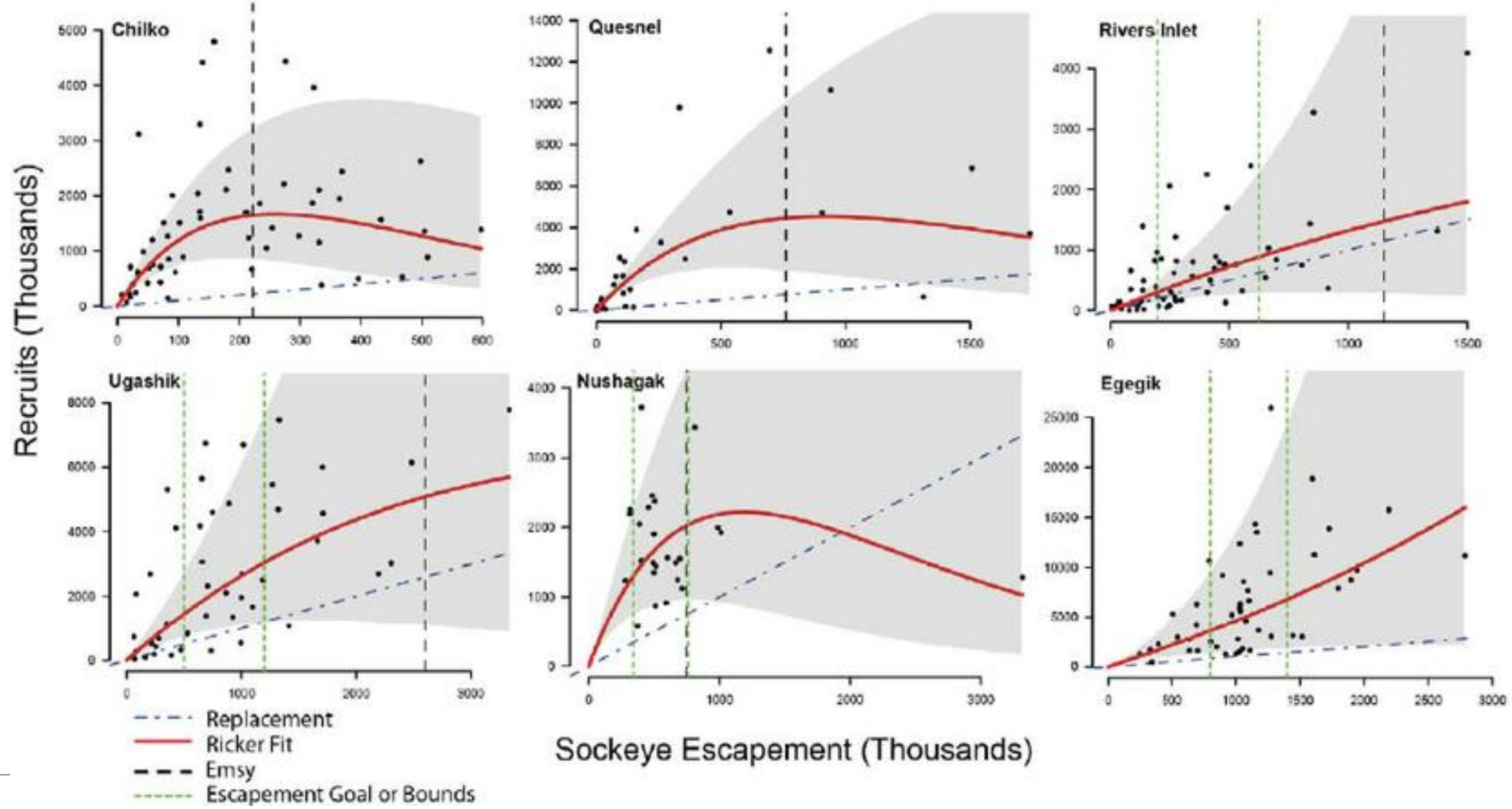

https://www.researchgate.net/figure/224050046_fig3_Fig\ure-3-Stock-recruitment-relationships-for-study-systems-fit-with-the-Ricker

