Figures and Tables
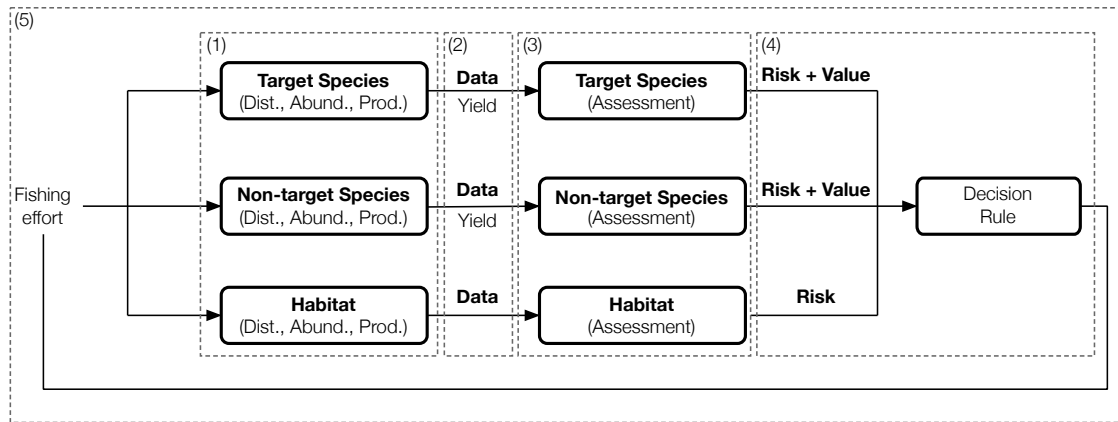

Figure 1: A simplified fishery managment system divided into 5 discrete units. (1) Applied Population Ecology, (2) Fisheries Data Science, (3) Stock Assessment Modeling, (4) Risk Assessment, (5) Management Strategy Evaluation.

Table 1: Variable definitions for a simulation of a multispecies fishery with no substock structure, used in Chapter 1. The population dynamics are driven by a simple Biomass Dynamics model (Hilborn and Walters, 1992, Ch, 8). Species catch is dependent on fishing mortality for each species, which is an input to the model. The current specification can be considered to be "coastwide" in the sense that it aggregates all discrete management units of each species into a single unit.

| *Variable*	*Description*
	Index Variables
S	Total number of species
F	Total number of fleets
T	Total number of years
s	Species index
f	Fleet index
t	Time index
	Biological Model
$B_{s,t}$	Biomass of species s at time t
$B_{s,0}$	Unfished biomass of species s
r_s	Average intrinsic rate of growth for speces s
	Observation Model
q_s	Survey catchability of species s at time t
$I_{s,t}$	Fishery independent CPUE of species s at time t
	Output (catch)
$F_{s,t}$	Fishing mortality of species s at time t
$C_{s,t}$	Total catch of species s at time t
	Stochastic Model
σ_s^2	Process error variance for species s
$\epsilon_{s,t}$	Process error for species s at time t, $\left(\epsilon_{s,t} \sim N(0, \sigma_s^2)\right)$
σ^2	Assemblage level process error variance
ϵ_t	Assemblage level process error at time t, $\left(\epsilon_t \sim N(0, \sigma^2)\right)$
τ_s^2	Observation error variance for species s
$\delta_{s,t}$	Observation error for species s at time t $\left(\epsilon_{s,t} \sim N(0, \tau_s^2)\right)$
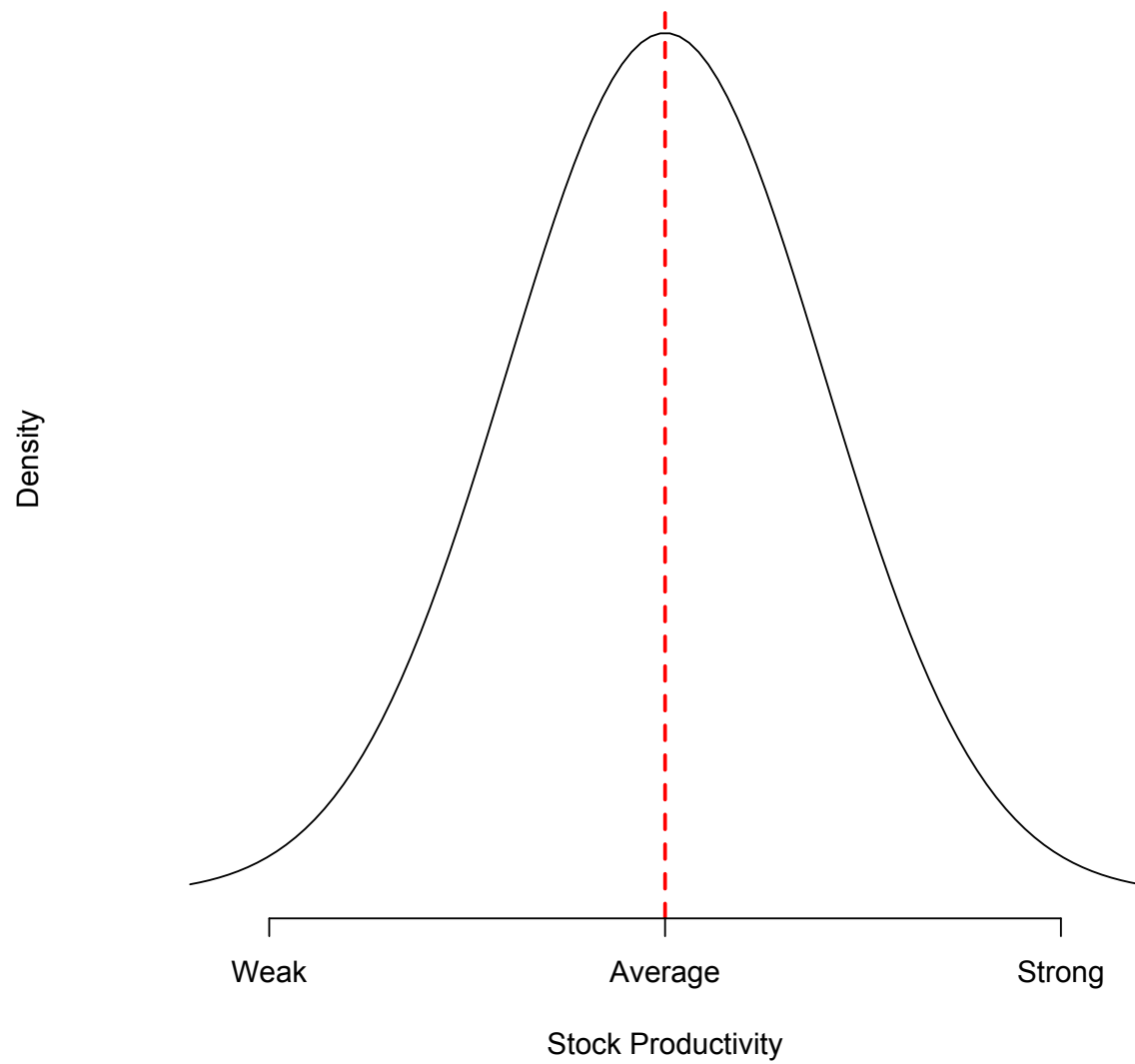
Figure 2: A conceptual model of the distribution of stock productivities in Pacific salmon. Harvesting according to the average productivity level leads to overfishing of the weakest stocks.

