Table of Contents

List of Figures

Chapter 1

Development of an Agent-Based Within Season Depletion Model

1.1 Introduction

This chapter focuses on the development of new stock assessment methodology for Dungeness crabs *Metacarcinus magister* [2] (or *Cancer magister* [1]). Traditional questions addressed by stock assessment require evaluation of stock status, mean productivity, and the potential consequences of management options [28]. Numerous stock assessment methods have been developed to address these sorts of questions; Punt et al. [23] reviews many of these methods. Some of these methods, such as Zhang et al. [30], show ways to model the size composition of the stock of interest. (In Chapter **??** I discuss how fitting to size composition data helps estimate natural mortality under an assumed growth model.) Most of the stock assessment questions typically considered are investigated on an annual time step [23]; however, Punt et al. [22] provides a weekly model of the Australian Prawn fishery, Robert et al. [24] develops a weekly depletion model of Moroccan octopus, and there are other weekly time step models of invertebrate fisheries. Considerably less attention has been devoted to developing models of within season fishery dynamics for evaluation of in-season management procedures; within season modeling of fisheries dynamics can explore the interplay between license restrictions, harvest control rules, the empirical behaviour of the fishing fleet, and in season changes in stock attributes, e.g. moult condition.

As the number of things being kept track of increases traditional array based modeling approaches become cumbersome. For example, it is easy to use arrays for statistical catch-at-age models. It is not particularly difficult to use array based models to allow variability in growth. However, to keep track of variability in moult, variability in growth, and changes in vulnerability over time, a number of arrays must be linked. To model such scenarios a modeler may find it useful think carefully about data structures that make developing the model easier. One such approach is to use object oriented programming to model groups of organisms as instances of a single programming class. This approach is essentially an agent-based or individual-based model and is explored in this chapter.

There are two different types of harvest controls that can be used to regulate fishing activity: output control (i.e. total allowable catch), and input control (i.e. rules directly limiting exploitation rates by restricting effort). Many fisheries use a combination of both methods. Understanding the relationship between effort and catch on a fine timescale can help assess how input controls (potentially in combination with output controls) regulate realized, as opposed to targeted, exploitation rates. Learning about the relationship between weekly effort and catch may be a challenging problem because weather, the dockside price of the resource, and availability of alternative employment, can be important drivers of how much effort is deployed over a short time period [28]. Several fisheries have regulations that drive within year changes to the abundance of the legally harvestable part of the stock. For example, the snow crab (*Chionoecetes opilio*) fishery in the Gulf of Saint Lawrence can only take hard-shell male crabs that have a carapace greater than $95mm$ and is also subjected to an annual quota [8]. Both snow crab and Dungeness crab can only be harvested when their shells are hard [8, 30].

According to Fisheries and Oceans Canada (D.F.O.) the existing crab management regime is inconsistent with modern Canadian policy [7]; there is much debate on how to bring input controlled fisheries into compliance [9]. In particular, DFO has suggested eight different potential management options: commercial seasonal closures, closure of large areas in each crab area, establishment of total allowable catch regulation (possibly via individual transferable quotas), differential size limits (between the commercial and first nations fisheries), reduced total maximum number of traps for the fleet and trap limits for each sized vessel, increased escape ring size, allowing vessels to transfer some of their traps to another vessel (trap stacking), and commercial license retirement[7]. A within season model of fisheries dynamics can help partially evaluate at least some of these proposed management options and assess the efficacy of the existing management regime. For example, it is unclear what, if anything, the current management regime does to constrain the exploitation rate of legal male crabs. It is also unclear if there is a minimum density of legal male crabs, below which the fishery cannot profitably continue.

The spatial scale that stock-recruit processes occur at is uncertain; Park et al. [21] point out that larvae from the Washington State in the United States can be carried, at least in some years, as far north as Alaska. Jamieson and Phillips [16] found that larval distribution is mediated by both currents and larval behaviour. Additionally, it is uncertain if high fishing mortality on male crabs impairs mating success of female crabs, although Hankin et al. [14] found that high fishing mortality on males did not significantly reduce the proportion of mature females receiving a sperm plug in Northern California. Having a sperm plug is a strong indicator of mating success [20].

To assess the relationship between weekly catch and weekly effort it is not necessary to explicitly address the spatial scale of the stock recruitment relationships of the Dungeness crab stock, since we are only concerned with the number of crabs recruiting to Area A in the Hecate Strait and do not need to know where the recruits come from. This does not mean that the biology and behaviour of Dungeness crab are unimportant, there is a strong seasonal moulting pattern that coupled with the restriction on retaining soft-shell crab likely drives the seasonality of this fishery. The Dungeness crab fishery is regulated by a complex mix of effort controls, including size, sex, and seasonal restrictions. In addition to these restrictions, there are also restrictions upon the number of licenses that can fish in an area, the size of boats that can fish in an area, the number of traps deployed on a boat of a given size, the maximum soak time of traps, and restrictions on the design of traps [29].

The Dungeness crab fishery in the Hecate Strait is regulated in a manner that is consistent with other Dungeness Crab fisheries in North America. In particular, only hard shell male crabs larger than $165mm$ can be retained. The size restriction varies by jurisdiction. For example, Washington State has set a restriction of 6.25 inches (158.75mm) point to point and the minimal size limit in Alaska is 6.5 inches (165.1mm). Since soft shell crab are not legally harvested, and cannot be marketed, it is important to characterize the moult pattern of crabs.

This chapter develops a within season depletion model that characterizes the relationship between weekly fishing effort and catch when seasonal availability of the resource is highly variable. The model relates weekly observed effort to weekly observed catches in a highly seasonal fishery driven by weather and seasonal moulting episodes. While the model developed in this chapter does not seek to explain why fishing effort is highly seasonal, it uses the biology of the crab stock and patterns in weekly crabbing effort to explain weekly catches.

1.2 Model Description

This chapter presents a depletion model based on aggregations of crabs. Each aggregation of crabs has its own growth rate and week of year that it moults. The model relates weekly effort to the weekly catch needed to satisfy the following criteria: crabs have variability in moult timing, crabs have variability in growth rates, and the harvest rate of crabs depends on the distribution of shell conditions (between soft and hard shell crabs).

The model developed is an agent-based model, and each aggregation of crabs has an associated abundance. There are few stock assessments that have used individual-based models; individual-based models are generally used in fisheries science to model fleet dynamics (for example Walters and Martell [28]) or simulation studies like Shin and Cury [25] and Beard and Essington [3]. For the purposes of this text, agent-based models and individual-based models are the same thing. Agent-based models are often used to model dynamic networks of interacting agents [13]; however, the focus of the aggregation-based model developed in this chapter is simply to keep track of the state of different components of the stock. Since there is limited need to model behaviour of animals in most stock assessments, few people use agent-based models in stock assessments. Grimm et al. [12] point out there is no standard approach to describing agent-based models; there is no standard protocol for describing them, and they are often described verbally without a clear indication of the equations, rules, and schedules used in the model.

The model in this chapter includes male crabs only, they recruit to the model when their shell is $100mm$ in size. Male crabs are harvested when their shells are hard, and their carapace is larger than $165mm$. The model has two distinct conceptual levels: the aggregation level and the population level. Each aggregation has it's own growth rate and moulting schedule. The following subsections first describe how an individual aggregation is initialized and advanced each week, and then how the aggregations are assembled into a population of crabs. Finally, the likelihood function that is used to fit the catches predicted by the model to the observed catches is presented. (Some code segments are presented in Appendix .1.)

1.2.1 Definition of Aggregation

A population of crabs in the model has variable moulting schedules and growth rates can be assembled from aggregations of crabs that have identical moult schedules and growth rates. In this subsection the dynamics of a single such aggregation is discussed; the assembly of these aggregations into a population is presented later.

The state of each aggregation is advanced one week using two separate routines for the biology and fishing dynamics. The population of crabs advances by updating the state of many different aggregations of crabs. These routines are applied to each aggregation each week.

Biological dynamics of a single aggregation

Figure 1.1 presents a flow chart for the routine that advances the biology of a single aggregation of crabs by a single week. A description of each node is presented below. Equations in this subsection apply only to a single aggregation. When presenting routines that advance a single aggregation the chapter does not use a subscript to denote which aggregation is being referenced. However, when the aggregations are assembled into a population, a subscript denoting aggregation is added.

1. Check if aggregation is alive. For the aggregation to be alive, the date in weeks must be greater than or equal to the birth-week of the aggregation. If the aggregation is alive go check if the aggregation changes shell condition, otherwise (it is dead) do nothing and return to the simulation.

2. Check if the aggregation changes shell condition. If the number of weeks in a shell condition is less than or equal to the duration of the shell conditions (see table Table 1.1), then the shell condition remains the same and the counter of the number of weeks in shell condition is incremented by one and natural mortality is applied. If the shell condition changes, then test if the crabs moult. While the order of shell conditions (5, 4, 3, 2, 1, 6, 8, 7) is non-intuitive, they follow the D.F.O. soft shell protocol [10]. When crabs leave shell condition 8, they moult into shell condition 5. If the number of moults exceeds the maximum number of

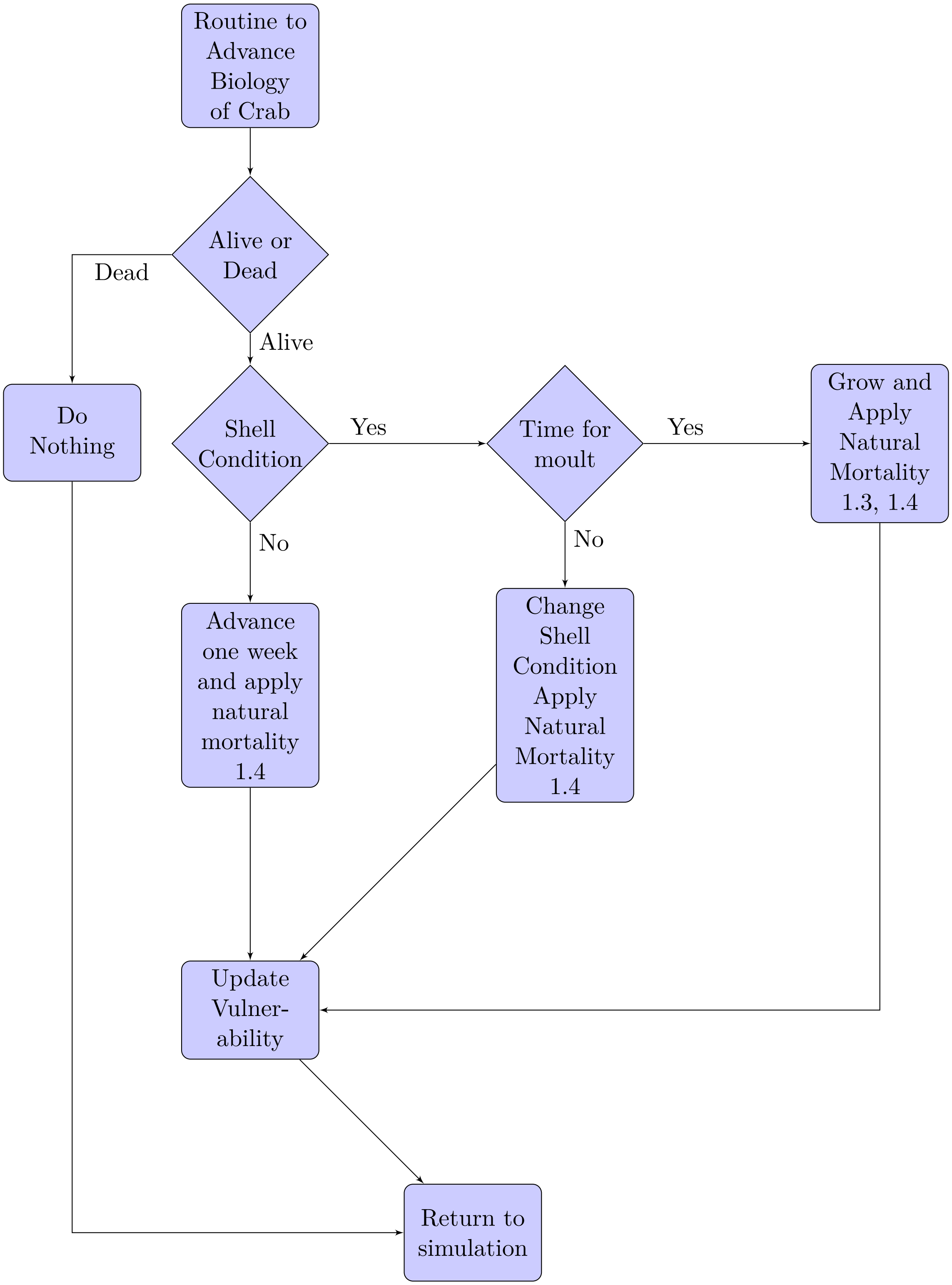

Figure 1.1: Biological Events Flowchart: This flow chart shows how the biology of a single aggregation is advanced each week. The numbers in the nodes are relevant equations.

moults (4 moults) then, instead of transitioning from shell condition 6 into shell condition 8, they transition into shell condition 7 (old shell) where they remain for the rest of their lives. The different shell conditions are shown in Table 1.2. Note that the sum of the durations in weeks, excluding shell condition 7, is 52. This is required since I assume crabs moult once a year, on a fixed schedule. (It is assumed there is no variability in the inter-moult period.) Crabs enter shell condition 1 and become legal to harvest 13 weeks after moulting.