Spatial Stock Assessment Methods: A Overview

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A conventional (age-structured) stock assessment (circa 2018)-I

- Age- and sex-structured population dynamics model.
- Multiple fleets (survey and fishery); fleets differ in terms of:
  - nature (e.g. recreational vs commercial);
  - gear type (e.g. trawl vs longline); and
  - location (e.g. state).
- Time-invariant natural mortality and growth.
- Selectivity and retention by fleet (and perhaps in blocks).
- Fitted to index, length-frequency, and conditional age-at-length data.

A conventional (age-structured) stock assessment (circa 2018)-II

- Data weighting for composition data based on “Francis weighting”.
- Multiple sensitivity tests to explore the consequences of uncertainty in:
  - fixed parameters;
  - data set choices; and
  - data weighting.

Outline

- What is a spatial stock assessment?
- Why spatial stock assessments?
- A brief history of spatial assessments
- Assessments and population structure
- Modelling movement
- Modelling recruitment
- Modelling growth and natural mortality
- Parameter estimation
- Multi-species spatial models
- Final thoughts

What is a spatial stock assessment?

A stock assessment that includes **multiple areas**, where the model **keeps track of the numbers by area**, i.e. the N-matrix is of the form:

$N^{A}_{y,a}$ - numbers by year, age and area

This approach to stock assessment differs from the **areas-as-fleets** approach on which most stock assessments are currently based.

What is a spatial stock assessment?

$$N_{y,a}^{s,A} = \begin{cases} R_y^{s,A} & \text{if } a = 0 \\ \sum_{s'} \sum_{A'} X_{y-1,a-1}^{s's,A',A} N_{y-1,a-1}^{s',A'} e^{-Z_{y-1,a-1}^{s,A}} & \text{otherwise} \end{cases}$$

where $N_{y,a}^{s,A}$ is the number of animals of age a of stock s in area A at the start of year y, $R_y^{s,A}$ is the recruitment (at age 0) to stock s and area A at the start of year y, $Z_{y,a}^{s,A}$ is the total mortality on animals of age a and stock s in area A during year y, and $X_{y,a}^{s',s,A',A}$ is the proportion of animals of stock s' and age a in area A' that move at the end of year y to stock s and area A (dispersal / movement).

Areas-as-fleets-I

If the length- or age-composition for the **same** gear type differs between two areas then either:

- the population is spatially homogenous, and selectivity differs between the areas (areas-as-fleets):

$$C_{y,a}^{f,A} = \frac{S_a^{f,A} F_t^{f,A}}{Z_{y,a}} N_{y,a} (1 - e^{-Z_{y,a}})$$