Quota

Q

Q_P

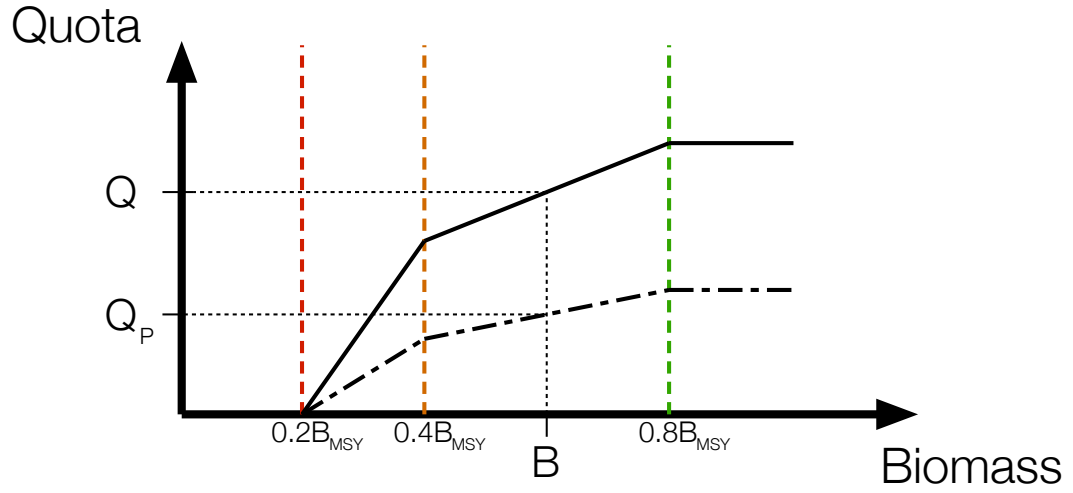$0.2B_{MSY}$ $0.4B_{MSY}$ B $0.8B_{MSY}$

Biomass

Figure 3: A harvest control rule showing how the presence of pinch-point species affects the harvesting of directed species. The solid black line is the normal harvest control rule for a high productivity directed species, set by stock assessment, while the dashed black line shows the effective harvest control rule in the presence of technical interactions with pinch-point species. For a given stock biomass B the directed species quota is Q, but pinch-point species reduce that to an effective or utilised quota of Q_P. The reduction in resources caused by the pinch-point species is then $Q - Q_P$.
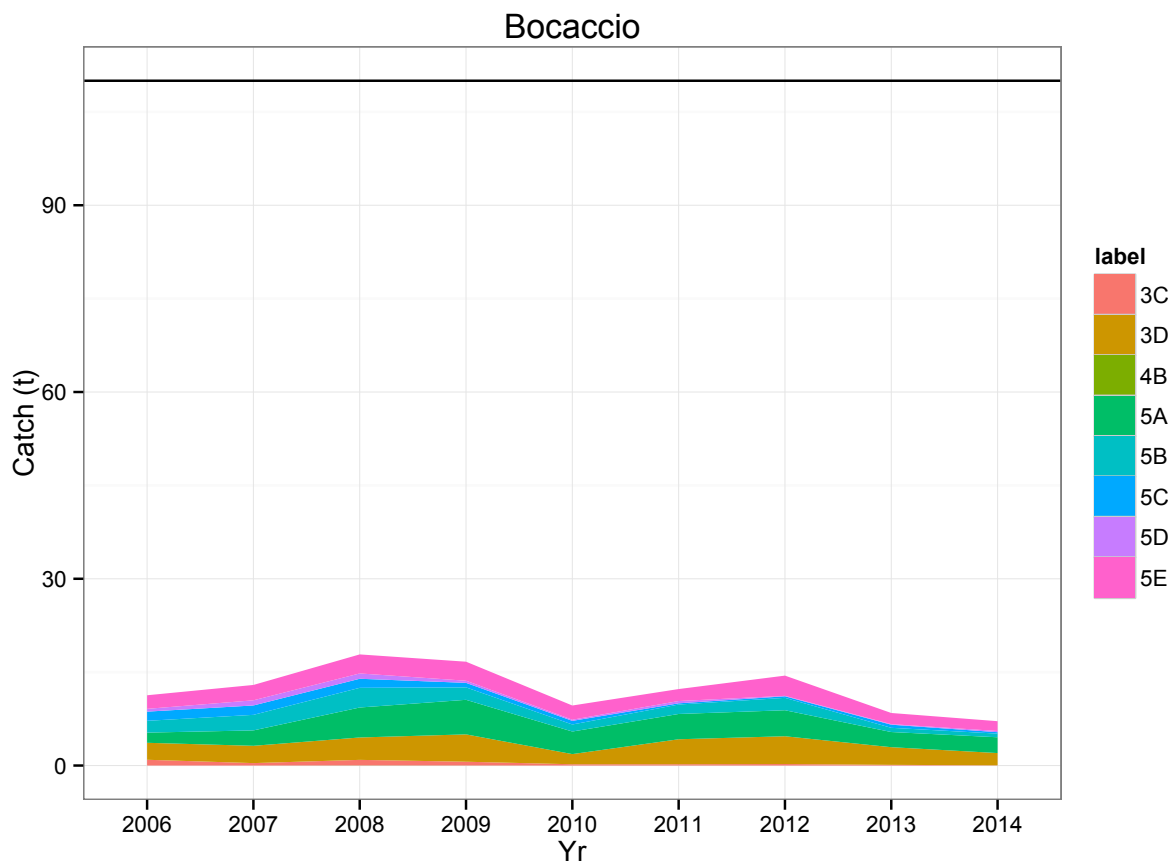
Figure 4: Quota utilisation of Bocaccio rockfish in the BC integrated groundfish fishery. The black line represents the average annual total allowable catch (taken from the Pacific Region Integrated Fishery Management Plan) and the coloured polygons represent the biomass of removals in each management area.