Shell Condition	1	2	3	4	5	6	8	7
Duration in weeks	6	4	6	2	1	8	25	∞

Table 1.1: Shell Condition Duration Table in weeks

Shell Condition	Soft Shell Survey Definition	Time Since Moult	Code
Soft	Soft Just Moulted	2-6 Days	5 and 4
	Very New	6 Days - 1 Month	3
	New	1-3 Months	2
Hard	Newly hard	3-6 Months	1
	Between New and Old	6-12 Months	8
	Old	12-24 Months	6
	Very Old	More than 24 Months	7

Table 1.2: The hardness of crab shells determined by how much time has elapsed since the moult.

3. Check if aggregation moults. If crabs are transitioning from shell condition 8 into shell condition 5, then they moult. Otherwise advance the shell condition, apply natural mortality, and reset the counter on the number of weeks in a shell condition.

4. If crabs moult then they grow according to Equation 1.3, where L_{new} is the length of crabs in the aggregation after growing and L_{old} is the length of crabs in the aggregation prior to moulting. In Equation 1.3 the intercept is drawn as: $\beta \sim N(\mu = 18.07, \sigma = 3.29)$ when the aggregation is initialized, some aggregations grow faster than others. (Note there is no variability in the slope.) Once the aggregation's growth model intercept β is defined, it never changes. Each time an aggregation moults a counter is also incremented so that after a set number of moults (5 moults) crabs stop moulting and transition into shell condition 7. Unlike Zhang et al. [30], this model does not have size-dependent moulting probabilities; it assumes that crabs moult annually until they stop moulting, this may be an oversimplification. However, allowing crabs to moult or not moult would substantially increase the number of aggregations required to

model the population; this is because some aggregations would have to skip moult, and the model would need to include aggregations that stopped moulting early. It is important to remember that the week does not advance until the routine returns to the simulation; each equation is applied in sequence.

5. The weekly mortality depends on the shell condition of the aggregation. The weekly mortality rate is a function of the shell condition, this function is given in Equation 1.4, where A_t is the abundance in aggregation, M_{sc} is the relative weekly mortality for each shell condition, and μ scales the relative weekly mortalities. For the purposes of this chapter, μ is set based on the results of Chapter **??**, to 10 as the default. (However, μ was 15 in the high mortality case.) In chapter **??**, the model is fit to the size composition data and it is possible to estimate μ; the estimates guided the choice of the order of magnitude of μ in this chapter. In their annual model Zhang et al. [30] used both an instantaneous annual mortality ($M = .5$) and a post moult survival rate (70% survive). While it is not possible to estimate the mortality rate on each shell condition, it is clear that mortality is several-fold higher on soft shell crabs than hard shell crabs. Table 1.4 shows the assumed weekly relative natural mortality; these weekly relative mortalities were partially informed by the numbers in Zhang et al. [30]. Soft shell crabs should have much higher weekly mortality than hard shell crabs, but estimating the relative mortalities is probably impossible.

Fisheries dynamics on a single aggregation

Figure 1.2, presents a flow chart for the routine that conducts the fishery on a single aggregation.

1. Check if aggregation of crabs is alive. If the aggregation is alive go to check if the crab in the aggregation are legal, otherwise do nothing and return to the simulation.

2. Check if aggregation is legally available for harvest. The size and sex of the aggregation of crabs must be checked. If the aggregation is in soft shell condition three (not legal) apply the handling mortality equation 1.7. If the aggregation is legal apply the harvest equation 1.7.

3. Harvest the crabs if they are legal. To harvest the crabs commercially Equation 1.7 is applied. E_t is the total fishing effort. The parameter q is the catchability of a unit of effort. The

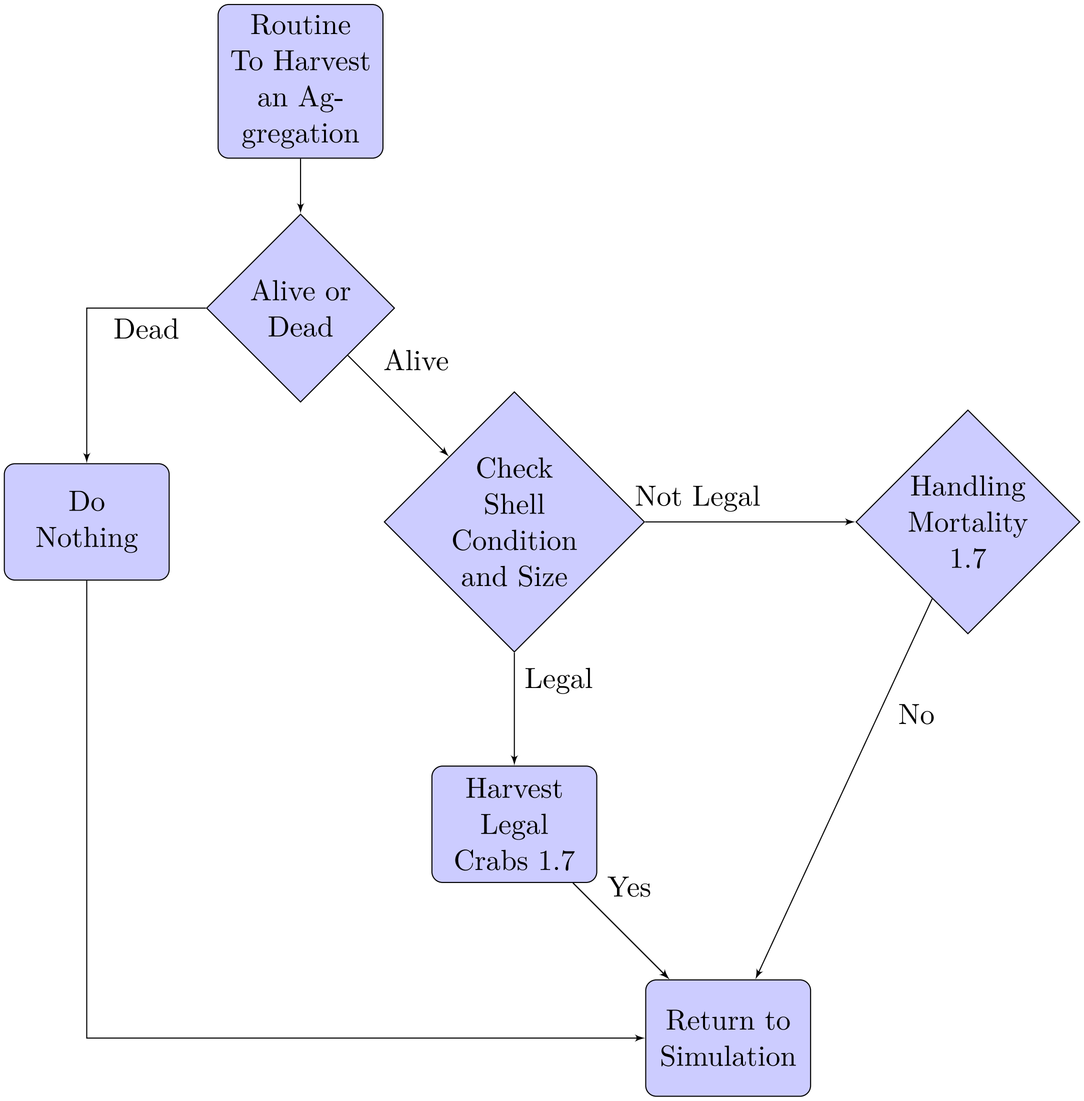

Figure 1.2: Fishing Flowchart: This flowchart shows how fishing is applied to each aggregation on a weekly time step. (*SC* is the shell condition.) The numbers in the nodes are relevant equations.

possibly time varying vulnerability of the aggregation is expressed as v_t. This chapter sets $v_t = 1$; however in Chapter **??** time varying vulnerability is considered. To convert from numbers of crabs harvested to mass of crabs harvested from an aggregation equation 1.3 is used.

4. Apply handling mortality to non-legal crabs. The handling mortality routine only kills crabs in shell condition 3. This is based on comments that the Area A fisherman's association has made; however it is likely that handling mortality may impact other shell conditions. If the

crabs are in shell condition 3, handling mortality is implemented according to Equation 1.7, where the parameters are as in Equation 1.7. However, not all of the crabs that get caught are killed and none of the crabs that are caught contribute to the catch. The handling mortality constant M_h, was set at .49 so that few crabs survive three captures in shell condition 3.

Symbol	Definition
L_{new}	Length after moult
L_{old}	Length before moult
α	Slope of linear growth model
β	Intercept of linear growth model (mm)
$Mass$	Mass in grams of crab at a given length
A_t	Abundance in aggregation at time t
A_{t_b}	Abundance in aggregation before applying relevant equation
	(the population is advanced one week only after all aggregations have been advanced)
A_{t_a}	Abundance in aggregation after applying relevant equation
A_t^T	Population abundance in aggregation at time t
A_t^a	Abundance in aggregation a at time t
μ	Mortality scalar on weekly mortality
M_{sc}	Weekly mortality by shell condition
C_t	catch in number of crabs in week t
q	catchability
E_t	Effort in week t
V_t	Vulnerability of an aggregation in time t
M_h	Handling mortality fraction. Only applies if soft shell

Table 1.3: Table that defines symbols in equations

$$L_{new} = \alpha L_{old} + \beta \tag{1.1}$$

$$\alpha = 1.069 \tag{1.2}$$

$$\beta \sim N(\mu = 18.07mm, \sigma = 3.29)$$

$$M_{ass} = .0001(L)^{3.0597} \tag{1.3}$$

$$A_{t_a} = A_{t_b}(1-\mu M_{sc}) \tag{1.4}$$

$$C_t = q v_t E_t A_{t_b} \tag{1.5}$$

$$A_{t_a} = A_{t_b} - C_t \tag{1.6}$$

$$A_{t_a} = A_{t_b} - M_h q v_t E_t A_{t_b} \tag{1.7}$$

Shell Condition	1	2	3	4	5	6	8	7
Weekly mortality	.0005	.010	.015	.025	.05	.005	.005	.5

Table 1.4: Assumed weekly mortality by shell condition. Note that crabs only enter shell condition 7 after four moults and are assumed to be senescent.

