits over time for each age class for Population 1 under average condition with egg survival being a function of female size (see equation 13).

Fig. 4. The two panels represent only the contrasting effects of fish condition. The top figure shows the number of potential recruits over time for each age class for Population 1 with all fish in good condition and egg survival being a function of female size. The bottom figure shows the number of potential recruits over time for each age class for Population 1 with all fish in poor condition with egg survival being a function of female size.

Fig. 5. The two panels represent only the contrasting effects of stock structure due to changes in mortality. The top figure shows the number of potential recruits over time for each age class for Population 1 under average condition with egg survival being a function of female size. The bottom figure shows the number of potential recruits over time for each age class for Population 3 under average condition with egg survival being a function of female size.

Fig. 6. The 6 panels represent the simultaneous effects of stock structure, fish condition and temporal differences in survival. The three left panels shows the total number of potential recruits over time for each of Populations 1, 3 and 5 under average, good and poor condition with egg survival being a function of female size. The three right panels shows the total number of potential recruits produced either during the early middle or late period of the spawning season for each of Populations 1, 3 and 5 under average, good and poor condition with egg survival being a function of female size.

Fig 1

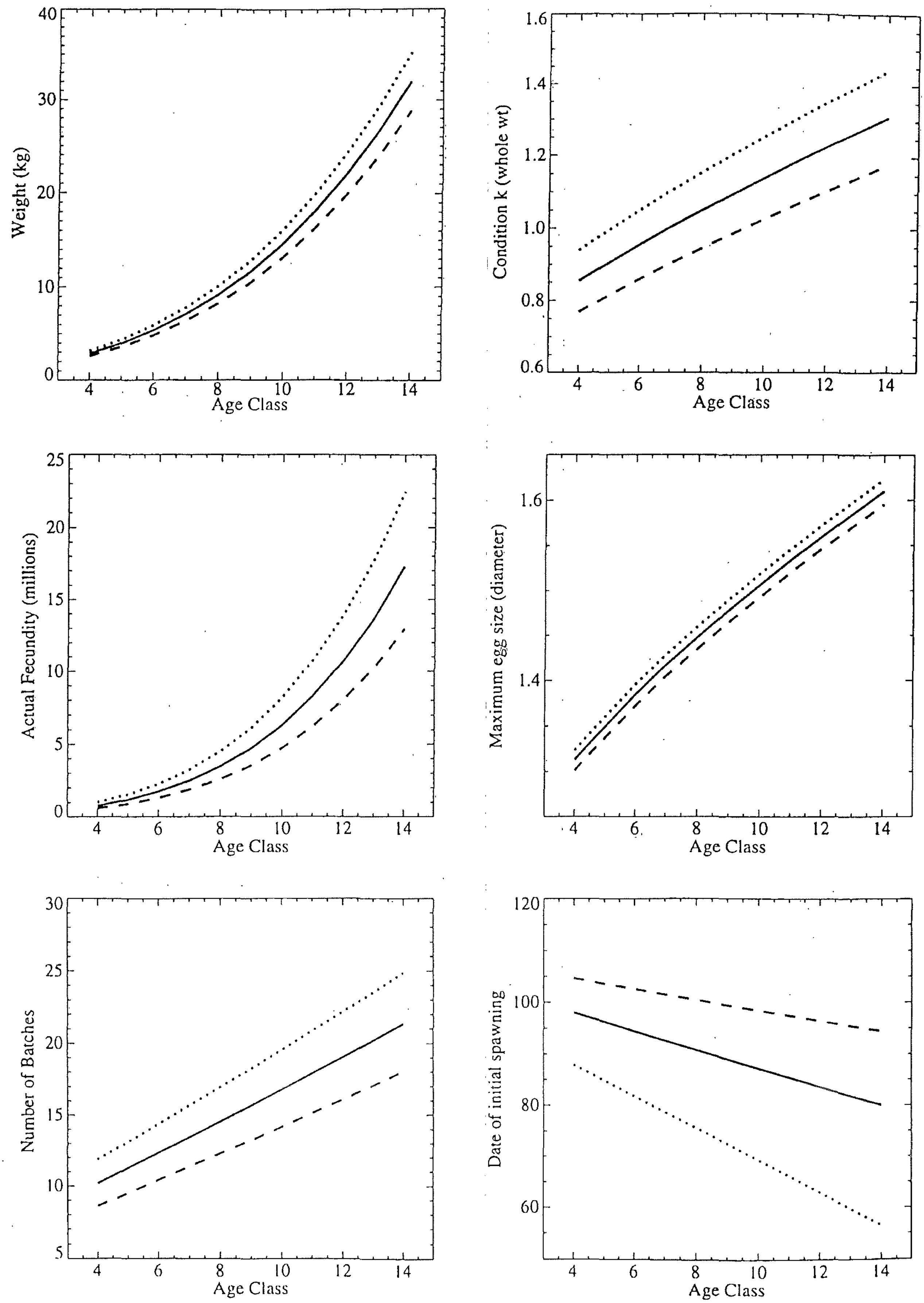
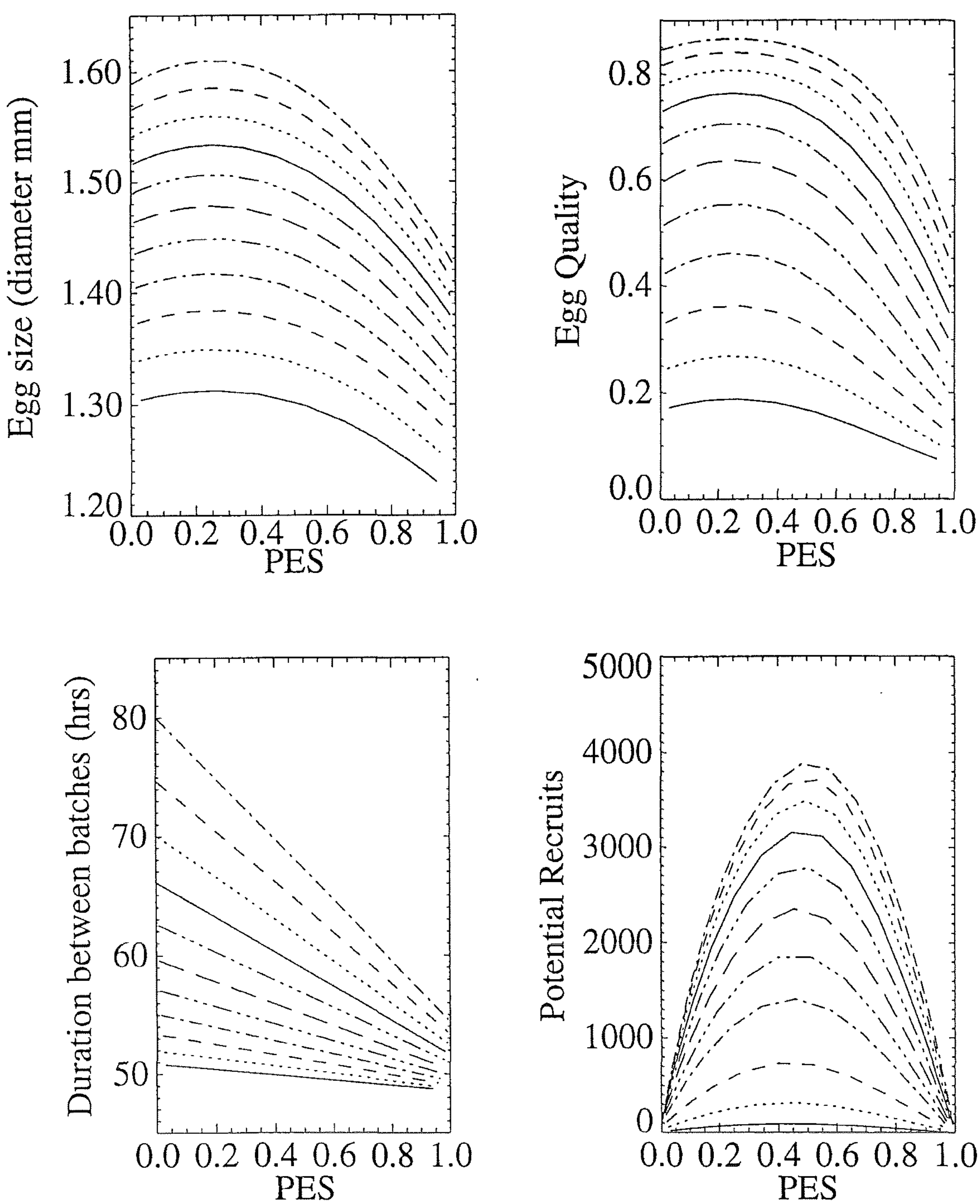