Figure 5: Quota utilisation of lingcod in the BC integrated groundfish fishery. The black line represents the average annual total allowable catch (taken from the Pacific Region Integrated Fishery Management Plan) and the coloured polygons represent the biomass of removals in each management area.
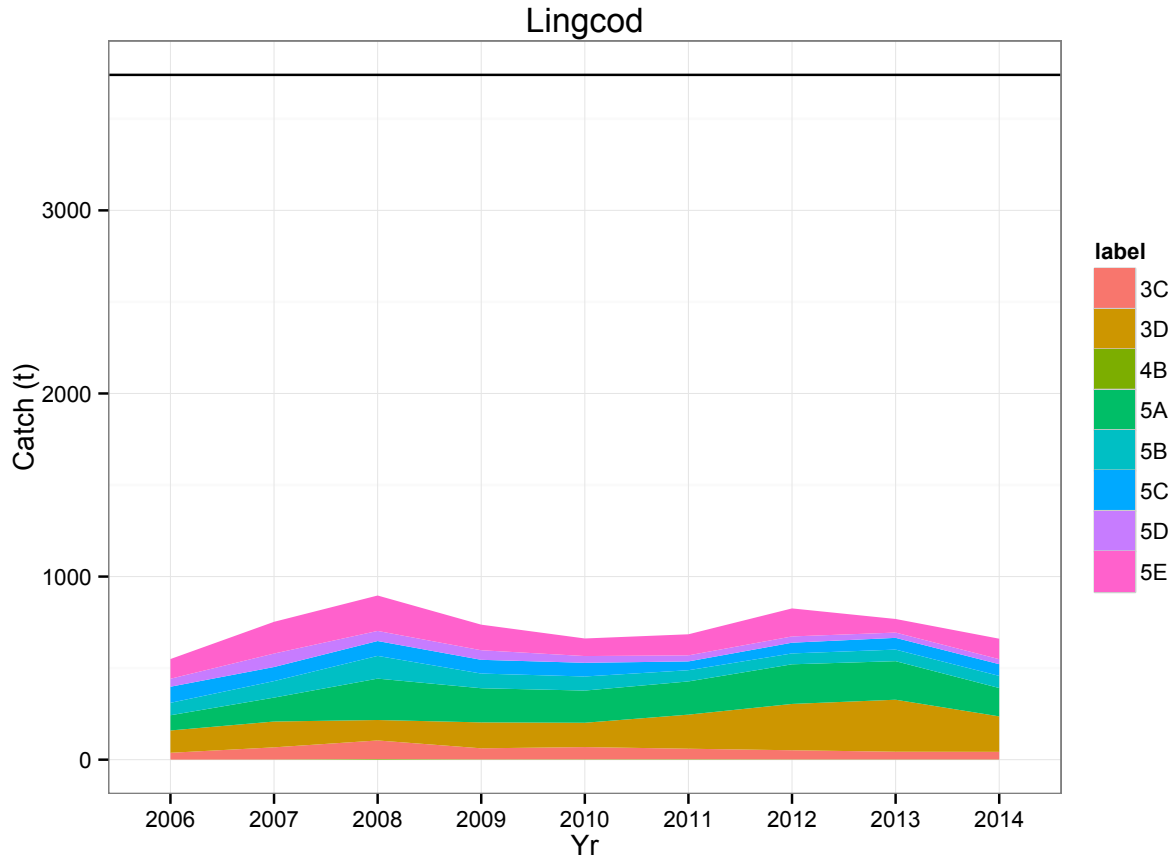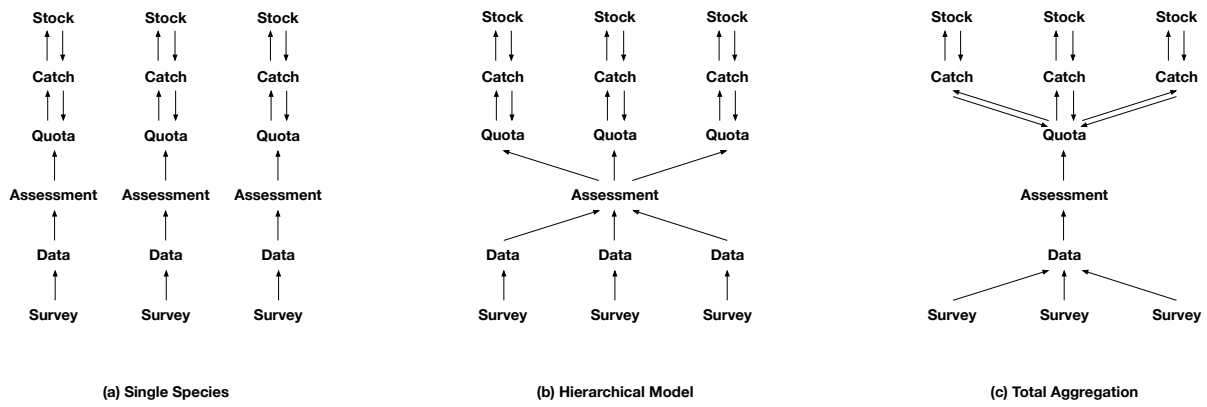

Figure 6: Three models of fishery management: (a) status quo, single species approach; (b) hierarchical multi-species model; (c) total aggregation of species

Table 2: The simulation model to produce data for the estimation procedure in Chapter 1. The simulator generates time series of catch, biomass and CPUE for species s with input parameters Θ_s. All variables are defined in Table 7.

Simulation Parameters

(T2.1) $\quad \Theta_s = \left(B_{s,0}, r_s, q_s, \{F_{s,t}\}_{t=1}^T, \sigma_s^2, \tau_s^2 \right)$

Initial States $(t = 1)$

(T2.2) $\quad B_{s,1} = B_{s,0} \cdot e^{\epsilon_{s,t} - \sigma_s^2/2}$

Catch $(1 \leq t \leq T)$

(T2.3) $\quad C_{s,t} = \left(1 - e^{F_{s,t}} \right) \cdot B_{s,t}$

State Dynamics $(2 \leq t \leq T)$

(T2.4) $\quad B_{s,t} = \left(B_{s,t-1} + r_s B_{s,t-1} \left(1 - \frac{B_{s,t-1}}{B_{s,0}} \right) - C_{s,t-1} \right) \cdot e^{\epsilon_{s,t} - \sigma_s^2/2}$

Observations $(1 \leq t \leq T)$

(T2.5) $\quad I_{s,t} = q_s \cdot B_{s,t} \cdot e^{\delta_{s,t} - \tau_s^2/2}$

Table 3: A truncated version of the hierarchical stock assessment model used as the estimation procedure Chapter 1. The hierarchical model in this version shares a prior distribution on process error deviations $\epsilon_{s,t}$, representing correlations in environmental variation due to species with shared habitat. All variables used here are defined in Table 7 except σ^2, which is the assemblage level variance for the shared prior on process error terms.