1.2.2 Assembly of Aggregations into Population

The aggregations described above are assembled into a population according to rules described below. Each aggregation of crabs has a birth-week, that along with the moulting schedule, determines the shell condition of that aggregation of crabs in any week. A population of crabs is initialized by setting a regular pattern of birth-weeks for the decade prior to the first fishing season of interest; initializing the number of aggregations according to the pattern shown in Figure 1.4. Although most of the analyses undertaken used the variable pattern (shown in black) to drive the moult pattern, the constant moult pattern (shown in red) was also fit to data. The population is advanced by advancing each aggregation one week according to the routines shown in the previous section. (See 1.1 and 1.2). Each aggregation has its own growth rate, and depending on it's age and birth-week, will have a uniquely determined size and shell condition. By having more aggregations with birth-weeks in particular months, a main moulting period can be established. Figure 1.4

shows how many aggregations are initialized in each week as black and red points and a scaled line showing the proportional catches in 2003. The moult timing was assumed to be fixed; estimating the number of aggregations moulting in each week is infeasible. There are assumptions made about when crabs moult relative to the fishery's opening and the duration in shell conditions; for example, in the model, aggregations moult every 52 weeks after they are initialized and the same number of aggregations is initialized each week of the year for every year. In week i of each year (where i is between 1 and 52) the same number of aggregations is initialized in each year. The initial abundance in each year is determined by estimating the abundance of the aggregations initialized in a single year; the abundance entering the model in week i is $N_y \cdot num(i)$ where N_y is the estimated abundance in a year and $num(i)$ is the number of aggregations born in week i. Equation 1.8 shows how to compute the total weekly catches, where TC_t is the total catch in kilograms in week t and $CM_{t,a}$ is the catch in kilograms removed from aggregation a at time t. (num_t is the number of living aggregations at time t.) Other quantities of interest can easily be computed in a similar fashion, for example, the total legal abundance can be computed by summing the legal abundance (1.9) at time t of all the living aggregations in week t. The legal abundance of an aggregation ($LA_{t,a}$) is the abundance in an aggregation if the aggregation is larger than 165 mm and in hard shell. The legal abundance is zero otherwise.

$$TC_t = \sum_{a_t=1}^{num_t} \frac{.0001 L_{old,a}^{3.0597}}{1000} \tag{1.8}$$

$$TLA_t = \sum_{a_t=1}^{num_t} LA_{t,a} \tag{1.9}$$

1.2.3 Parameter Estimation

There are two sources of data used in this chapter: the vessel monitoring system effort data and the logbook reported catch and VMS effort data. The units of weekly effort are the number of traps being hauled out of the water according to the VMS system in that week; this doesn't take

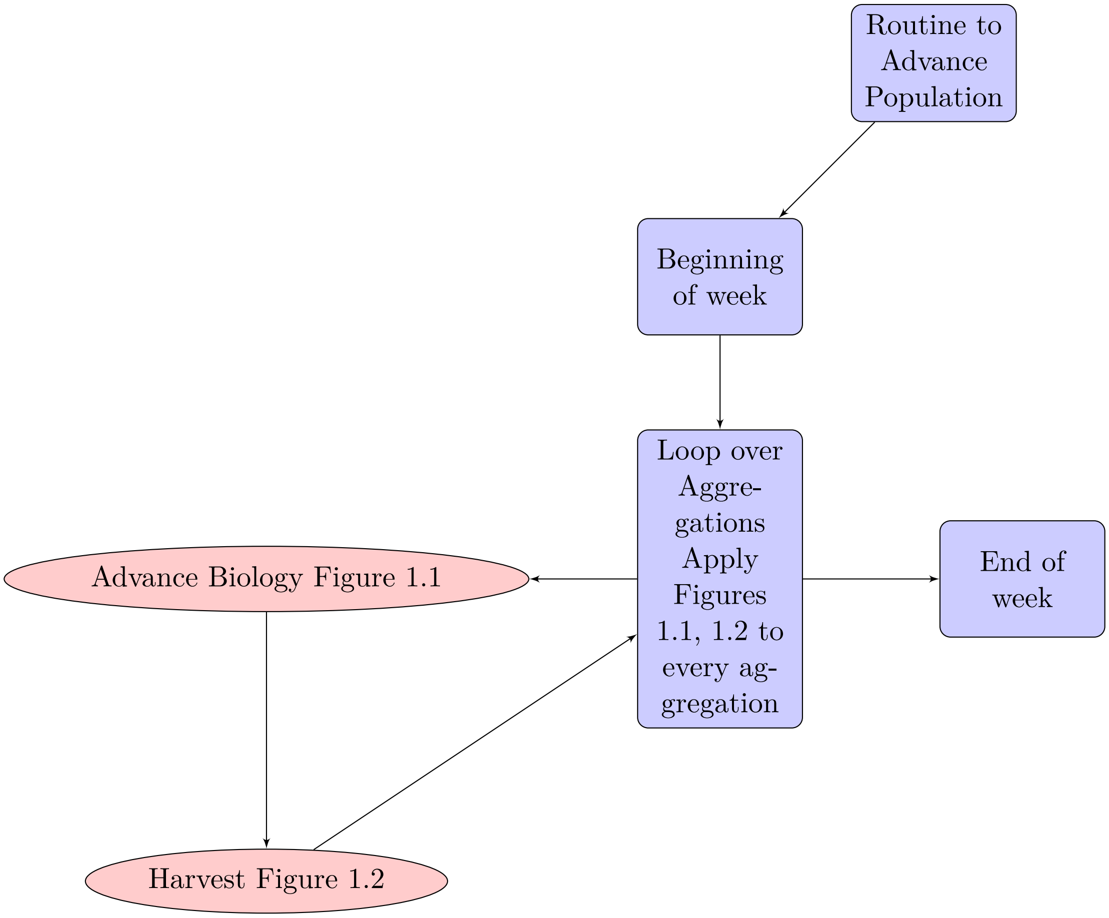

Figure 1.3: Population Flowchart: This flowchart shows how a population of aggregations is advanced. The loop between advance biology and harvest an agent emphasizes that there are many aggregations that need to be updated.

into account soak times, bait type, or any of the other ways that effort may vary. The data is fully discussed in Chapter **??**.

There are six parameters, $N1$, $N2$, $N3$, $N4$, $N5$, q, estimated when fitting this model to the weekly catch and effort data: the initial abundance of each aggregation corresponding to one fishing season, and the catchability. N_1 is the initial abundance in all aggregations born in the first eight years (it takes about three moults for a cohort to reach legal size), it sets the population structure in 2003; the eight year initialization set the initial age/size composition. N_2 is the initial abundance of all aggregations born in the ninth year, it largely sets the population structure in 2004. N_3, N_4 and N_5 are the initial abundance of all aggregations born in the 10th, 11th, and 12th years and largely sets the population structure in 2005, 2006, 2007 respectively. “Largely set” means the cohort that will be legal sized and yet exposed to one or more years of fishing. In the 10 years prior to the

Table 1.5: Opening and Closing Dates 2001-2014 (This table ignores minor variation in the opening and closing dates of some sub areas; the model is not spatial and treats the entire area as a unit.

Year	Open	Close	Open
2001	1-Jan	1-Mar	5-Jul
2002	1-Jan	4-Mar	5-Jul
2003	1-Jan	19-Apr	8-Jul
2004	1-Jan	19-Apr	2-Jul
2005	1-Jan	28-Apr	29-Jul
2006	1-Jan	Unknown (after 5-May)	26-Jul
2007	1-Jan	3-Apr	16-May
2008	1-Jan	22-Apr	16-Jul
2009	1-Jan	18-May	20-Jul
2010	1-Jan	19-Apr	15-Jun
2011	1-Jan	28-Feb	13-Jul
2012	1-Jan	13-May	30-Jun
2013	1-Jan	5-Jul	1-Aug
2014	1-Jan	1-Mar	23-May

five years of effort data, it is assumed that the average observed effort was applied each week. It should be noted that the initial abundance of each aggregation is not the initial abundance of the population at the beginning of the season; the size of the population in each week is the sum of the abundances across all extant aggregations. Each aggregation, born in a single year, has the same initial abundance in the week that it recruits into the model. However, the abundance of the population at the beginning of the first fishing season with known weekly effort is set by allowing the model to run for the decade while being exposed to the average amount of fishing effort in the fishing season. Although a real population is exposed to highly seasonal effort, the weekly effort in the years before the first fishing season of interest is set as the average weekly fishing effort in the first season. (The effort is not seasonal in the run up years.)

Many of the parameters in the model are fixed. For example, the weekly natural mortality, the duration in each shell condition, the growth rate of crabs, are known. The vulnerability regime (in Chapter **??**), and the time of the main moult, are all assumed to be known. To fit the model to the weekly catch and effort data, the chapter assumes the differences between the model predicted catches and observed catches are normally distributed; the negative log likelihood function is given by Equation 1.10. The model does not distinguish between observation and process error, in large part because most of the legal biomass is harvested each year and effort is recorded by the vessel monitoring system.

$$nll(x) = \sum -log(\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(C-\hat{C})^2}{2\sigma^2}}) \tag{1.10}$$

In addition to fitting the model to the observed weekly catch and effort data (for parameter estimation), two additional analysis were undertaken: a simulation evaluation of the model to ensure that parameters were estimable, and a yield per recruit analysis.

1.2.4 Simulation Evaluation

The simulation evaluation uses the historically observed patterns in effort and fixed simulation parameters P_{ij} to compute simulated catches. The simulated catches are computed according to equation 1.11. The function f is the model run with parameters drawn from a normal distribution according to the Equation 1.11. In addition, process error in catchability was simulated using Equation 1.12, while the process error was fixed the observation error on catches (Equation 1.13) was applied to the catches given from Equations 1.11 and 1.12. Where $N(\mu,\sigma)_s$ is drawn for each simulation and $N(\mu,\sigma)_t$ is drawn for each week. In this chapter σ_{proc} is set to be: 0, and .1.

$$\begin{aligned} C_j &= f(P_{a,5j}, P_{6j}, E) \\ P_{a,j} &\sim abs(N(\mu = .32, \sigma = .15)_s) \cdot 10^8 \\ P_{q,j} &\sim abs(N(\mu = 1.75, \sigma = .1))_s \end{aligned} \tag{1.11}$$

$$\begin{aligned} C_j &= f(P_{a,5j}, P_{6j}, E) \\ P_{a,j} &\sim abs(N(\mu = .32, \sigma = .15)_s) \cdot 10^8 \\ P_{q,j,t} &\sim abs(N(\mu = 1.75, \sigma = .1)_s e^{(\sigma_{proc} \cdot N(\mu=0,\sigma=1)_t - \frac{\sigma_{proc}^2}{2})} \end{aligned} \tag{1.12}$$

The indices and parameters used to create the simulated data sets are shown in table 1.6.

Table 1.6: Simulation indices and Parameters

Parameter	Label
j	Simulation index
$P_{a,j}$	Initial aggregation abundance in year a
$P_{q,j}$	Simulated Catchability

1.13

$$RC_j \sim N(C_j, \sigma_{obs} C_j) \tag{1.13}$$

The scale σ_{obs} in equation 1.13 is: .001, .01, .05, .1. After simulated catch and effort data are made, the model is fit to the recorded catches and the relative error is computed. The bias and relative error are computed as in equation 1.14, where: θ are the parameters N_1 through N_5 and q, N_w is the number of weeks, and $\overline{C^{sim}}$, $\overline{A^{sim}}$, and $\overline{U^{sim}}$, are the average weekly catch, weekly abundance, and weekly exploitation rate respectively.

$$\begin{aligned}
bias &= \frac{\theta_{est} - \theta_{true}}{\theta_{true}} \\
biascatch &= \frac{1}{N_w} \sum_w \frac{(C_t^{est} - C_t^{sim})}{\overline{C^{sim}}} \\
biasabund &= \frac{1}{N_w} \sum_w \frac{(A_t^{est} - A_t^{sim})}{\overline{A^{sim}}} \\
biasweeklyu &= \frac{1}{N_w} \sum_w \frac{(U_t^{est} - U_t^{sim})}{\overline{U^{sim}}} \\
REcatch &= \frac{1}{N_w} \frac{\sqrt{\sum_w (C_t^{est} - C_t^{sim})^2}}{\overline{C^{sim}}} \\
REabund &= \frac{1}{N_w} \frac{\sqrt{\sum_w (A_t^{est} - A_t^{sim})^2}}{\overline{A^{sim}}} \\
REweeklyu &= \frac{1}{N_w} \frac{\sqrt{\sum_w (U_t^{est} - U_t^{sim})^2}}{\overline{U^{sim}}}
\end{aligned} \tag{1.14}$$

1.2.5 Yield Per Recruit

The other supplementary results were obtained in the yield per recruit analysis. Computing yield per recruit is challenging because the weekly exploitation rate varies seasonally and is driven by weekly fishing effort, the yield per recruit of a soft shell crab is zero. Nevertheless, it is interesting to try and quantify how much yield per recruit is lost under different assumptions of handling mortality. To compute the yield per recruit, the chapter runs the model for 20 years with an initial abundance of 100 crabs in each aggregation. The chapter uses the effort trajectory from 2003 and adjusts fishing mortality by increasing catchability and multiplying the effort by a scalar. The two ways to increase fishing mortality are increasing catchability or increasing effort. While there are strong restrictions on the number of traps being used by the fishery and the design of traps [29]; increases in fishing activity and improvements to the gear are possible. To compute yield per recruit, the chapter converts using Equation 1.3 from carapace width to mass. The yield per recruit plotted is the average of the total yield of each aggregation divided by the initial recruits (at 100 mm) in the aggregation.