Weight (kg)
Condition k (whole wt)
Actual Fecundity (millions)
Maximum egg size (diameter)
Number of Batches
Date of initial spawning
Age Class

Fig 2



Egg size (diameter mm)
1.20
1.30
1.40
1.50
1.60
Egg Quality
0.0
0.2
0.4
0.6
0.8
Duration between batches (hrs)
50
60
70
80
Potential Recruits
0
1000
2000
3000
4000
5000
0.0 0.2 0.4 0.6 0.8 1.0
PES

Fig3

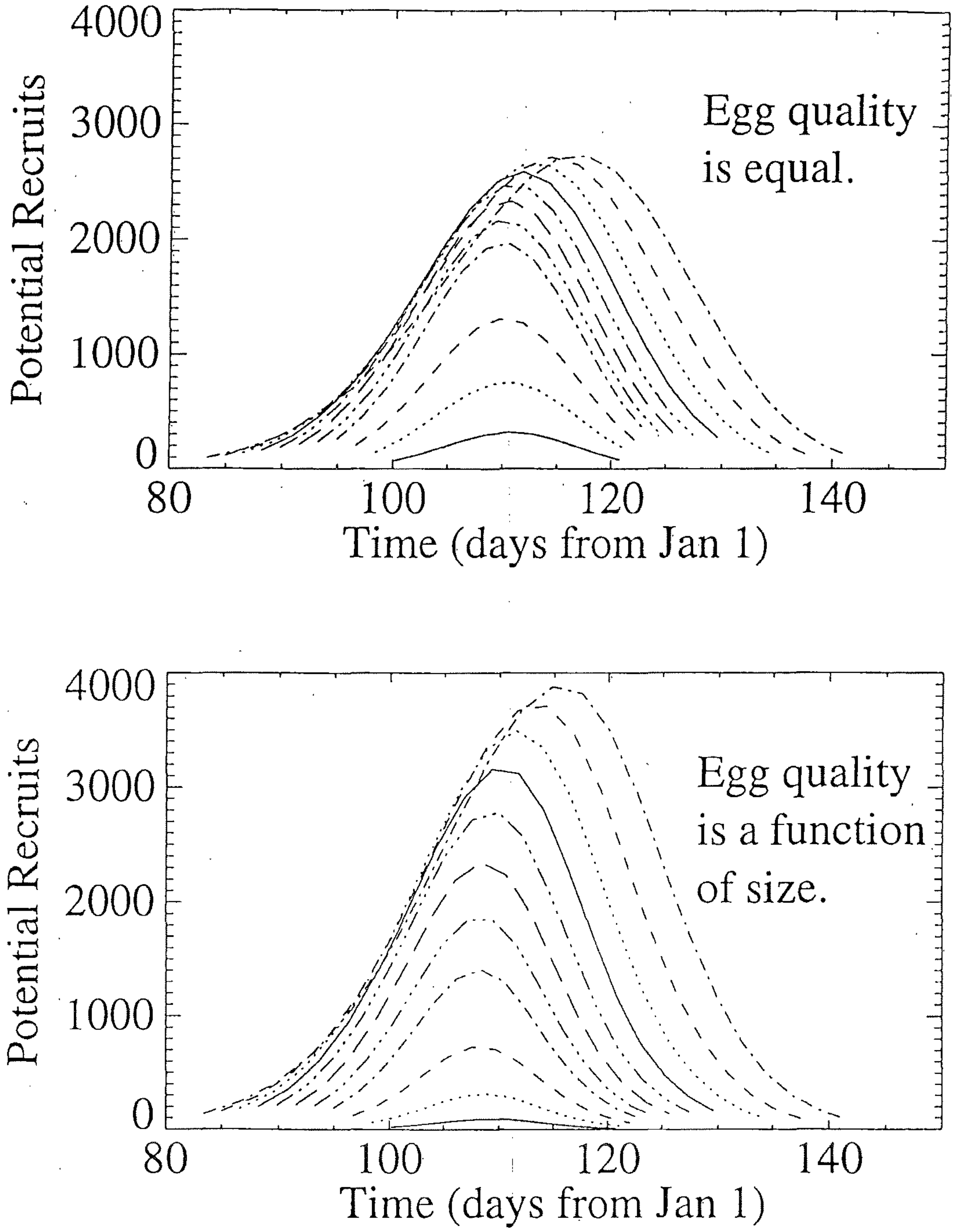
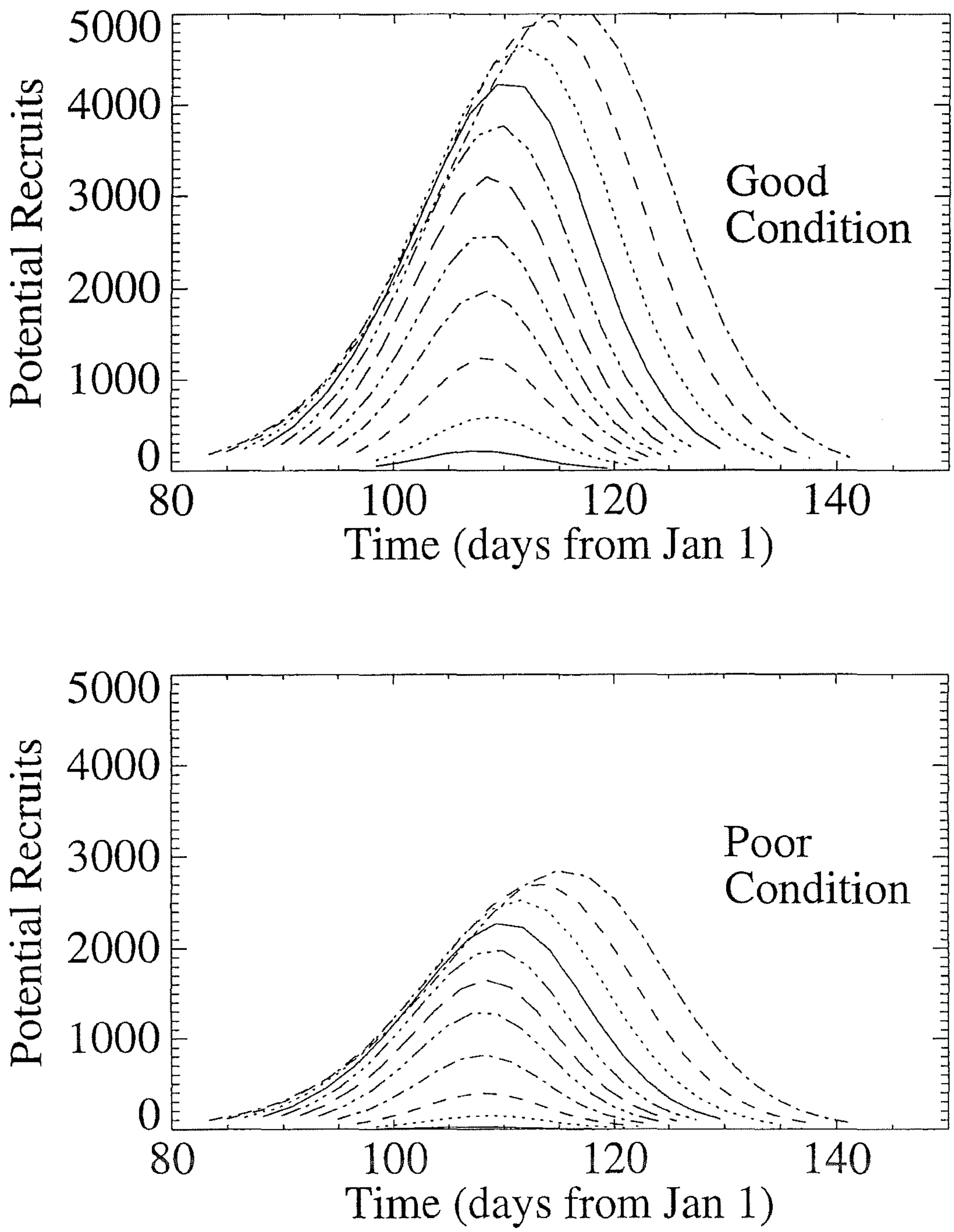

4000
3000
2000
1000
0
Potential Recruits
Egg quality
is equal.
80
100
120
140
Time (days from Jan 1)
4000
3000
2000
1000
0
Potential Recruits
Egg quality
is a function
of size.
80
100
120
140
Time (days from Jan 1)