Assessment Parameters

(T3.1) $\quad \Theta_s = \left\{ B_{s,0}, r_s, q_s, \tau_s^2, m_{B,s}, v_{B,s}^2, \{I_{s,t}\}_{t=1}^T, \{C_{s,t}\}_{t=1}^T \right\}$

(T3.2) $\quad \Theta = \left\{ \{(\Theta_s)\}_{s=1}^S, \sigma^2, m_q, v_q^2 \right\}$

Population Dynamics Model

(T3.3) $\quad B_{s,1} = B_{s,0} \cdot e^{\epsilon_t - \sigma^2/2}$

(T3.4) $\quad B_{s,t} = \left(B_{s,t-1} + r_s B_{s,t-1} \left(1 - \frac{B_{s,t-1}}{B_{s,0}}\right) - C_{s,t-1} \right) \cdot e^{\epsilon_t - \sigma^2/2}, \, 2 \leq t \leq T,$

Observational Model $(1 \leq t \leq T)$

(T3.5) $\quad \bar{I}_{s,t} = q_s \cdot B_{s,t} \cdot e^{\delta_{s,t} - \tau_s^2/2}$

Statistical Model

Data Likelihood

(T3.6) $\quad \mathcal{L}_s \left(\{I_{s,t}\}_{t=1}^T \mid \Theta_s \right) = \left(\frac{1}{\sqrt{2\pi\tau_s^2}} \right)^T \cdot \prod_{t=1}^T e^{-\frac{(\bar{I}_{s,t}/I_{s,t})^2}{2\tau_s^2}}$

Shared Assemblage Priors

(T3.7) $\quad p(\epsilon_{s,t} \mid \sigma^2) = \left(\frac{1}{\sqrt{2\pi\sigma^2}} \right)^S T \cdot \prod_{s=1}^S \prod_{t=1}^T e^{-\frac{\epsilon_{s,t}^2}{2\sigma^2}}$

(T3.8) $\quad p(\log q_s \mid m_q, v_q^2) = \frac{1}{\sqrt{2\pi v_q^2}} \cdot e^{-\frac{(\log q - m_q)^2}{2v_q^2}}$

Species Priors

(T3.9) $\quad p(\log B_{0,s} \mid m_{B,s}, v_{B,s}^2) = \frac{1}{\sqrt{2\pi v_{B,s}^2}} \cdot e^{-\frac{(\log B_{0,s} - m_{B,s})^2}{2v_{B,s}^2}}$

Posterior Density

(T3.9) $\quad \mathcal{P} \left(\Theta \mid \{I_{s,t}\}_{(s,t)=(1,1)}^{(S,T)} \right) = \prod_{s=1}^S \left[\mathcal{L}_s \left(\{I_{s,t}\}_{t=1}^T \mid \Theta_s \right) \cdot p(\epsilon_{s,t} \mid \sigma^2) \cdot p(\log q \mid m_q, v_q^2) \cdot p(\log B_{0,s} \mid m_{B,s}, v_B^2 \right.$

(a) Individual Species Time Series

| | | | | Observation Model |

$I_{S,1}$ $I_{S,2}$ $\cdots$ $I_{S,T}$

$B_{S,1} \rightarrow B_{S,2} \rightarrow \cdots \rightarrow B_{S,T}$ Process Model

$\{q_S,\, B_{S,0},\, r_S,\, \sigma_S^2,\, \tau_S^2\} = \Theta_S$ Parameters

$\{m_B,\, v_B,\, m_r,\, v_r,\, m_\sigma,\, v_\sigma,\, m_\tau,\, v_\tau\} = \overline{\Theta}_S$ Species Hyperparameters

,

(b) Assemblage Hierarchical Model

$\boldsymbol{I_1}$ $\boldsymbol{I_2}$ $\cdots$ $\boldsymbol{I_S}$ Observation Model

$\boldsymbol{B_1}$ $\boldsymbol{B_2}$ $\cdots$ $\boldsymbol{B_S}$ Process Model

Θ_1 Θ_2 $\cdots$ Θ_S Species Parameters

α^2 Assemblage Parameters

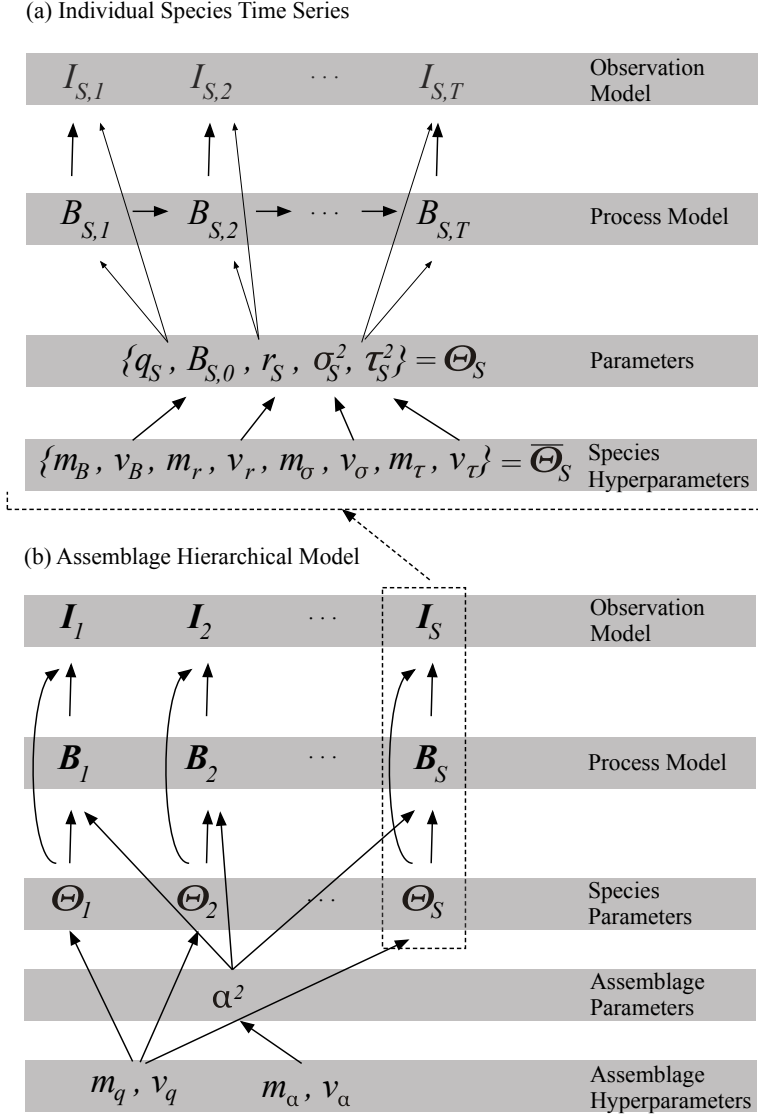$m_q,\, v_q$ $m_\alpha,\, v_\alpha$ Assemblage Hyperparameters