To compute the relative handling loss equation 1.15 is applied. In equation 1.15, NH is the weekly catch without handling mortality and H is the weekly catch under the assumed handling mortality, where $M_h = 0$ for NH and $M_h = .49$ for H. Recall that M_h is used in equation 1.7 to compute how many soft shell crabs are killed in an aggregation. Handling mortality is driven by both effort and the fraction of the population in soft shell, so is highly seasonal. Therefore, taking the average handling loss over weeks makes sense.

$$H = \sum_{T} \frac{NH_t - H_t}{H_t} \tag{1.15}$$

1.3 Results

As discussed in the Methods section there are three different sets of results that were computed: this chapter estimated parameters in an agent-based model that fit the observed weekly catch given the effort series for three different mortality and growth regimes, it completed a simulation evaluation

Title	Equation Number	Summary	Terms
Growth	1.3	Grows crabs	α slope, β intercept
Mortality	1.4	Natural mortality	A_t abundance, M_{sc} shell condition mortality, μ mortality scale
Harvest	1.7	Harvests legal males	q catchability, v_t vulnerability, E_t effort, A_t abundance
Handling mortality	1.7	Kills soft shell crabs	M_h handling mortality rate
Size to Mass	1.3	Converts size in mm to mass in grams	
NLL	1.10	Fits model to Catch and effort data	

Table 1.7: Summary of equations

of the model, and did a yield per recruit analysis. Results of each of these analyses are shown in the following subsections.

1.3.1 Relative Errors

Tables 1.8, 1.9 and 1.10 show the relative errors and bias in the parameters when the observation error multiplier σ in equation 1.13 is varied. ($\sigma_{obs} = 0.001, 0.05, 0.1$). The first table assumes no process error and the second table shows the results under process error on the catchability coefficient q. It is interesting that under auto-correlated process error on catchability the bias does not seem to increase much. It is quite possible that a depletion model having 52 weeks of data for each initial abundance and a single catchability across all years is reasonably robust to both process and observation error particularly since there is a significant decline in the amount of crab being caught each week over the course of the season.

The relative error appears to remain on the same scale as σ_{obs}. It is reassuring that the catchability parameter seems reasonably unbiased. It should be noted that since the model is fit to weekly observations and the data is informative, there are many weeks in a year to inform the depletion model.

1.3.2 Parameter Estimates

In all scenarios the catchability remained nearly the same. However, the high mortality scenario required higher initial abundances than the other scenarios. Interestingly, changing the growth rate

	N1	N2	N3	N4	N5	q	Bias OC	Bias A	Bias U	RE OC	RE A	RE U
cv .001	0.06	0.07	0.06	0.07	0.06	0.00	-0.00	0.02	-0.02	0.00	0.02	0.02
cv .05	0.03	0.09	0.08	0.04	0.05	0.00	-0.00	0.01	-0.01	0.08	0.02	0.02
cv .1	-0.00	0.11	0.10	0.01	0.04	0.01	-0.00	0.00	-0.01	0.17	0.05	0.02

Table 1.8: Mean bias and Relative Error in estimates of initial abundance (N_i), catchability (q),observed catch (oc), weekly abundance (A), and weekly exploitation rate (U).

	N1	N2	N3	N4	N5	q	Bias OC	Bias A	Bias U	RE OC	RE A	RE U
cv .001	0.08	0.07	0.06	0.06	0.06	0.02	-0.00	0.02	-0.02	0.00	0.02	0.03
cv .05	0.08	0.06	0.02	0.05	0.08	0.00	-0.01	0.02	-0.03	0.09	0.04	0.05
cv .1	0.09	0.05	-0.03	0.05	0.09	-0.02	-0.02	0.03	-0.05	0.17	0.06	0.08

Table 1.9: Mean bias and Relative Error in estimates of initial abundance (N_i), catchability (q),observed catch (oc), weekly abundance (A), and weekly exploitation rate (U). Under the process error ($\sigma_{proc} = .1$) simulations.

did not change the initial abundances very much. The fast growth scenario had somewhat smaller initial aggregation abundances than the base and slow growth scenarios. The parameter estimates and their confidence intervals are shown in Tables 1.11,and 1.11 for the variable and constant moult scenarios respectively. Only the base case is shown for the constant moult scenario. Catchability q is scaled by a factor of 10^{-6} and the initial abundances are scaled by a factor of 10^8. Remember that this is the initial abundance of each aggregation and that there are 3080 aggregations born each year. Crabs recruit to the model at 100mm and recruit to the fishery at 165mm, there are a few thousand tonnes (or about 10^9 grams) of crab caught each year. A legal sized crab is about 600 grams so there should be a bit more than 10^7 legal crabs in the fishery, since $10^6 \cdot 3080$ is about 10^9 implying the population must be reduced by less than two orders of magnitude over the course of about 3 years as crabs reach legal size. Since Zhang et al. [30] estimated that the post moult survival rate was 70% this appears to be reasonable. There was minimal difference in the fits between the two moult patterns, the base case with the variable moulting birth pattern had a negative log-likelihood value of 6038.9 and the base case with the constant moulting birth pattern had a negative log-likelihood value 6040.1. Since the models with both of the moulting birth patterns shown in Figure 1.4 have the same number of parameters the fit under the variable moult pattern is modestly better. In the next chapter a more comprehensive comparison between the constant and variable moult patterns is undertaken, extensive comparisons are best made after fitting the model using size composition

	N1	N2	N3	N4	N5	q	Bias OC	Bias A	Bias U	RE OC	RE A	RE U
cv .001	0.08	0.07	0.06	0.06	0.06	-0.00	-0.00	0.02	-0.02	0.00	0.02	0.03
cv .05	0.08	0.06	0.03	0.05	0.08	-0.02	-0.01	0.03	-0.04	0.09	0.04	0.06
cv .1	0.10	0.06	-0.01	0.06	0.10	-0.05	-0.02	0.04	-0.06	0.18	0.08	0.09

Table 1.10: Mean bias and Relative Error in estimates of initial abundance (N_i), catchability (q),observed catch (oc), weekly abundance (A), and weekly exploitation rate (U). Under the process error ($\sigma_{proc} = .8$) simulations.

data. However, it should be noted that the estimated catchability was 1.75 under the variable moult birth pattern and 1.65 under the constant moult birth pattern.

Parameter	N1	N2	N3	N4	N5	q
Base	0.42	0.59	0.31	0.11	0.37	1.75
Base CI	0.4-0.44	0.56-0.62	0.29-0.34	0.09-0.14	0.35-0.40	1.61-1.89
High Mortality Parameter	1.47	2.13	1.16	.39	1.33	1.66
High Mortality CI	1.38-1.57	2.02-2.26	1.07-1.26	0.31-0.48	1.25 -1.43	1.51-1.81
Slow Growth Parameter	0.53	0.72	0.38	0.16	0.46	1.75
Slow Growth CI	0.51-0.57	0.68-0.76	0.35-0.41	0.13-0.19	0.43-0.49	1.61-1.9
Fast Growth	0.34	0.51	0.28	0.080	0.31	1.75
Fast Growth CI	0.32-0.37	0.49-0.54	0.26-0.31	0.06-0.10	0.29-0.33	1.61-1.89

Table 1.11: Variable Moult Parameter estimates N1 through N5 is 10^8 crabs per aggregation, and catchability (q) is in crabs (10^{-6}) per trap haul.

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Parameter	N1	N2	N3	N4	N5	q
Base	0.41	0.56	0.30	0.13	0.37	1.65
Base CI	0.39-0.44	0.53-0.59	0.28-0.30	0.09-0.11	0.35-0.40	1.52-1.8

Table 1.12: Constant Moult Parameter estimates N1 through N5 is 10^8 crabs per aggregation, and catchability (q) is in crabs (10^{-6}) per trap haul.

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1.3.3 Correlation Matrices

In all of the correlation matrices the catchability was negatively correlated with the annual initial abundances (N_1,N_2,N_3,N_4 and N_5). In Table 1.13 shows the estimated correlation matrices for the different scenarios. These correlation matrices were computed by using the inverse Hessian, note that N_i and q are negatively correlated and that the N_i are positively correlated with each other. The correlation matrices for the constant moult scenarios were similar to the correlation matrices for the variable moult scenarios, for brevity I only show the correlation matrices for the variable moult scenarios.

Base	N1	N2	N3	N4	N5	q
N1	1	0.42	0.364	0.136	0.432	-0.557
N2	0.42	1	0.504	0.204	0.629	-.8
N3	0.364	0.504	1	0.117	0.514	-0.66
N4	0.136	0.204	0.117	1	0.168	-0.258
N5	0.432	0.629	0.514	0.168	1	-0.784
q	-0.557	-0.807	-0.66	-0.258	-0.784	1

High	N1	N2	N3	N4	N5	q
N1	1	0.462	0.412	0.149	0.482	-0.598
N2	0.462	1	0.542	0.218	0.676	-0.835
N3	0.412	0.542	1	0.11	0.563	-0.693
N4	0.149	0.218	0.11	1	0.173	-0.264
N5	0.482	0.676	0.563	0.173	1	-0.814
q	-0.598	-0.835	-0.693	-0.264	-0.814	1

Slow	N1	N2	N3	N4	N5	q
N1	1	0.464	0.386	0.163	0.457	-0.585
N2	0.464	1	0.536	0.234	0.642	-0.818
N3	0.386	0.536	1	0.175	0.525	-0.67
N4	0.163	0.234	0.175	1	0.215	-0.293
N5	0.457	0.642	0.525	0.215	1	-0.789
q	-0.585	-0.818	-0.67	-0.293	-0.789	1

Fast	N1	N2	N3	N4	N5	q
N1	1	0.302	0.314	0.0875	0.372	-0.486
N2	0.302	1	0.4	0.167	0.593	-0.772
N3	0.314	0.4	1	-0.0159	0.491	-0.629
N4	0.0875	0.167	-0.0159	1	0.0916	-0.201
N5	0.372	0.593	0.491	0.0916	1	-0.774
N6	-0.486	-0.772	-0.629	-0.201	-0.774	1

Table 1.13: Correlation Matrices of the Base case, High Mortality Case, Slow Growth Case and Fast Growth Case

1.3.4 Catch and Effort

Figure 1.7 shows the fit of the model to the weekly catch data. There do not appear to be many differences between the base case, slow growth, fast growth and high mortality scenarios in their ability to explain the observed catches given the observed effort. In all cases, it misses the catch in mid-June 2004 and September, October, and November in 2003. It is worth noting that it did not predict too much catch when effort was relatively high in March of 2003 or October of 2007; this suggests that the model is capturing the seasonal patterns in the fishery and that catch is not simply proportional to effort.

1.3.5 Legal Abundance

Figures 1.9 shows how the legal abundance of crabs, according to the model, changes over the season. There do not appear to be large differences in the legal abundance over time between the different growth and mortality scenarios. However, if you look carefully, the high mortality case does predict higher legal abundances earlier in the year. Since catchability is similar across scenarios (see Table **??**) it is not surprising that the differences are modest. One general pattern is that the decline in legal abundance flattens out in about September. This is not surprising since the weekly catches after September are small. Also, the legal abundance drops during the moult, since soft shell crabs are not legal to harvest.

1.3.6 Weekly Exploitation Rates

Figure 1.10 shows the estimated weekly exploitation rates for the different scenarios. In all scenarios the estimated weekly exploitation rate follows a similar pattern to the numbers of traps pulled. It should be noted that the weekly exploitation rates in the winter and spring are very low.

1.3.7 Yield Per Recruit

The yield per recruit analysis in this chapter assumes, rather than estimates, the natural mortality scalar μ. It appears that for believable values of catchability and the observed effort series the amount of catch lost due to handling is less than 20%. This may be significant, but is likely to be quite sensitive assumptions about size selectivity and mortality.

1.4 Discussion

The interplay between the biology of the crabs and the observed patterns in fishing effort reduces the legal abundance of crabs to about one quarter (see figure 1.9) of the initial legal abundance, according to the model presented in this chapter. This is significant since the catch per trap haul drops by at least an order of magnitude over the course of a fishing season. (In many years there is a 90% decline of catch per trap haul). It is clear that very little effort is deployed in the winter.

As shown, the model can fit the weekly catch and effort series, and estimate the weekly exploitation rate. Furthermore, the simulation evaluation of the model shows that, there is modest bias, *i.e.* the bias is less than 15% even with 10% observation error. (See table 1.8). It seems that adding process error on catchability doesn't increase bias too much, probably because the data is quite informative. Since we are mostly interested in estimating the weekly exploitation rate, the model appears to perform reasonably well. There does not appear to be a much better fit assuming a variable moulting pattern compared to assuming a sensibly chosen constant moult pattern. However, it should be noted that the constant moult pattern was chosen to have the moult in the week where the number of aggregations in the variable moulting pattern was maximized. It is interesting that legal abundance is approximately one order of magnitude larger than harvest. If management depends on detecting when a certain fraction of the crab population has recently moulted incorporating variability in moult timing may be useful. Since crabs are initialized in shell condition 1, it should be noted that the peak in birth weeks is 3 weeks prior to the peak in fishing effort. Shell condition 1 is assumed to last 6 weeks so in the variable moult pattern about half the birth-week pattern has passed when it peaks. The timing of the birth-week wave relative to the observed fishing effort wave was not estimated. The model assumes that the moult happens before the fishing season occurs in the same weeks each year. In reality, we know that fishery does not open the same weeks each year, so it is likely that moult does not happen in the same weeks each year.