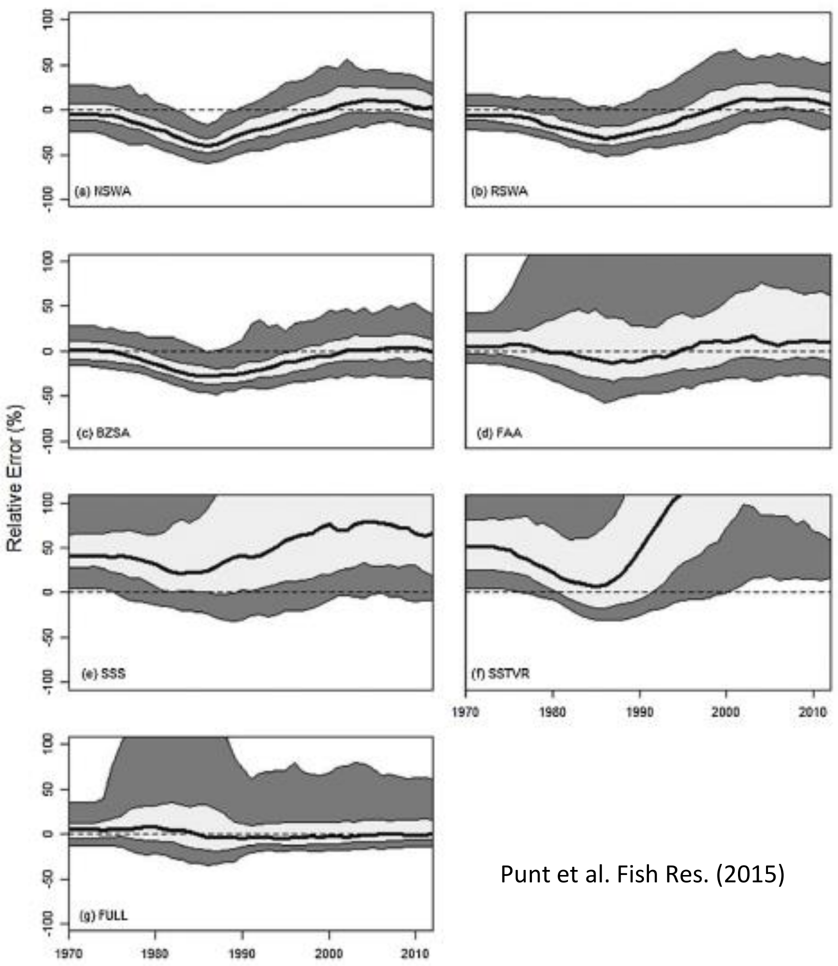
- the population is not spatially homogenous, and selectivity may not differ between the areas:

$$C_{y,a}^{f,A} = \frac{S_a^{f} F_y^{f,A}}{Z_{y,a}^{A}} N_{y,a}^{A} (1 - e^{-Z_{y,a}^{A}})$$

Areas-as-fleets vs spatial assessment

Approaches to handling spatial structure range from:

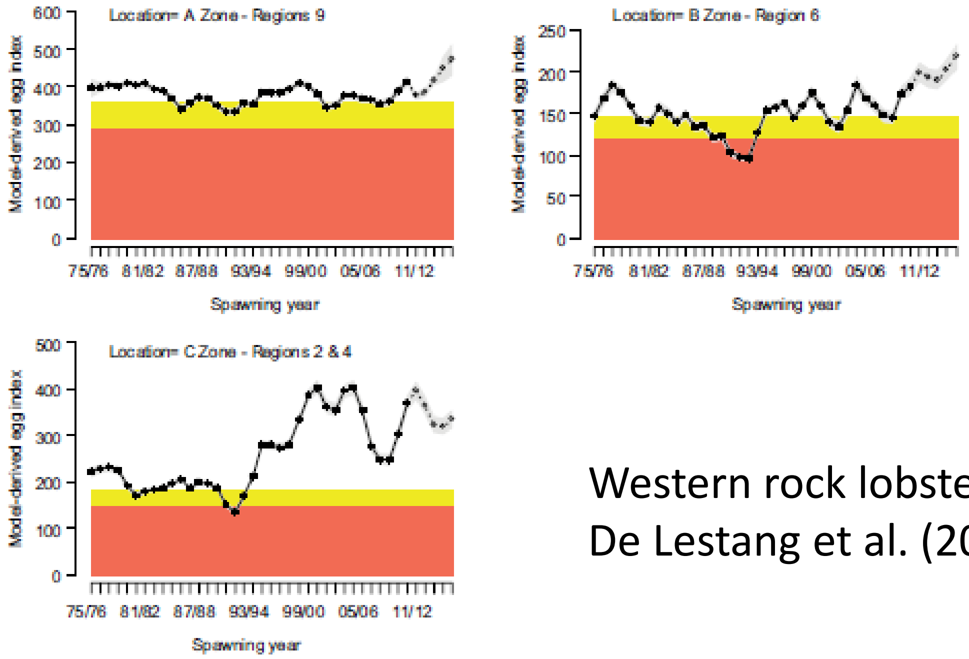
- Ignoring it and pooling over space -> bias (but achieving potentially greater precision)
- Areas-as-fleets -> lesser bias and lesser precision than ignoring spatial structure (perhaps only if selectivity in the assessment is some-shaped and time-varying)
- Spatial model -> least bias and poorest precision.