Figure 7: A conceptual diagram of the hierarchical model used for estimation in Chapter 1. Part (a) shows the individual species process and observation models, with species specific parameters and hyperparameters. Part (b) compresses the time series into bold italicised variables, and shows the hierarchically arranged multispecies assemblage with shared multispecies parameters and hyperparameters.
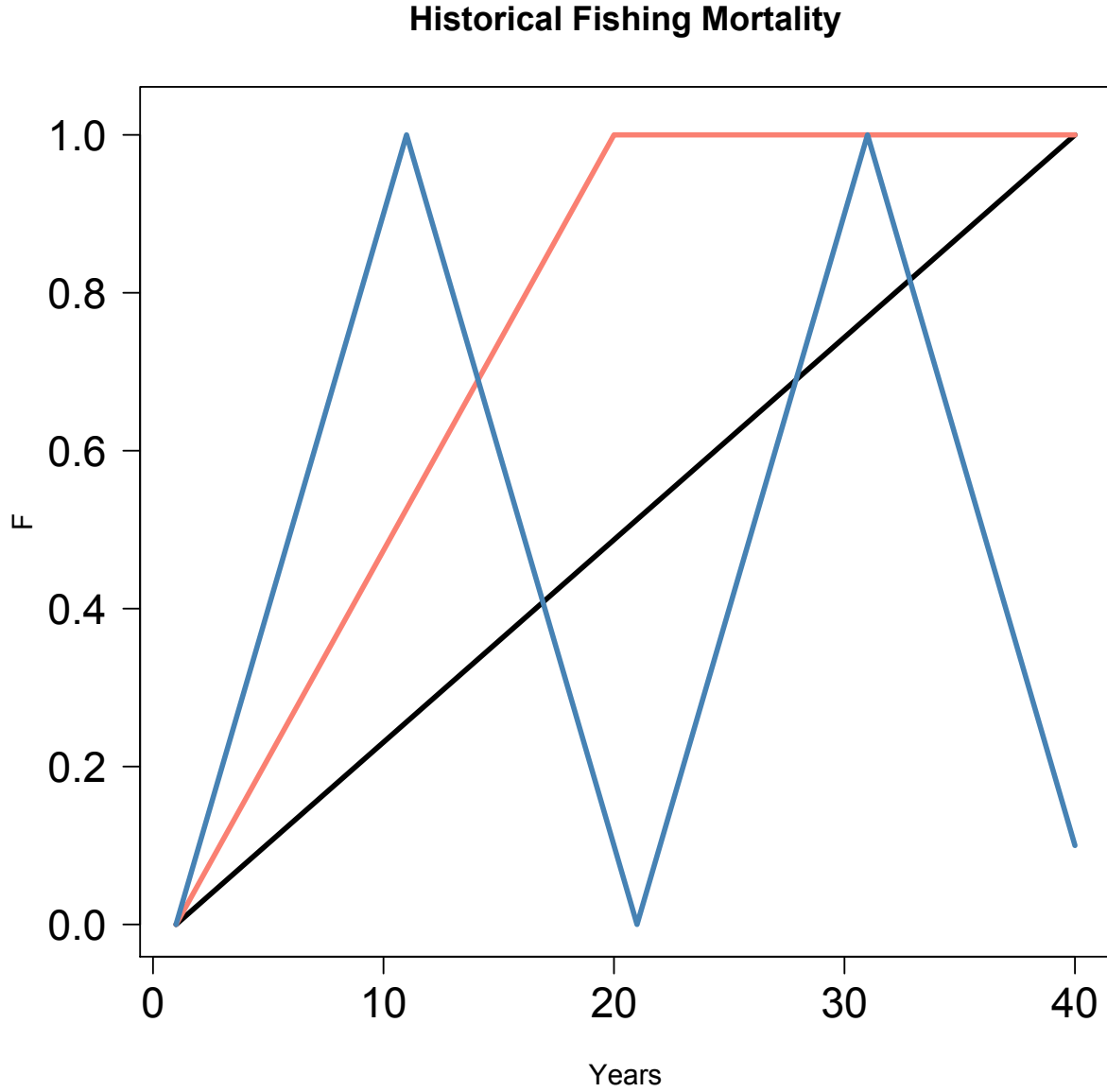
Historical Fishing Mortality

Figure 8: Three instantaneous fishing mortality F_t trends over 40 years of management history. The black line shows a steady linear increase over the time period to a maximum of $F_t = 1$. The red line shows a fishery that developed over 20 years and then held fishing mortality steady at $F_t = 1$ for the following 20. Both trajectories correspond to developmental periods of a fishery, which provides little information about a stocks response to alleviating fishing pressure. Finally, the blue line shows a more informative trajectory, with periods of increasing and decreasing fishing pressure over the 40 year management period. Here, stock dynamics will respond to the changes in fishing pressure and provide more information about productivity than the other two cases.

Table 4: Variable definitions for a simulation of multispecies fishery used in Chapter 2, where each species has multiple stocks. The population dynamics are driven by a simple Biomass Dynamics model (Hilborn and Walters, 1992, Ch, 8), with immigration and emigration between stocks of a species summarised by a migration rate $\phi_{s,i,j}$. Catch is driven by fishing mortality for individual stocks, which is an input to the model.

Variable	*Description*
	Index Variables
s	Species index
j	Stock index
f	Fleet index
t	Time index
S	Total number of species
J_s	Total number of stocks of species s
F	Total number of fleets
T	Total number of years
	Biological Model
$B_{s,j,t}$	Biomass of stock j of species s at time t
$B_{s,j,0}$	Unfished biomass of stock j of species s
$r_{s,j}$	Intrinsic rate of growth for stock j of speces s
$\phi_{s,j,i}$	Net migration rate between stocks j and i of species s
	Observation Model
$q_{s,j}$	Survey catchability of stock j of species s at time t
$I_{s,j,t}$	Fishery independent CPUE of stock j of species s at time t
	Catch
$F_{s,j,t}$	Fishing mortality of stock j of species s at time t
$C_{s,j,t}$	Total catch of stock j of species S at time t
	Stochastic Model
$\sigma^2_{s,j}$	Process error variance for stock j of species s
$\epsilon_{s,j,t}$	Process error deviation for stock j of species s at time t, $\left(\epsilon_{s,j,t} \sim N(0, \sigma^2_{s,j})\right)$
σ^2_s	Process error variance for species s
$\epsilon_{s,t}$	Process error deviation for species s at time t, $\left(\epsilon_{s,t} \sim N(0, \sigma^2_s)\right)$
σ^2	Assemblage level process error variance
ϵ_t	Assemblage level process error deviations at time t, $\left(\epsilon_t \sim N(0, \sigma^2)\right)$
τ^2_s	Observation error variance for species s
$\delta_{s,j,t}$	Observation error for stock j of species s at time t $\left(\epsilon_{s,j,t} \sim N(0, \tau^2_s)\right)$

Table 5: The simulation model to produce data for the estimation procedure in Chapter 2. The model generates time series of catch, biomass and CPUE for stock j of species s with input parameters Θ_s. All variables are defined in Table 7.