The management of Dungeness crab is based, coast wide, on a simple effort control rule; only male crabs larger than a fixed size can be retained. In British Columbia, the minimum size limit is 165 mm. There are seasonal changes in the price of crabs in British Columbia [29]; however, there is disagreement about what causes the price drop when Area A is opened. Anecdotally there are two plausible reasons for the price drop: Area A is large enough to flood the market, and alternatively the Chinese are not willing to pay as much for Area A crab since the crab undergo longer shipping times. To my knowledge there are no public studies on mortality rates of shipping live crabs. In addition to the seasonal pattern in price, there is variation in the moult timing by location as evidenced by the California crab fishing season being in the fall and winter while the British Columbia crab fishing season is in the summer. It has historically been thought that the decline in catch, within fishing seasons, was directly due to the harvest of crabs [30]. However, clearly both catch and effort decline over the fishing season; the decline in fishing effort is most likely driven by catch rates, seasonal changes in the price of crabs, other economic opportunities are available to fishermen, and the fixed and variable costs of fishing.

This chapter has some implications for Canada's ongoing discussion about managing effort control fisheries. In particular, DFO [7] outlines several potential reforms to the existing management regime. It is important to develop stock assessment methods that can be used to gain a better understanding of realized annual exploitation rates in highly seasonal input controlled fisheries to evaluate if reform is needed. There are generally four different quantitative approaches for the stock assessment of crustaceans: direct survey approaches, change in ratio approaches, index removal approaches, and depletion based methods [4, 6, 11, 27]. While, in principle, it is possible to integrate multiple approaches into a single stock assessment, this chapter takes a depletion based approach [26].

A depletion based approach is uniquely suited for the study of within season dynamics of fisheries [18] [6]. DeLury [6] developed the basic ideas when trying to estimate the population of lobster off Prince Edward Island. The exploitation rate can be estimated at the same resolution as the time series of fishing effort; if you have a weekly time series of effort, you can estimate weekly exploitation rates.

There are multiple ways to handle the accounting associated with a depletion based model to a population; these can be broadly categorized as either population dynamics models or agent-based models. The choice between agent-based and population dynamics models is mostly one of conceptual clarity, speed of running, and ease of programming. Many models developed for Dungeness crab take a population dynamics approach, for example, Zhang et al. [30] and Inc. [15]. Still, agent-based models have been developed for fisheries problems. Most of the agent-based approaches treat the fleet, and other humans, as the agents [28]. However, Shin and Cury [25] and Daewel et al. [5] show that it is not, in principle, impossible to take an agent-based approach to modeling biological processes. While the model in this paper is an agent-based model, the agents have an abundance assigned to them. This makes it somewhat intermediate between a population dynamics approach, and an agent-based model where each individual crab is modeled.

This chapter uses an agent-based model because the number of things that are tracked was large and using an agent-based approach made the accounting easier. In contrast with Zhang et al. [30] and Inc. [15], this model keeps track of not only the size composition, but also shell conditions. It would be possible to develop a population dynamics model that kept track of the proportions of each size class that were in each week of each shell condition; it is unclear how that would be in anyway simpler than building a population up from a collection of agents each behaving in a well defined way.

Perhaps a more significant difference between this chapter and other stock assessment work is that I do not try to learn anything about a stock recruit relationship; looking into how a crab population responds to the selective removal of large male crabs, without costly manipulative experiments, would probably be impossible. It is unclear if the productivity increases, stays the same, or decreases under sustained removal of large male crabs. While most theory suggests that removal of large quantities of biomass can result in over-fishing, Momot [19] found that the removal of male crayfish (*Orconectes virilis*) increased recruitment and productivity in lakes near Thunder Bay Ontario. The model developed in this paper does not make any claims about how exploitation impacts productivity or recruitment.

For management purposes, yield per recruit may not be the most useful quantity to compute. It may be more useful to study profit per recruit, since seasonal patterns in the price of crab exits and likely seasonal patterns in the cost of fishing and access to fish processing. It should be clear that there likely is only a tenuous relationship between fleet profitability and yield per recruit. Since handling mortality on sub-legal crabs is a key management consideration, incorporating mortality on sub-legal crabs is important for evaluating yield per recruit. Kruse et al. [17] does attempt to experimentally investigate handling mortality in Dungeness crab. Handling mortality is applied, in this model, to shell condition 3 crabs regardless of their size. This may accentuate the handling losses if small crabs do not enter (or can escape) the crab traps. It is important to compare the chapter's yield per recruit to Zhang et al. [30]'s estimates of yield per recruit. Zhang et al. [30] estimated the yield per recruit to be about 460 grams; however, crabs recruit to their model at 130*mm* rather than at 100*mm* as in my model. The yield per recruit in the analysis should be significantly smaller than what Zhang et al. [30] estimated since crabs will have to survive at least one additional moult and probably two additional years of non-moulting natural mortality. A more comprehensive discussion of yield per recruit is undertaken later in this thesis when natural mortality is estimated. It should be noted that for the observed effort series and a sensible estimate of catchability, less than 15% of the catch is lost. Even if the number of traps being hauled increased substantially (without an increase in catchability) the percent of catch lost would not increase significantly. However, if catchability increases than it is possible to incur larger handling mortality losses.

It is interesting that constant catchability allows fitting the catch data well from the beginning to the end of the season. There is some evidence that all of the crabbing fleet is actively fishing when catch rates are high, but as catch rates decline, some vessels drop out of the fishery, see Chapter **??**. It is also interesting to note that the model is able to fit the data assuming different values for natural mortality. Chapter **??** uses size composition data to estimate natural mortality assuming a known growth rate.

Unfortunately, there does not exist a fishery independent estimate of population size at the beginning and end of the fishing season, so it is impossible to compare the results from this weekly depletion model to those from a direct survey. While it is always good to have alternative estimates to compare, there is no particular reason to distrust this depletion model.

There are a few things to note when evaluating the simulation evaluation results: the observed effort series was used for all the simulations, the selected initial abundance for each year was set to be plausible under the effort series, and the same effort and moult schedule was used in all the simulations. The good fits to data, even under modest observation error, are most likely due to the large data set and large within season decline in effort. The model only estimates 6 parameters and has 260 data points. As long as the fishery opens after the moult (or is mostly inactive during the moult), variation in moult timing has minimal impact on the estimates. It is unlikely that much fishing effort would be deployed during the main moult, since nobody wants to harvest unmarketable crabs.

The model presented in this chapter does not look at spatial distribution of fishing effort or evaluate if there are any areas that are area closures, such as shipping lanes, glass sponge reef conservation areas, and other locations where setting crab traps is impossible.

To conclude, it is clear that seasonal dynamics in effort are important to understanding how the Dungeness crab fishery is conducted and depletion models on a weekly time step can estimate weekly exploitation rates under the current management regime. Using a depletion model can provide understanding of the implications of the existing management regime, including estimates of the escapement of large males.

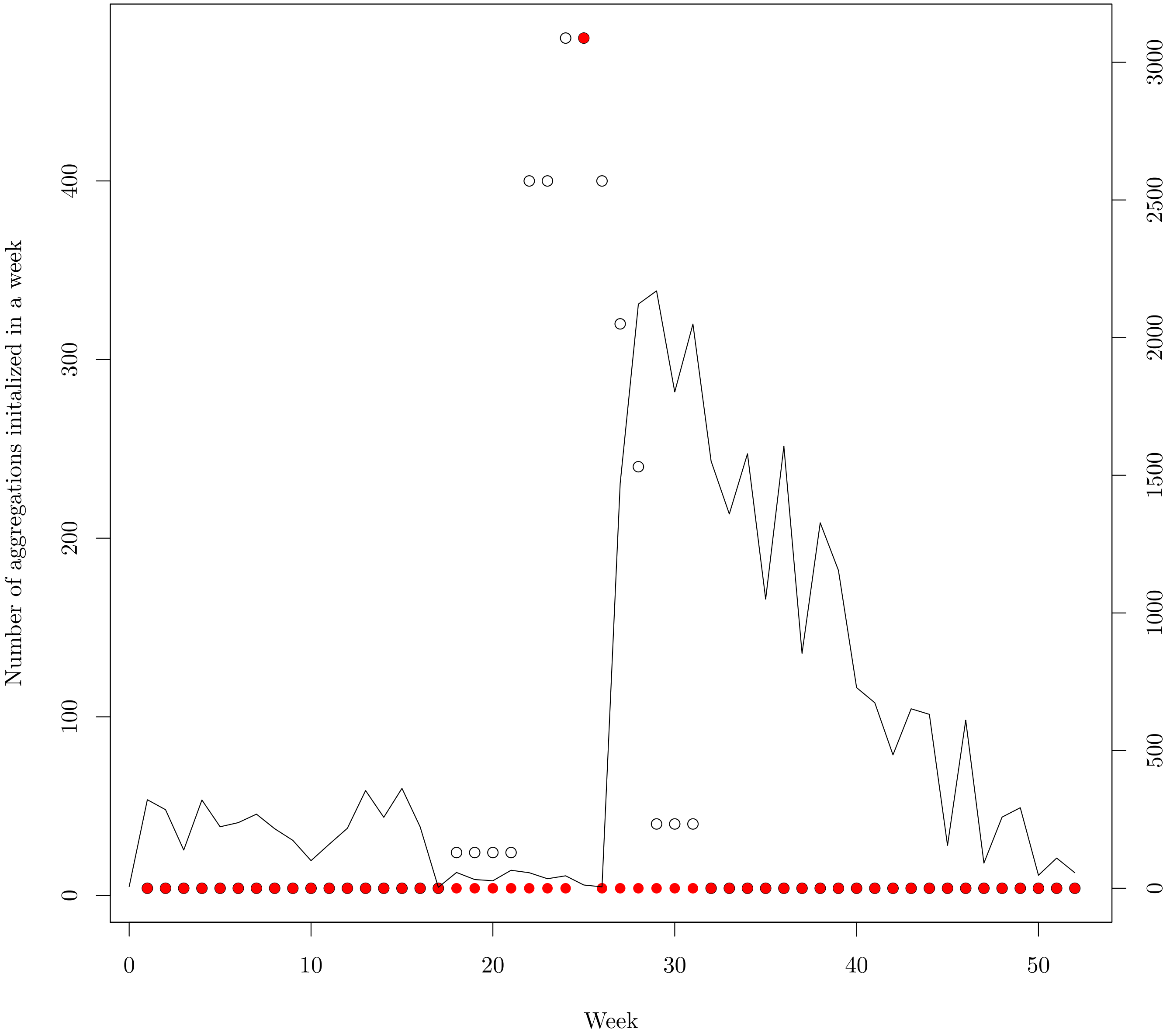

Figure 1.4: The dots show the number of aggregations born in each week. The black dots (left axis) are for the variable moult schedule, and the red dots (right axis) are for the constant moult schedule. The line shows the relative effort pattern in 2003 for reference; the crab moult several weeks prior to the fishery.