Punt et al. Fish Res. (2015)

Why spatial stock assessments?

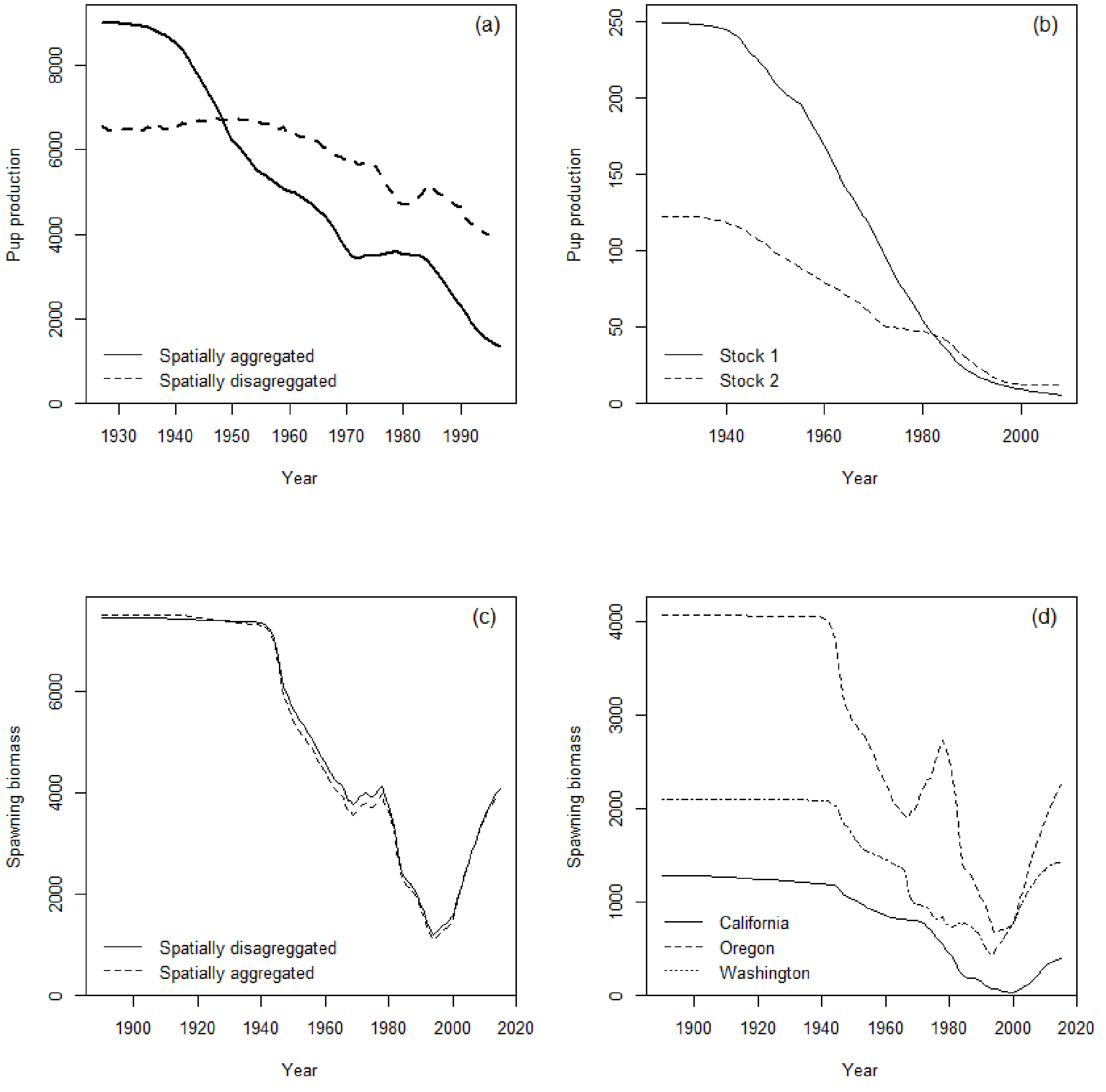
- Increased biological realism.
- Data show different trends in different areas (not explained by differences in selectivity).
- Decision makers want results reported by area.
- Desire to reduce bias due to spatial structure.