Parameters

(T5.1) $\quad \Theta_{s,j} = \left(B_{s,j,0}, r_{s,j}, q_{s,j}, \{\phi_{s,j,i}\}_{i \neq j}, \{F_{s,j,t}\}_{t=1}^{T}, \sigma_{s,j}^2, \tau_{s,j}^2, T \right)$

Initial States $(t = 1)$

(T5.2) $\quad B_{s,j,1} = B_{s,j,0} \cdot e^{\epsilon_{s,j,t} - \sigma_{s,j}^2/2}$

Catch $(1 \leq t \leq T)$

(T5.3) $\quad C_{s,j,t} = \left(1 - e^{F_{s,j,t}} \right) \cdot B_{s,j,t}$

State Dynamics $(2 \leq t \leq T)$

(T5.4) $\quad B_{s,j,t} = \left(B_{s,j,t-1} + r_{s,j} B_{s,j,t-1} \left(1 - \frac{B_{s,j,t-1}}{B_{s,0}} \right) + \sum_{i \neq j} \phi_{s,j,i} \cdot B_{s,i,t-1} - C_{s,j,t-1} \right) \cdot e^{\epsilon_{s,j,t} - \sigma_{s,j}^2/2}$

Observations $(1 \leq t \leq T)$

(T5.5) $\quad I_{s,j,t} = q_{s,j} \cdot B_{s,j,t} \cdot e^{\delta_{s,j,t} - \tau_{s,j}^2/2}$

Table 6: A truncated version of the hierarchical stock assessment model used as the estimation procedure Chapter 2. The hierarchical model in this version shares a prior distribution on process error deviations $\epsilon_{s,t}$, representing correlations in environmental variation due to species with shared habitat. All variables used here are defined in Table 7.

Assessment Input Parameters

(T6.1) $\quad \Theta_{s,j} = \left(B_{s,j,0}, r_{s,j}, q_{s,j}, \{\phi_{s,j,i}\}_{i \neq j}, \tau_{s,j}^2, \{I_{s,j,t}\}_{t=1}^T, \{C_{s,j,t}\}_{t=1}^T \right)$

(T6.2) $\quad \Theta_s = \left(\{\Theta_{s,j}\}_{j=1}^{J_s}, \sigma_s^2 \right)$

Population Dynamics Model

(T6.3) $\quad B_{s,j,1} = B_{s,j,0}$

(T6.4) $\quad B_{s,j,t} = \left(B_{s,j,t-1} + r_{s,j} B_{s,j,t-1} \left(1 - \frac{B_{s,j,t-1}}{B_{s,j,0}} \right) + \sum_{i \neq j} \phi_{s,j,i} \cdot B_{s,i,t-1} - C_{s,j,t-1} \right) \cdot e^{\epsilon_{s,t}}, \ 2 \leq t \leq T,$

Observational Model $(1 \leq t \leq T)$

(T6.5) $\quad \bar{I}_{s,j,t} = q_{s,j} \cdot B_{s,j,t} \cdot e^{\delta_{s,j,t}}$

Statistical Model

Data Likelihood

(T6.6) $\quad \mathcal{L}_{s,j} \left(\{I_{s,t}\}_{t=1}^T \mid \Theta_s \right) = \left(\frac{1}{\sqrt{2\pi \tau_s^2}} \right)^T \cdot \prod_{t=1}^T e^{-\frac{(\bar{I}_{s,t}/I_{s,t})^2}{2\tau_s^2}}$

Stock Specific Priors

Shared Species Priors

(T6.7) $\quad p(\epsilon_{s,t} \mid \sigma^2) = \left(\frac{1}{\sqrt{2\pi\sigma^2}} \right)^S T \cdot \prod_{s=1}^S \prod_{t=1}^T e^{-\frac{\epsilon_{s,t}^2}{2\sigma^2}}$

Shared Assemblage Priors

Posterior Density

(T6.8) $\quad \mathcal{P} \left(\Theta \mid \{I_{s,t}\}_{(s,t)=(1,1)}^{(S,T)} \right) = \left[\prod_{s=1}^S \mathcal{L}_s \left(\{I_{s,t}\}_{t=1}^T \mid \Theta_s \right) \right] \cdot p(\epsilon_{s,t} \mid \sigma^2)$

(a) Individual Stock Time Series

| $I_{S,J,1}$ | $I_{S,J,2}$ | $\cdots$ | $I_{S,J,T}$ | Data Model |

| $B_{S,J,1}$ | $B_{S,J,2}$ | $\cdots$ | $B_{S,J,T}$ | Process Model |

$\{q_{S,J},\ B_{S,J,0},\ r_{S,J},\ \sigma^2_{S,J},\ \tau^2_{S,J}\} = \Theta_{S,J}$ — Stock Parameters

$\{m_B,\ v_B,\quad\quad,\ m_\sigma,\ v_\sigma,\ m_\tau,\ v_\tau\} = \overline{\Theta}_{S,J}$ — Stock Hyperparameters

(b) Species Hierarchical Model

| $\boldsymbol{I_{S,1}}$ | $\boldsymbol{I_{S,2}}$ | $\cdots$ | $\boldsymbol{I_{S,J}}$ | Data Model |

| $\boldsymbol{B_{S,1}}$ | $\boldsymbol{B_{S,2}}$ | $\cdots$ | $\boldsymbol{B_{S,J}}$ | Process Model |

| $\Theta_{S,1}$ | $\Theta_{S,2}$ | $\cdots$ | $\Theta_{S,J}$ | Stock Parameters |

α^2 — Species Parameters

$m_q,\ v_q \qquad m_\alpha,\ v_\alpha \qquad m_r,\ v_r$ — Species Hyperparameters