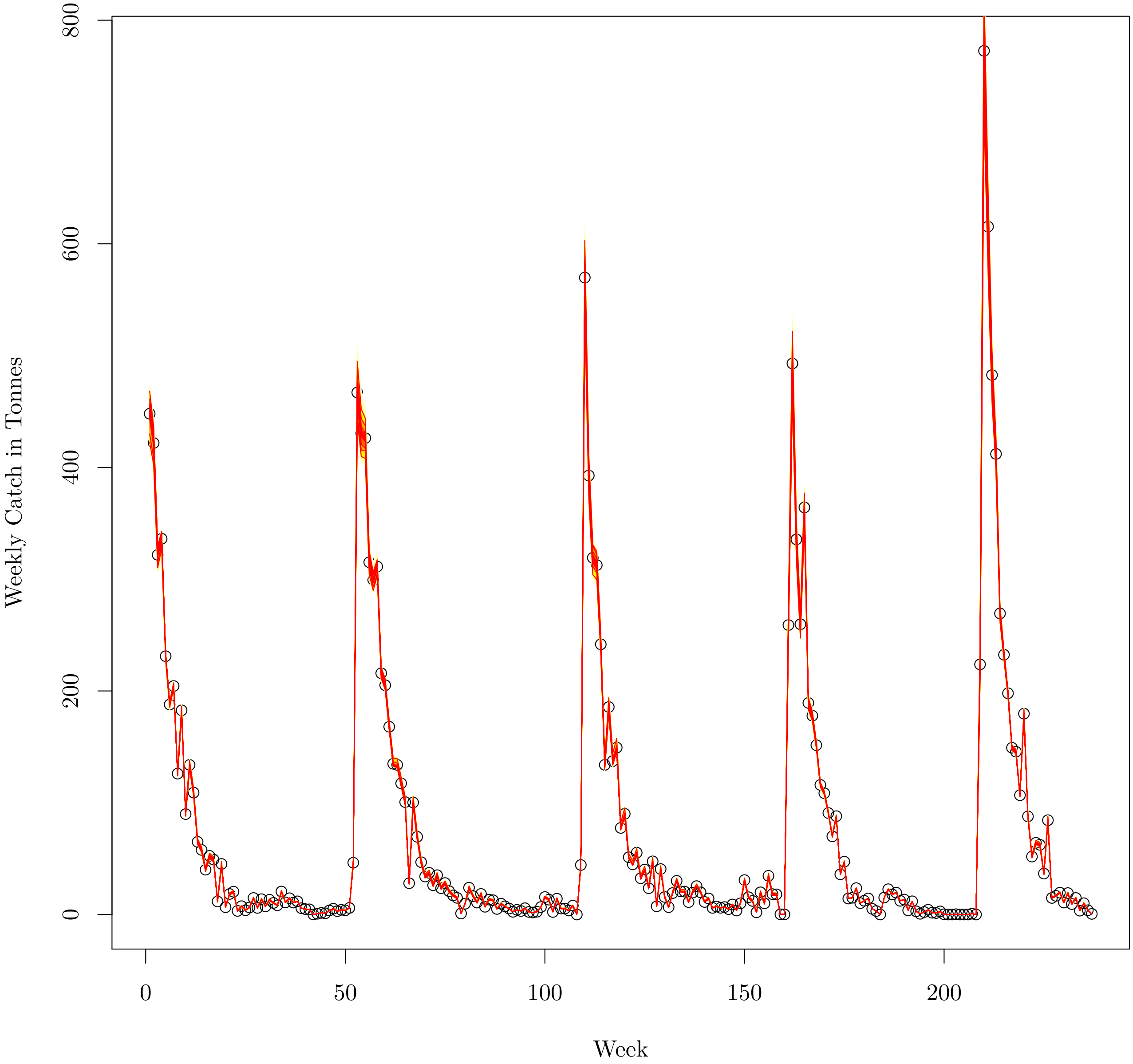

Figure 1.5: Simulated Catches in Tonnes by week under process error ($\sigma_{proc} = .1$).

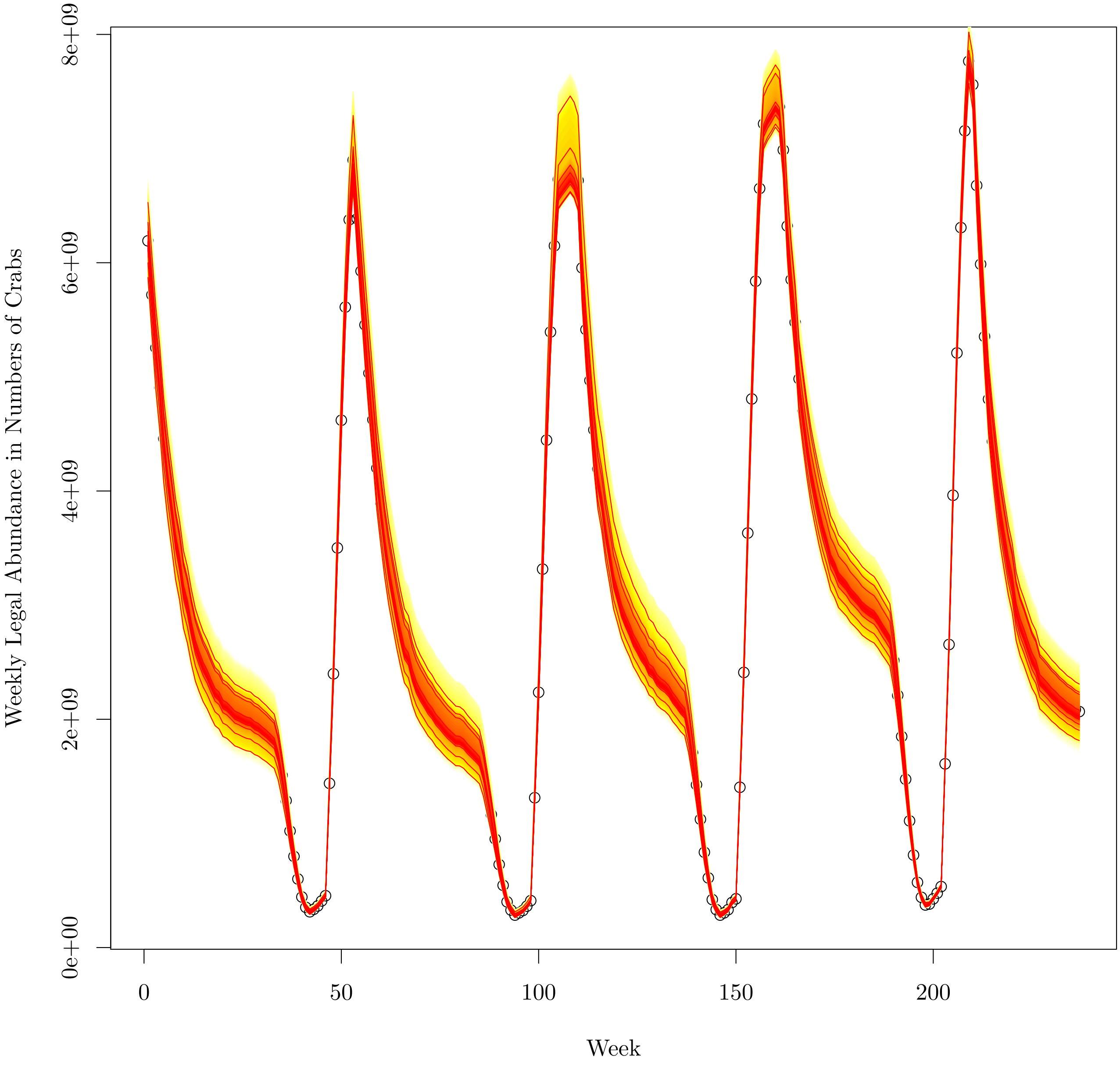

Figure 1.6: Simulated Legal Abundance in numbers of crabs by week under process error ($\boldsymbol{\sigma}_{proc} = .1$).

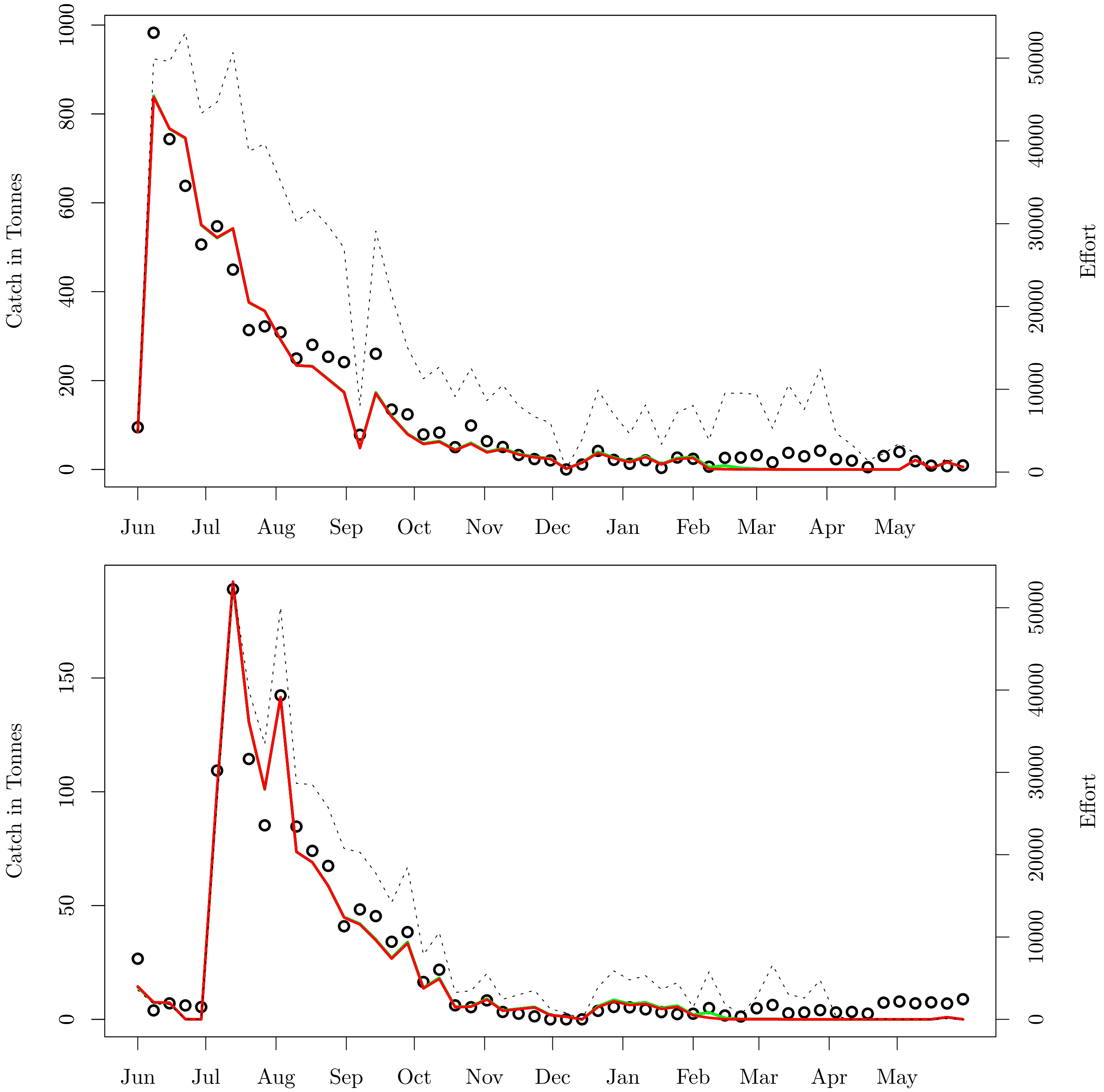

Figure 1.7: Seasonal Fits: The left y-axis shows the observed catches (dots), and predicted catch (solid line). The right y-axis shows the number of traps hauled (dashed lines). The years are, from top to bottom, 2004 and 2006 and are representative of high and low abundance years. The base case, slow growth, fast growth, and high mortality cases are plotted in black, blue, green, and red respectively. The fits are so close to each other that it is nearly impossible to tell them apart.