Western rock lobster
De Lestang et al. (2012)

Why spatial stock assessments?

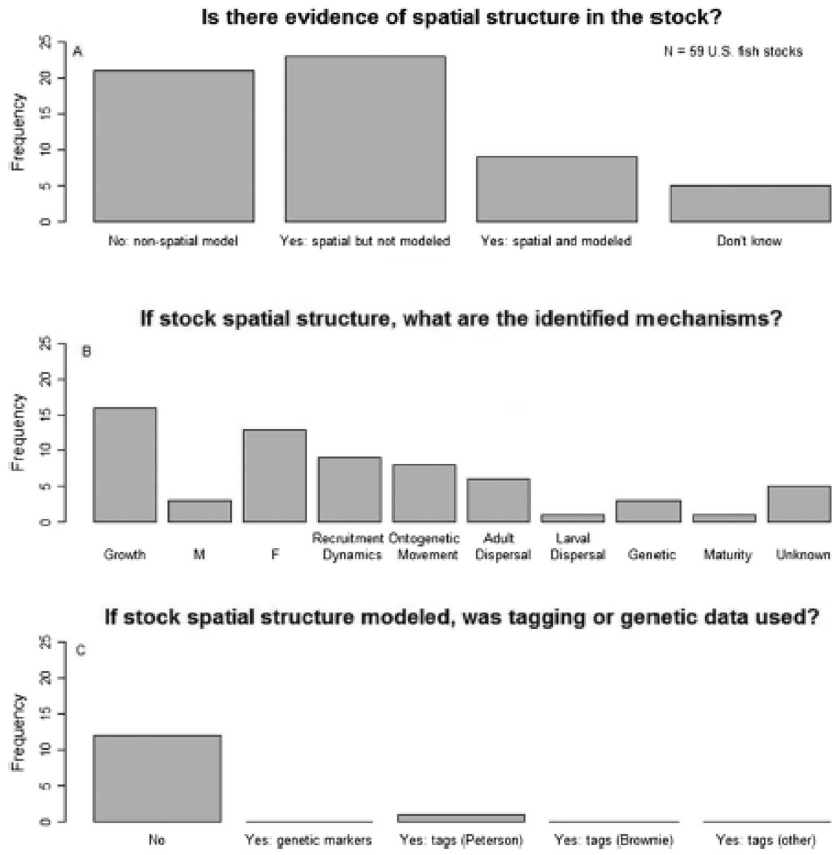
- Upper panels: School Shark
  - Left: Aggregated vs disaggregated assessments
  - Right: The two stocks
- Lower panels: Canary Rockfish
  - Left: Aggregated vs disaggregated assessments
  - Right: The three stocks



What is spatial?

The top three

- Growth.
- Fishing mortality
- Recruitment.



Berger et al.. CJFAS 2017

Core challenges for a stock assessment

- Whether and how will spatial structure be incorporated into the assessment? ✓
- How are number of areas, sexes, age- and length-classes selected?
- How are the fisheries and surveys aggregated for analysis? ✓
- Is the stock at (or close to) unfished equilibrium at the start of the modelled period?
- How is natural mortality modelled (a constant, a functional form, and age-, sex-, area -and time-varying?)? ✓
- How is growth modelled (functional form and sex-, area- and time-varying?)? ✓
- How are the growth and natural mortality parameters set (estimated or based on auxiliary analyses)? ✓
- How is movement and dispersal modelled? ✓
- Which parameters are estimated and which are pre-specified based on auxiliary information ✓
- How is account taken of the lognormal bias-correction factor?