(c) Assemblage Hierarchical Model

| $\boldsymbol{I_1}$ | $\boldsymbol{I_2}$ | $\cdots$ | $\boldsymbol{I_S}$ | Data Model |

| $\boldsymbol{B_1}$ | $\boldsymbol{B_2}$ | $\cdots$ | $\boldsymbol{B_S}$ | Process Model |

| Θ_1 | Θ_2 | $\cdots$ | Θ_S | Stock Parameters |

α^2 — Species Parameters

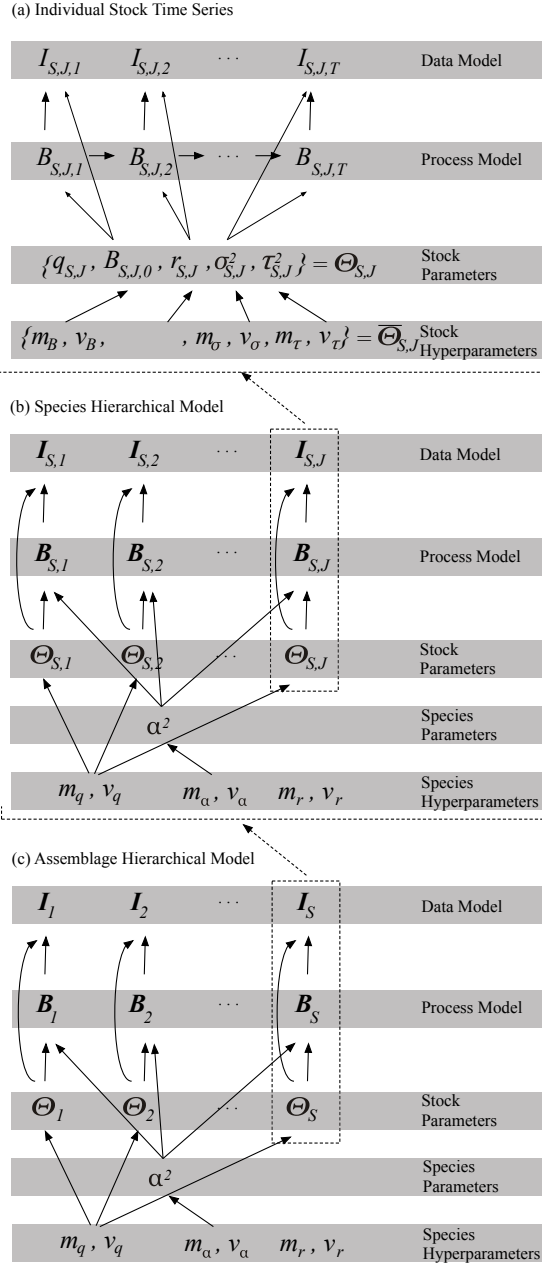$m_q,\ v_q \qquad m_\alpha,\ v_\alpha \qquad m_r,\ v_r$ — Species Hyperparameters

Figure 9: A conceptual diagram of the hierarchical model used for estimation in Chapter 2. Part (b) shows the hierarchically arranged species meta-population with species parameters and hyperparameters, where the time series in part (a) are compressed into bold, italicised symbols. Part (c) shows the hierarchically arranged multispecies assemblage, with shared multispecies parameters and hyperparameters.

Table 7: Variable definitions for the operating model simulation catch, effort, population dynamics and scientific observations in Chapter 3. The population dynamics are driven by a simple Biomass Dynamics model (Hilborn and Walters, 1992, Ch, 8), with immigration and emigration between stocks of a species summarised by a migration rate $\phi_{s,i,j}$. Catch is based on effort dynamics simulating targeting behaviour of harvesters.

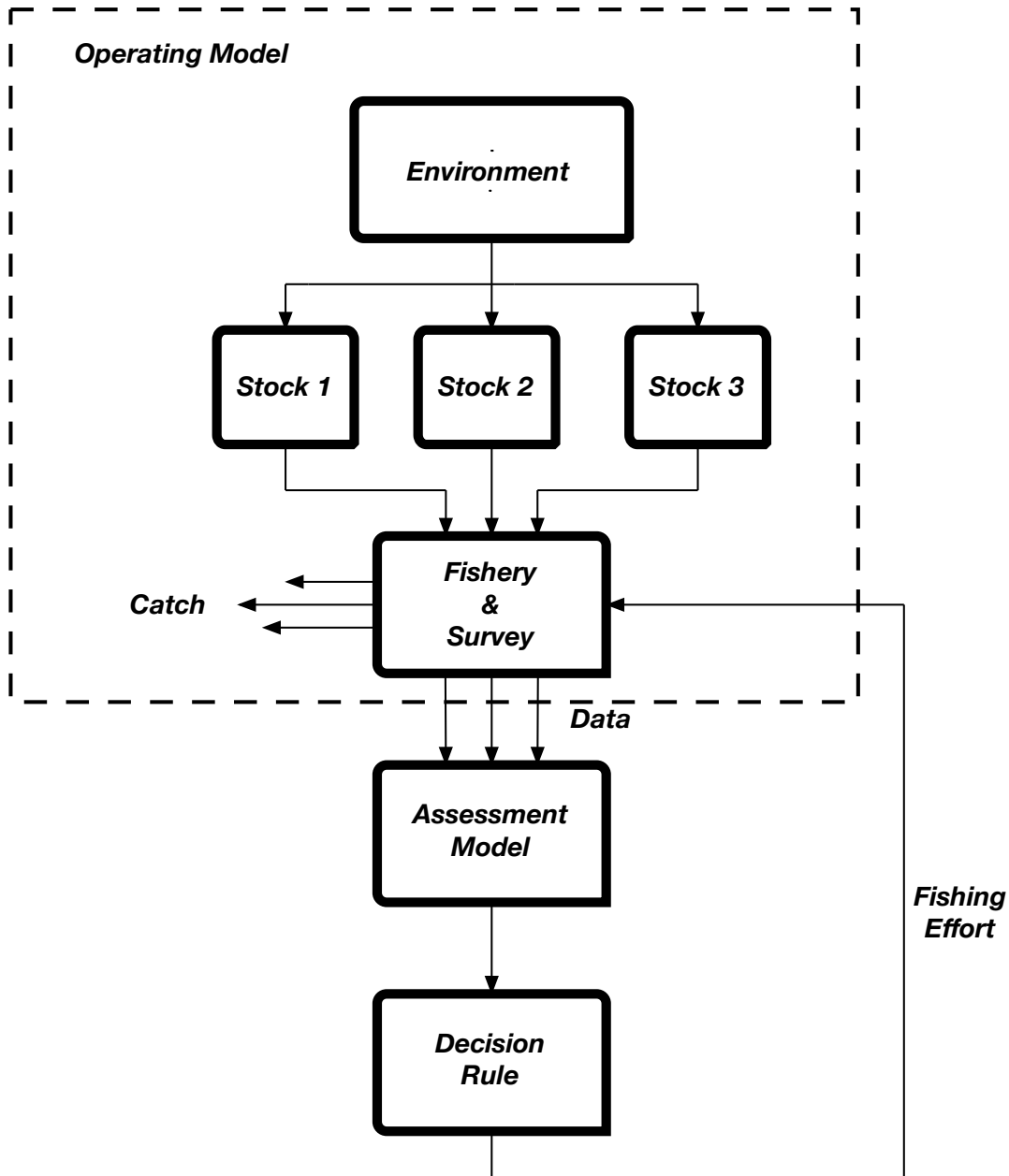| Variable	Description
	Index Variables
s	Species index
j	Stock index
f	Fleet index
t	Time index
S	Total number of species
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F	Total number of fleets
T	Total number of years
	Biological Model
$B_{s,j,t}$	Biomass of stock j of species s at time t
$B_{s,j,0}$	Unfished biomass of stock j of species s
$r_{s,j}$	Intrinsic rate of growth for stock j of speces s
$\phi_{s,j,i}$	Net migration rate between stocks j and i of species s
	Observation Model
$q_{s,j}$	Survey catchability of stock j of species s at time t
$I_{s,j,t}$	Fishery independent CPUE of stock j of species s at time t
	Catch
$E_{s,j,t,f}$	Fishing effort expended by fleet f to catch stock j of species s at time t
$C_{s,j,t,f}$	Total catch of stock j of species S at time t by fleet f
$C_{s,j,t}$	Total catch of stock j of species S at time t
$F_{s,j,t}$	Fishing mortality of stock j of species s at time t
	Stochastic Model
$\sigma^2_{s,j}$	Process error variance for stock j of species s
$\epsilon_{s,j,t}$	Process error deviation for stock j of species s at time t, $\left(\epsilon_{s,j,t} \sim N(0,\sigma^2_{s,j})\right)$
σ^2_s	Process error variance for species s
$\epsilon_{s,t}$	Process error deviation for species s at time t, $\left(\epsilon_{s,t} \sim N(0,\sigma^2_s)\right)$
σ^2	Assemblage level process error variance
ϵ_t	Assemblage level process error deviations at time t, $\left(\epsilon_t \sim N(0,\sigma^2)\right)$
τ^2_s	Observation error variance for species s
$\delta_{s,j,t}$	Observation error for stock j of species s at time t $\left(\epsilon_{s,j,t} \sim N(0,\tau^2_s)\right)$