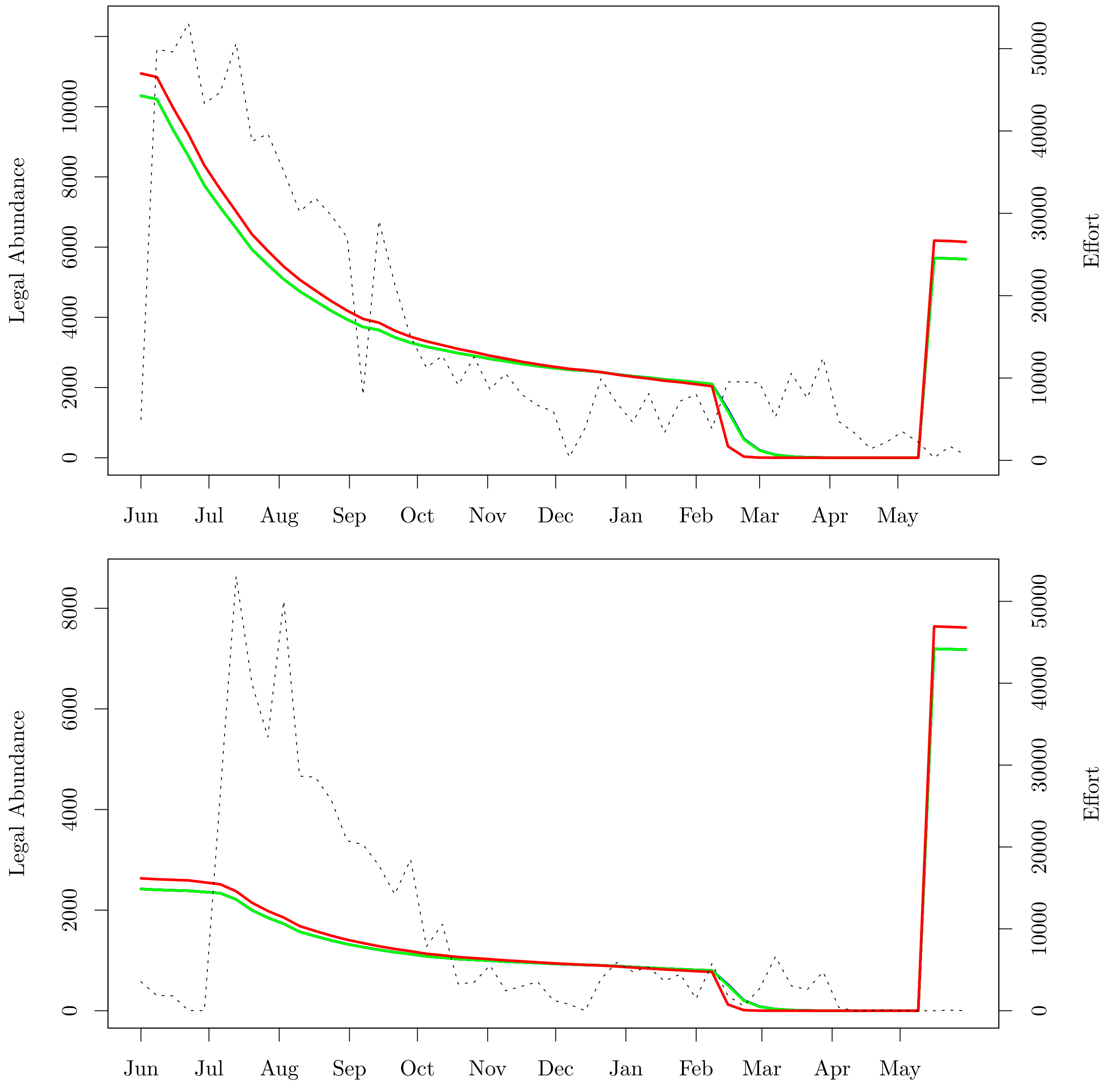

Figure 1.8: Seasonal Legal: On the left y-axis is an index of abundance in Tonnes. The solid lines are the legal abundance of crabs by week, as predicted by the model; the base case, slow growth, fast growth, and high mortality cases are plotted in black, blue, green, and red respectively. On the right y-axis is the number of traps hauled shown in the light dashed line. The years are, from top to bottom, 2004 and 2006 and are representative of high and low abundance years

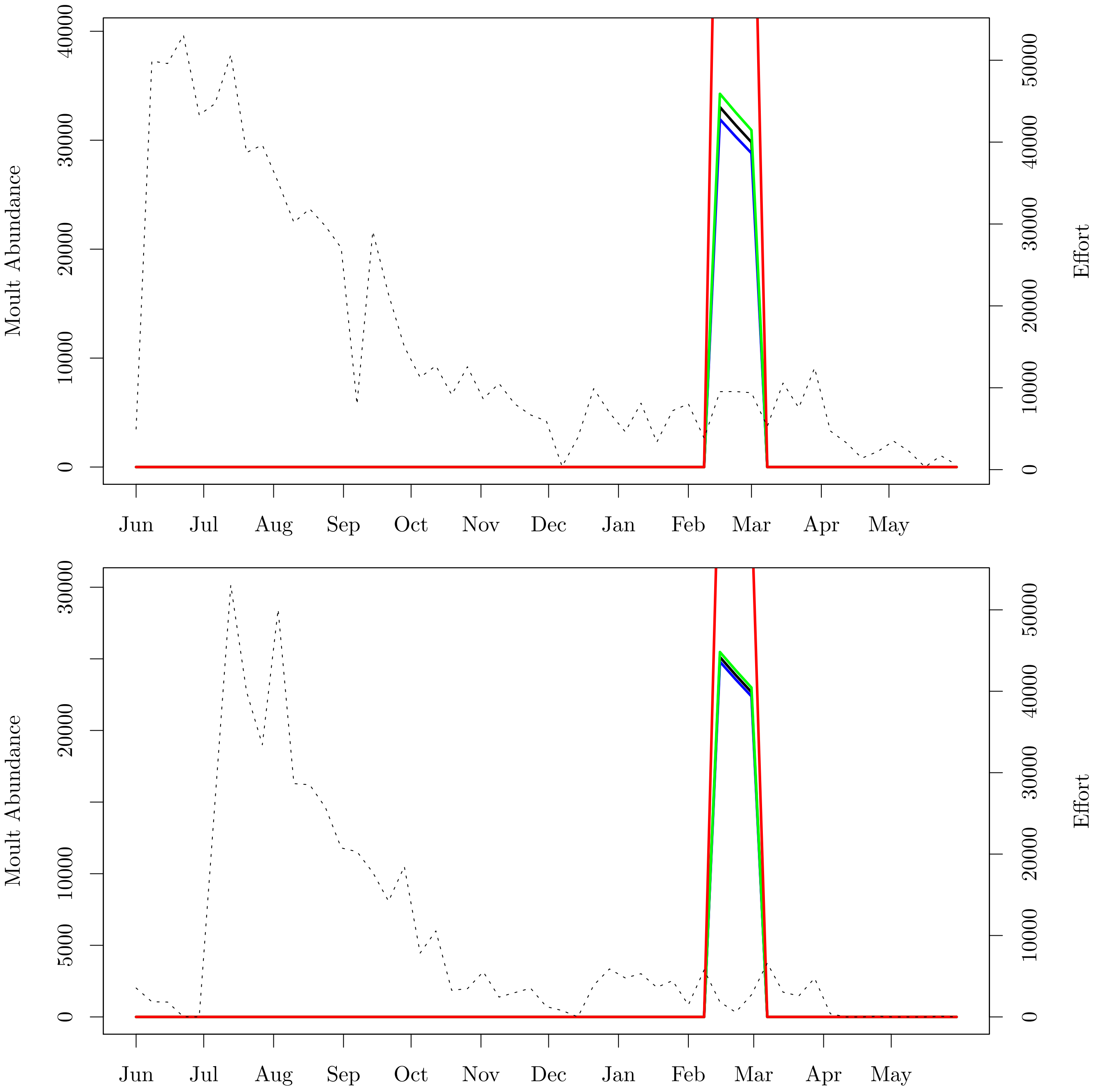

Figure 1.9: Seasonal Moult: On the left y-axis is an index of moult abundance in Tonnes. The lines that peak in the spring are the abundance of soft shell crabs; the base case, slow growth, fast growth, and high mortality cases are plotted in black, blue, green, and red respectively. On the right y-axis is the number of traps hauled shown in the light dashed line. The years are, from top to bottom, 2004 and 2006 and are representative of high and low abundance years

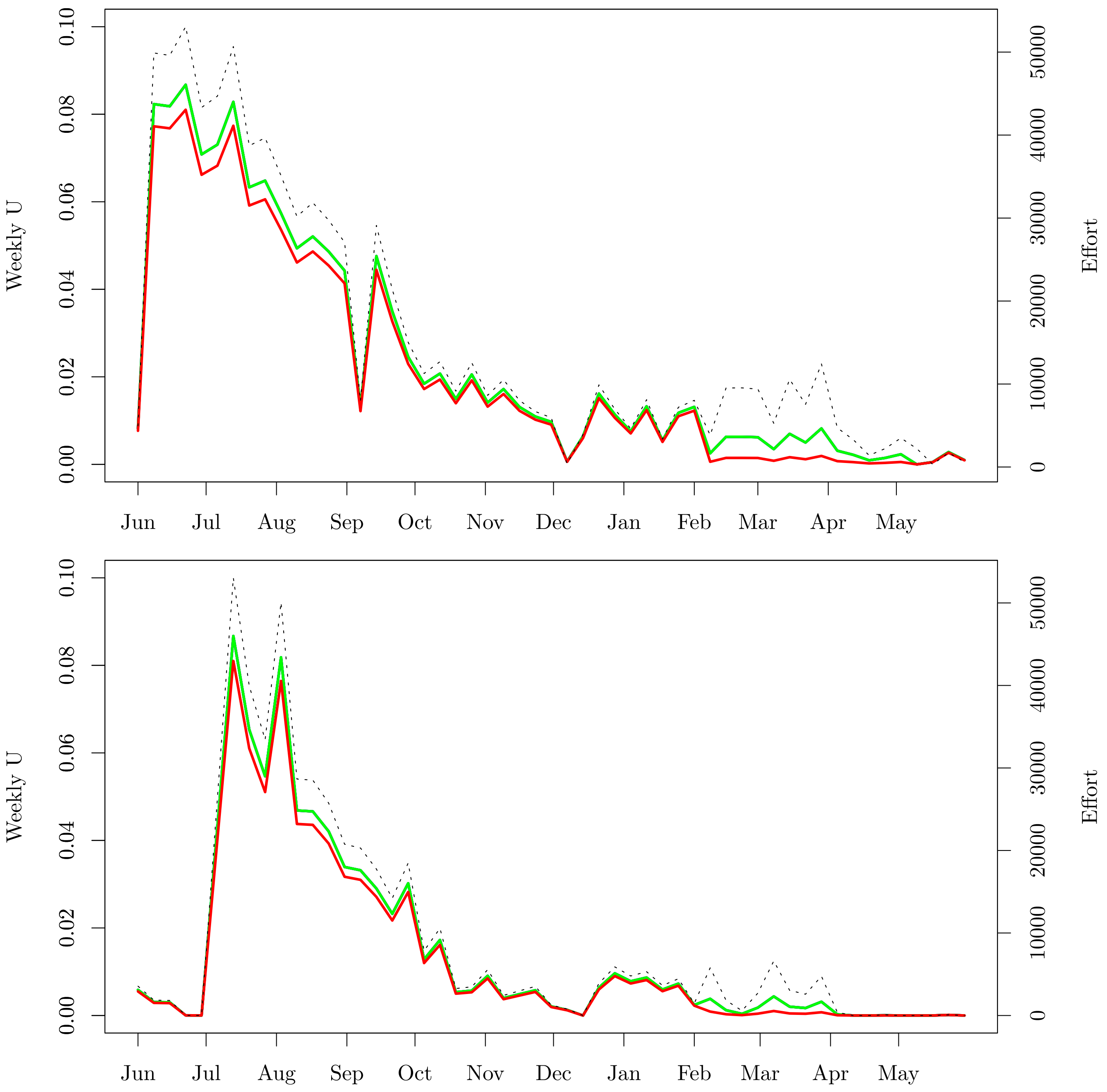

Figure 1.10: Weekly Exploitation: On the left y-axis is the estimated weekly exploitation rate (dots) and on the right y-axis is the number of traps pulled shown in the light dashed line; the base case, slow growth, fast growth, and high mortality cases are plotted in black, blue, green, and red respectively. The years are, from top to bottom, 2004 and 2006 and are representative of high and low abundance years.