- Is selectivity a function of age, size or both?
- Does selectivity vary over time and/or between areas and sexes? ✓
- Is selectivity domed-shaped for some or all of the fisheries and surveys? ✓
- Does catchability vary with biomass and/or over time? ✓
- How are the index data weighted?
- Are the data provided as age, length, weight composition?
- Are ageing data available in the form of conditional age-at-length?
- How are the composition data weighted? ✓
- Are recruitment deviations treated as random effects or is penalized likelihood applied? ✓
- How is uncertainty represented? ✓

A Brief History of Spatial Assessments

Stock Assessments (as we understand them; i.e. parameters being estimated from data) came to the fore in the 1970s based on (a) production models and (b) Virtual Population Analysis. The first papers to explore spatial structure (in a VPA context) were written towards the end of 1970s, but tuning methods were not applied at that time.

14731 249

J. Cons. int. Explor. Mer, 37(3): 249–260.

Sources of errors in and limitations of Virtual Population Analysis (Cohort Analysis)

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Various sources of errors in Virtual Population Analysis (VPA) are discussed. Errors in the assumed value of natural mortality create errors in estimated fishing mortalities of about the same size but with opposite sign if the total mortality varies moderately from year to year and the true natural mortality is constant. Stock size will be over- or under-estimated when natural mortility is over- or under-estimated, but estimated relative changes in stock size from year to year will be approximately correct. Fluctuations in total mortality caused by random fluctuations in natural mortality from year to year will disappear almost completely in VPA if a constant natural mortality is assumed. A trend in the true natural mortality with time or age will be converted to a trend in the VPA estimates of fishing mortalities. Relative strength of weak and strong year classes will be wrongly estimated by VPA if the true natural mortality varies with year class strength, and this may influence various regression lines commonly used for predicting year class strength from young fish survey indices. Errors in VPA caused by uneven distribution of natural or fishing mortality throughout the year are shown to be generally small and negligible. Effects of stock migration on VPA are discussed. For a year class which continuously migrates from an area A to an area B at a constant emigration rate, equations which give the number of fish of the year class at any time in each of the two areas are developed. These equations may be utilized in a technique similar to VPA for retrospective analysis, and the application of this technique is illustrated. If emigration is included in the natural mortality the traditional VPA may successfully be used in area A. There is, however, no simple way to adjust for immigration in area B, and the traditional VPA may give a completely wrong picture of the situation in this area.

Scanned by me in 1987!

A Brief History of Spatial Assessments

Assessment methods expanded in the 1980s with the introduction of Integrated Analysis (e.g. Fournier and Archibald, 1982). The first spatial integrated analysis model appears to be a generalization of CAGEAN for Pacific Halibut (Quinn et al., 1990)

Migratory Catch-Age Analysis

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Quinn, T. J. II, R. B. Deriso, and P. R. Neal. 1990. Migratory catch-age analysis. Can. J. Fish. Aquat. Sci. 47: 2315–2327.

We review techniques for estimating the abundance of migratory populations and develop a new technique based on catch-age data from geographic regions and our earlier technique, catch-age analysis with auxiliary information (Deriso et al. 1985, 1989). Data requirements are catch-age data over several years, some auxiliary information, and migration rates among regions. The model, containing parameters for year-class abundance, age selectivity, full-recruitment fishing mortality, and catchability, is fitted to data with a nonlinear least squares algorithm. We present a measurement error model and a process error model and favor the process error model because all model parameters can be jointly estimated. By application to data on Pacific halibut, the process error model converges readily and produces estimates with no significant bias. These estimates have relatively high precision compared to those from analyses which did not incorporate migration information. The error structure used in a model has a more significant impact on parameter estimates than migration rates. A sensitivity study of migration rates shows sensitivity of the order of the rates themselves.