Fig 4



5000
4000
3000
2000
1000
0
Potential Recruits
80
100
120
140
Time (days from Jan 1)
Good Condition
5000
4000
3000
2000
1000
0
Potential Recruits
80
100
120
140
Time (days from Jan 1)
Poor Condition

Fig 5

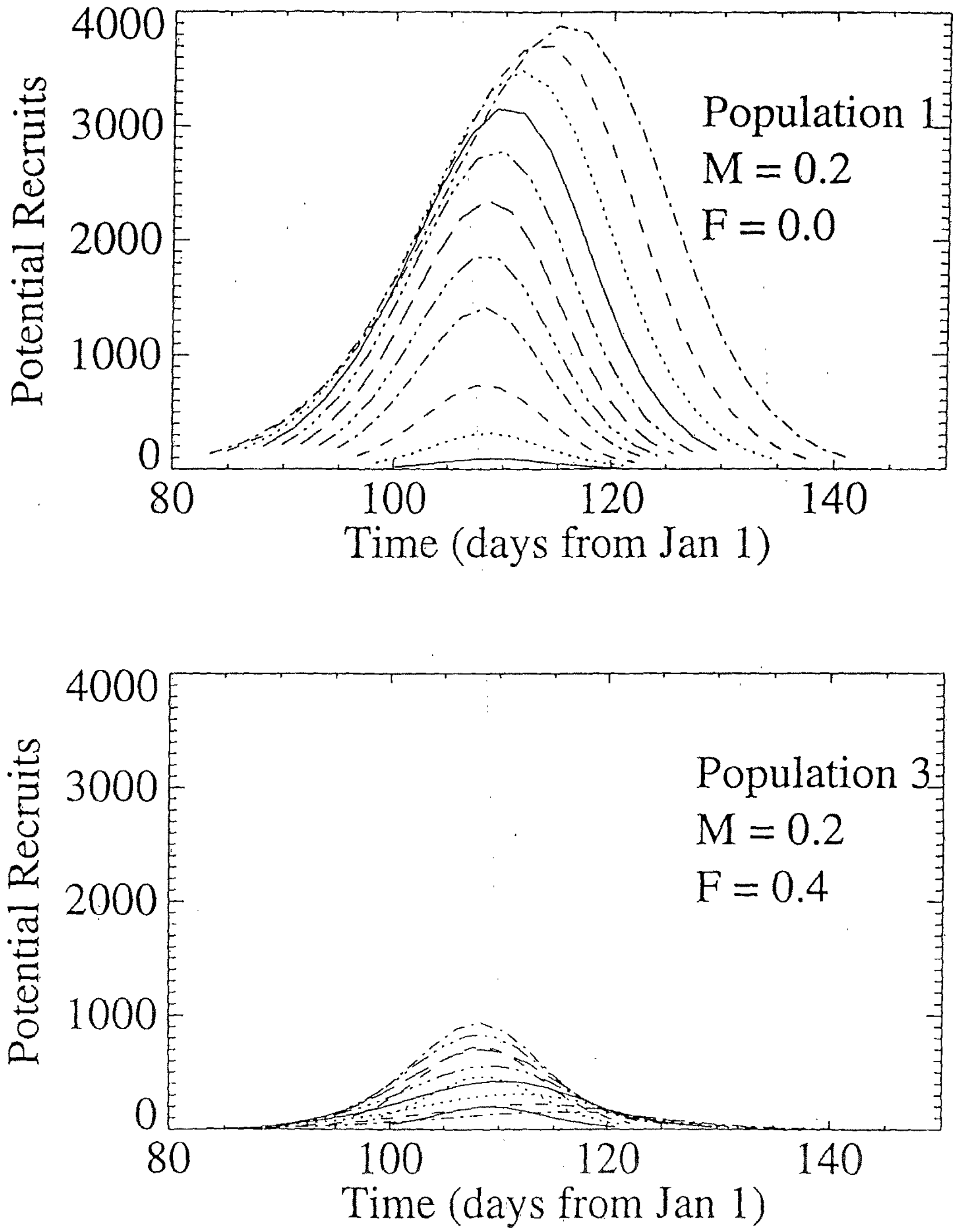
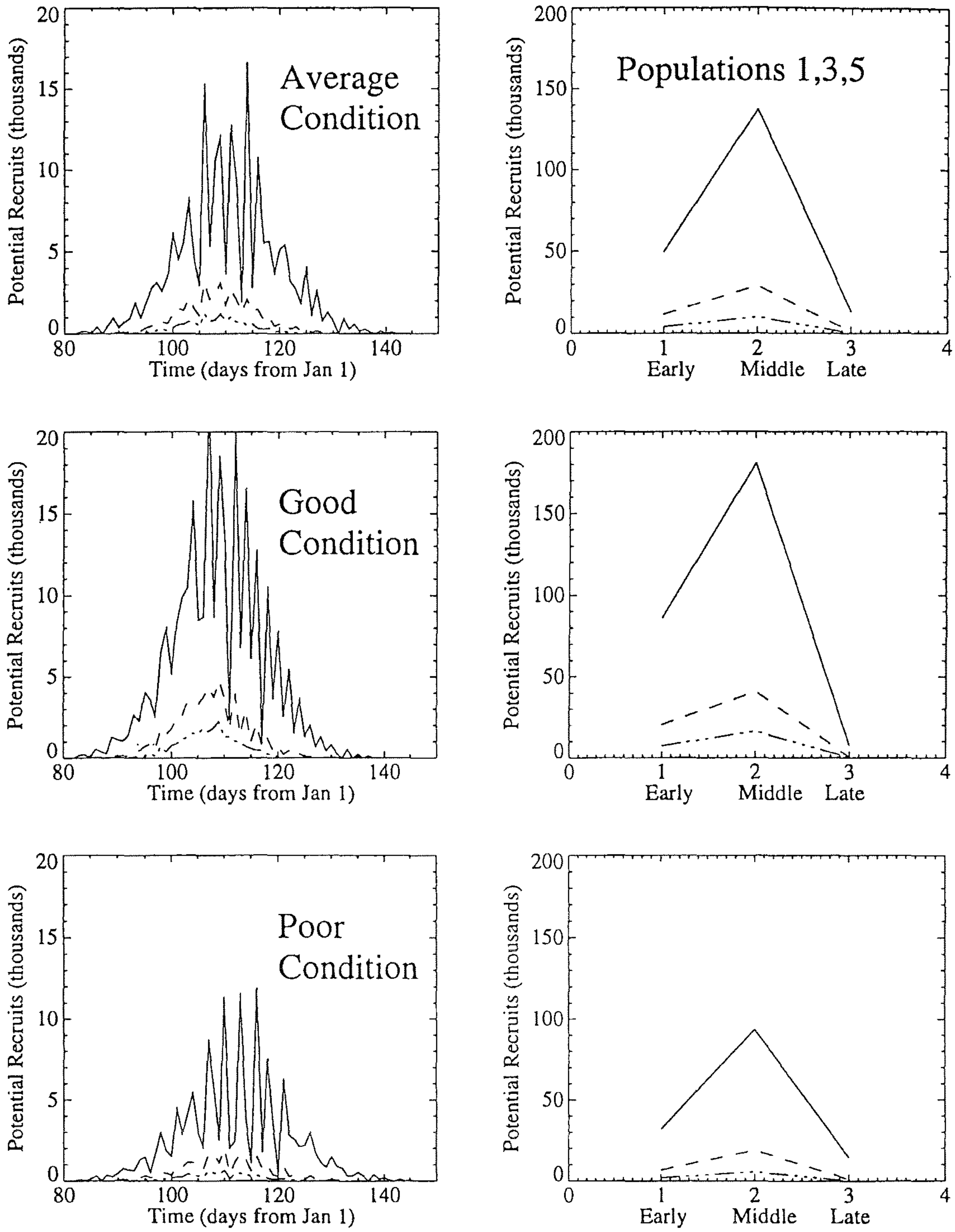

4000
3000
2000
1000
0
Potential Recruits
Population 1
M = 0.2
F = 0.0
80
100
120
140
Time (days from Jan 1)
4000
3000
2000
1000
0
Potential Recruits
Population 3
M = 0.2
F = 0.4
80
100
120
140
Time (days from Jan 1)

Fig 6


Average Condition
Populations 1,3,5
Good Condition
Poor Condition
Potential Recruits (thousands)
Time (days from Jan 1)
Early
Middle
Late