Figure 10: A multi-species closed loop conceptual model. The operating model is oulined by the dashed line, which simulates three species with no sub-stock structure. Data generated by scientific observations and fishery exploitation at time step t is provided to the assessment model. Assessment model output is passed through a decision rule, which provides catch advice for time step $t+1$. Fishing effort is then expended according to the catch advice, closing the loop and generating new data for the assessment model.
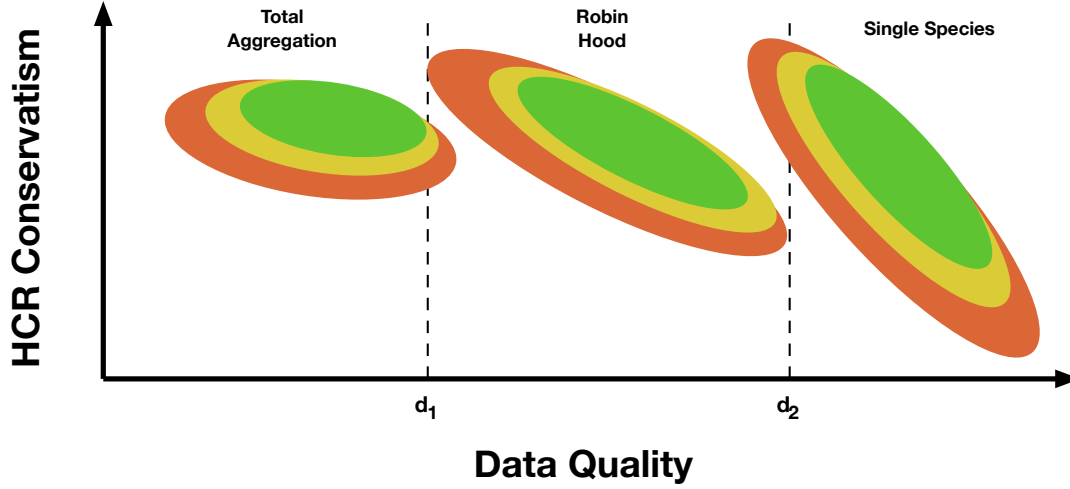
Figure 11: An example of stable risk regions for each model in Figure 6. The lines at d_1 and d_2 represent recommended data-requirement policy for each method. Green regions denote the least risky regions, with risk increasing across yellow into red. Green regions have an upper bound due to social factors, such as employment security.
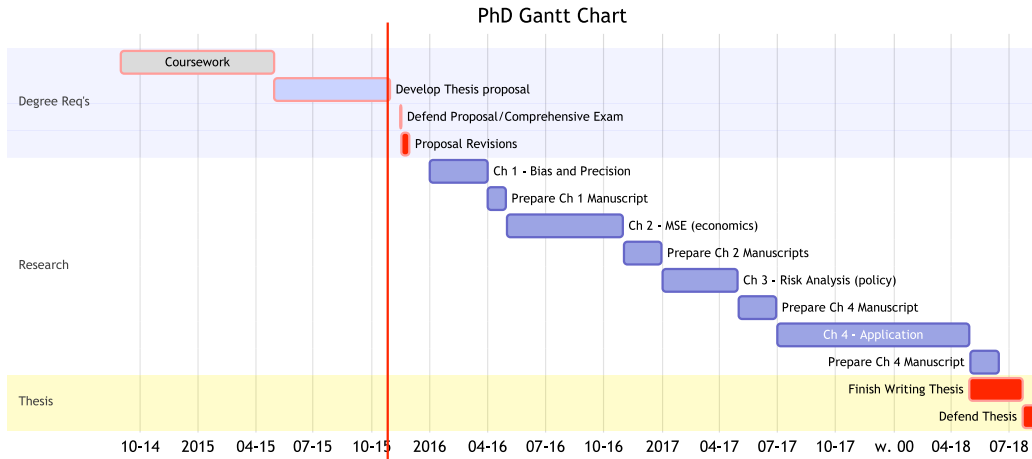

Figure 12: A Gantt chart outlining the timeline of degree requirements, research, publications and thesis writing. Estimated time of completion is July 2018.