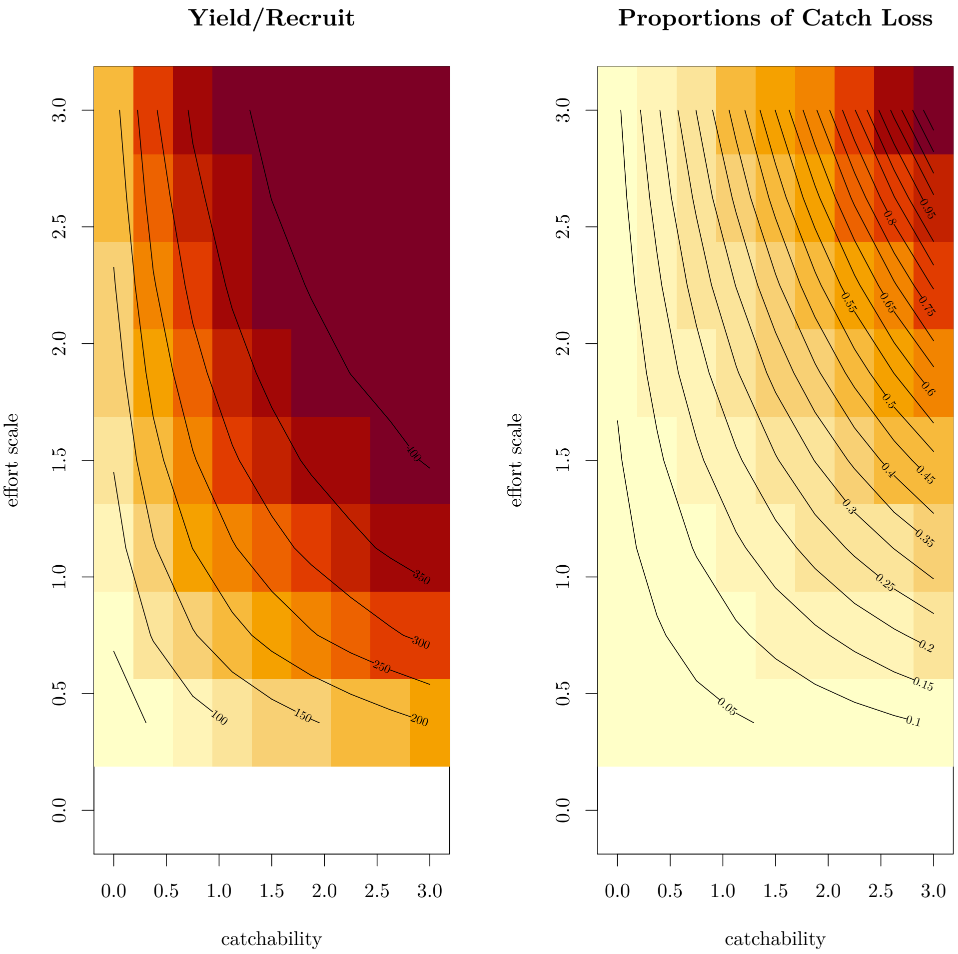

Figure 1.11: The handling mortality (M_h) is set in the figure at .49. Note that the mortality on shell condition three increases as a function of catchability and effort scale. It should be noted that the percentage lost is computed according to equation 1.15, and is not re-scaled by a factor of 100.

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.1 Source code Appendix

.1.1 Initialize Crab Aggregation

```



Crab_base::Crab_base
(int numberofmoults, int b_week,double g_rate,
    double A0,double vuln,double vuln2,
    double mort,double handmort,int i)
{/*! Each of these statistical aggregations of crabs has
   it's own growth rate, birth week, initial abundance,
   initial vulnerability and unique identification number.
   This constructor makes one of these objects.
   It is important to note there is no destructor for this class.
   We need to maintain a permanent record of the state of these objects.
```

```
*/

id=i;
growthrate=g_rate;
mortalityscale=mort;
birthweek=b_week;
Nmoults=numberofmoults;
vulreg=vuln;
vulreg2=vuln2;
handlingmort=handmort;


duration[1]=6;
duration[2]=4;
duration[3]=6;
duration[4]=2;
duration[5]=1;
duration[6]=8;
duration[8]=25;
duration[7]=1000;//mortality kills them

//make a map that does the order of the shell conditions
shell_map[1]=8;
shell_map[6]=5;
shell_map[5]=4;
shell_map[4]=3;
shell_map[3]=2;
shell_map[2]=1;
shell_map[8]=6;
```

```
shell_map[7]=7; //once in 7 always in 7


//set weekly mortalities
mortality[1]=.0001*mortalityscale;
mortality[2]=.002*mortalityscale;
mortality[3]=.003*mortalityscale;
mortality[4]=.0050*mortalityscale;
mortality[5]=.01*mortalityscale;
mortality[6]=.001*mortalityscale;
mortality[8]=.001*mortalityscale;
mortality[7]=.06*mortalityscale;


//set the vulnerability by shell condition
vulshell[1]=1.0;
vulshell[2]=vulreg;
vulshell[3]=vulreg;
vulshell[4]=vulreg;
vulshell[5]=vulreg;
vulshell[6]=vulreg;
vulshell[8]=vulreg;
vulshell[7]=vulreg;


//set the vulnerabilty for the variable vulnerability by
// aggeregation this sets the vector of vulnerabilities that
// get looped over

```

```
step=(vulreg/10.0);
for(int s=0;s<=9;s++)
      {
        var2.push_back((1-vulreg/2.0+step*s)/(1+vulreg/2.0));
      };
    moults.push_back(0);

if(A0>0){
abundance.push_back(A0);//set inital abundance
unfished_abundance.push_back(A0);
mature_abundance.push_back(0.0);

}else{
    abundance.push_back(0.0);//set inital abundance
    unfished_abundance.push_back(0.0);
    mature_abundance.push_back(0.0);

}
shell_condition.push_back(1);//set inital shell condition
weeks_in_shell.push_back(0); //weeks in shell start with zero
vulnerablity.push_back(vuln);// set inital vulnerability
real_time.push_back(birthweek);//set inital realtime inside crab class
age_of_crabs.push_back(0);
size.push_back(100.0);
weightvul.push_back(1.00);
week_of_year.push_back(real_time.back()%52);
dead=-1;// make the thing alive
}
```

.1.2 Go Fish

```
void Crab::go_fish(double Effort, double q,int date)
{ //! This function goes fishing.
 /// It first checks to see if it is alive.
 if((dead<0)&&(date>=birthweek)){ //check if alive

   /*!
    Then it checks to see if the size of the crabs in the statistical aggregati
    165 mm and that the shell condition is an element of 1,6,8,7.
   */

   double qvE=vulnerablity.back()*Effort*q; //just compute once
   double sizeb=size.back();
   int scb=shell_condition.back();
   double abund=abundance.back();
   //just make sure that abundance cannot go negative
   if(qvE>=1.00){qvE=1.00;}

   if(scb==3){// if shell condition 3 compute handling loss
    handling_loss.push_back(qvE*abund*handlingmort*.0001*pow(sizeb,3.0597));
    handlingmortality.push_back(-1.0*abund*log(1.0-(qvE*handlingmort)));
    abundance.back()=(abund-qvE*abund*handlingmort);

   };
   if(sizeb>=165 &&(scb==1||scb==6||scb==8||scb==7))
  //if hard shell  go fish
    {// This doesn't allow for the fleet to remove any soft shell crabs.
    handlingmortality.push_back(0.0);
```

```
        handling_loss.push_back(0.0);
          double yield=abund*qvE;//lets compute this just once!
          weekly_catch.push_back(yield);
          weekly_ypr.push_back((yield *.0001*pow(sizeb,3.0597))/abundance.front());
          abundance.back()=abund-weekly_catch.back();
        }else{
        ///if alive and didn't fish set weekly catch to zero.
        weekly_catch.push_back(0.0);
        weekly_ypr.push_back(0.0);
        handlingmortality.push_back(0.0);
        handling_loss.push_back(0.0);
      }




          if(abundance.back()<1e-126){ //this really is probably not needed
           // if abundance goes to zero stop worrying about the aggregation
            dead=real_time.back()-1; //set dead bigger than one.
            abundance.back()=0.0;};
        }


}
```

.1.3 Advance Population

```
void Crab_base::advance(int date){

  /*!
   This method advances the statistical aggregation of crabs by one week.
   It has to keep track of the state of the crabs each week.
   It has been designed so that the state of the crabs next week depends only on th
   state of crabs in the present week and some fairly simple transition rules.
   */
  /// First advance checks to make sure that the crabs are alive.
  if((dead<0)&&(date>=birthweek)){
    /// If the number of weeks in a shell condition is less than the duration, in w
    /// remain in a given shell condition then the shell condition remains the same
    /// is incremented and the size of crabs remains the same.
    /// Otherwise the shell condition must change and the crabs may possibly moult

  if(weeks_in_shell.back()<duration[shell_condition.back()]){
  shell_condition.push_back(shell_condition.back());
  weeks_in_shell.push_back(weeks_in_shell.back()+1);
  size.push_back(size.back());
  moults.push_back(0);
  }else{
    /// If shell condition is 6 then the crabs grow.



    if(shell_condition.back()==6)
      {
        //grow the crabs
        auto growthecrabs=[&](double &size){
        double tempsize=1.069*size+growthrate;//grow the aggregation
```

```
    if(tempsize<400){return tempsize;}
    else{ //just make a quick check to ensure that crabs cannot be
     //   impossible sized.  This check should never be needed.
     //   Having a check like this is only useful for debugging.
     /* std::cout<<"tempsize is bigger than 400"<<"size-"<<size */
     /* <<"growth-"<<growthrate<<"tempsize-"<<tempsize<<std::endl; */
     return 399.00;};
    };



   size.push_back(growthecrabs(size.back()));
   moults.push_back(1);
   Nmoults--;//decrement the number of remaining moults
   if(Nmoults<=0){/// If the number of moults remaining is less than or equal to
7
    shell_condition.push_back(7);
    }//after terminal moult
   }else
   { ///If not in shell condition 6 then the size doesn't change
    size.push_back(size.back());
    moults.push_back(0);
   } /// the shell condition changes according to the rules described in the fun
    shell_condition.push_back(shell_map[shell_condition.back()]);
    /// and the number of weeks in shell is reset to one.
    weeks_in_shell.push_back(1);

 }

```

```
/// age of crabs is incremented
age_of_crabs.push_back(age_of_crabs.back()+1);
/// week of year is incremented mod 52
week_of_year.push_back(real_time.back()\%52);//compute week of year
/// abundance is adjusted by shell condition dependent natural mortality.
/// \f$abundance_{w+1}=abundance_w \cdot (1-mortality_{shell condition})\f$s
auto killthecrabs=[&](double &abundance){return abundance*(1.0-mortality[shell_c
abundance.push_back(killthecrabs(abundance.back()));
unfished_abundance.push_back(killthecrabs(unfished_abundance.back()));
///if abundance drops below \f$10^6\f$ then the statistical aggregation dies and

if(abundance.back()<1e-126){
 dead=real_time.back();
 abundance.back()=0.0;
}
}
//abundance.back()=0.0;
 /// then real time is incremented
real_time.push_back(real_time.back()+1);
if(size.back()>165)
 {
  mature_abundance.push_back(abundance.back());
 }else
 {
  mature_abundance.push_back(0.0);
 }
```

.1.4 Initialize Population

```
void SimulationnoFemale::runsim()
{ //this method just runs the simulations for a year.

 int indexm=0;
 int indexf=0;
 int countyear=-1;
 for(int i=0;i<nweeks;i++)//simulate a year
   {
    int countm=0;
     week_of_year.push_back(i%52);
     if(week_of_year.back()==0){
     countyear++;
     /* std::cout<<"week of year \n"<< week_of_year.back()<<"\ncountyear\n"<<
     };
      double Ain=0;
      if(countyear<A0.size()&A0[countyear]>0)
       {
        Ain=A0[countyear];
       }
        A0out.push_back(Ain);


    if(i>=birth_males.size()){birth_males.push_back(1);}

    while(countm<birth_males[i]){
     // initialize a crab class for each aggrigation born in week i
```

```
          Crabs_males.push_back(Crab(4,i,R::rnorm(meangrm,vargrm),Ain,vulpar1,vulpa

        countm++;
        indexm++;

        }



        int am;
         // determine how many aggregations are alive
        am = get_alive_males(i);

        int size_alive=alive_males[i].size();
        advance_crab(alive_males[i],
        Crabs_males,Effort[i],Temp[i],vultype,i,catchability_males);//advance
        the crabs as shown in the next subsection
        real_time.push_back(i);

      }


};
```

.1.5 Advance Population

```
void SimulationnoFemale::advance_crab
         (std::vector<int> alive, std::vector<Crab> &Cm,
         double effort,double temp, int v,int d,double cbty)
```

```
      {


        auto looper=[&](int b,int e){
          for(int i=b;i<e;i++)
            {

        int k=alive[i];
        Cm[k].advance(d);//advance the crabs!!
        Cm[k].go_fish(effort,cbty,d);
        Cm[k].update_vul(v,effort,temp);//advance the crabs!
            }
        };

        if(alive.size()<14)

          {
            looper(0,alive.size());
          }else{
        int z=alive.size()/14;
        std::thread first(looper,0,z);
 //run on fourteen cores
        std::thread fourteen(looper,13*z,alive.size());

         first.join();
//join them up
         fourteen.join();
        };
      };
```

```cpp


int SimulationnoFemale::get_alive_males( int date)
  {
    std::vector<int>tmp;
          for(auto &ia : Crabs_males)
            {
              if((ia.dead==(-1))){
                tmp.push_back(ia.id);
              }
            }
          int out;
          alive_males.push_back(tmp);
          out=alive_males.back().size();
          if(out>Crabs_males.size())
          {std::cout<<"oh no! more aggregations are alive than exist?!"<<std::endl;
          return out;
  };
```