On passe en revue les techniques d'évaluation de l'abondance des populations migratoires et on élabore une nouvelle technique fondée sur les données relatives à la prise par âge provenant des diverses régions géographiques et sur notre technique antérieure, c'est-à-dire l'analyse des prises par âge au moyen de renseignements auxiliaires (Deriso et al. 1985, 1989). Les données nécessaires sont les données sur les prises par âge portant sur plusieurs années, certaines informations auxiliaires et les taux de migration entre les régions. Le modèle, qui comprend des paramètres relatifs à l'abondance de la classe d'âge, à la sélectivité en fonction de l'âge, à la mortalité par pêche en régime de plein recrutement et à la capturabilité est ajusté aux données à l'aide d'un algorithme non linéaire des moindres carrés. Nous présentons un modèle d'erreur de mesure et un modèle d'erreur de processus; nous préférons le modèle d'erreur de processus, car tous les paramètres de ce modèle peuvent être évalués conjointement. Lorsqu'il est appliqué à des données sur le flétan du Pacifique, le modèle d'erreur de processus converge facilement et produit des estimations sans erreur appréciable. Ces estimations ont une précision relativement élevée par rapport à celles des analyses qui ne comportaient pas de données sur la migration. La structure d'erreur employée dans un modèle a un impact plus appréciable sur les estimations des paramètres que les taux de migration. Une étude de la sensibilité des taux de migration montre une sensibilité de l'ordre des taux eux-mêmes.

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A Brief History of Spatial Assessments

The early 2000s (and subsequently) saw the development of variety of spatial assessments (that were used for management purposes).

A spatially disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean

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Abstract. A spatially disaggregated, length-based, age-structured model for yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean is described. Catch, effort, length-frequency and tagging data stratified by quarter (for the period 1962–99), seven model regions and 16 fisheries are used in the analysis. The model structure includes quarterly recruitment in each region, 20 quarterly age classes, independent growth patterns for juveniles and adults, structural time-series variation in catchability for all non-longline fisheries, age-specific natural mortality, and age-specific movement among the model regions. Acceptable fits to each component data set comprising the log-likelihood function were obtained. The model results suggest that declines in recruitment, and as a consequence, population biomass, have occurred in recent years. Although not obviously related to over-exploitation, the recruitment decline suggests that the productivity of the yellowfin tuna stock may currently be lower than it has been previously. Recent catch levels appear to have been maintained by increases in fishing mortality, possibly related to increased use of fish aggregation devices in the purse-seine fishery. A yield analysis indicates that average catches over the past three years may have slightly exceeded the maximum sustainable yield. The model results also reveal strong regional differences in the impact of fishing. Such heterogeneity in the fisheries and the impacts on them will need to be considered when future management measures are designed.

Additional keywords: length-based model, statistical age-structured model, spatial model, stock assessment

Stock assessment of school shark, *Galeorhinus galeus*, based on a spatially explicit population dynamics model

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Abstract. The school shark (*Galeorhinus galeus*) resource off southern Australia is assessed by use of an assessment approach that takes account of the spatial structure of the population. The population dynamics model underlying the assessment considers the spatial as well as the age-specific characteristics of school shark. It allows for a series of fisheries (each based on a different gear type), explicitly models the pupping/recruitment process, and allows for multiple stocks. The values for the parameters of this model are determined by fitting it to catch-rate data and information from tagging studies. The point estimates of the pup production at the start of 1997 range from 12% to 18% of the pre-exploitation equilibrium size, depending on the specifications of the assessment. Allowing for spatial structure and incorporating tag release–recapture data lead to reduced uncertainty compared with earlier assessments. The status of the resource, as reflected by the ratio of present to virgin pup production and total (1+) biomass, is sensitive to the assumed level of movement between the stocks in New Zealand and those in Australia, with lower values corresponding to higher levels of movement.

A Brief History of Spatial Assessments

The early 2000s (and subsequently) also saw the development of spatial models (fitted) to data to form the basis for management strategy evaluations (usually to assess the consequences of ignoring spatial variation in growth) as well as to provide the basis for assessments of stock status and to calculate catch limits.

Packages that allow for spatial structure

- CASAL & CASAL2
  - Used in New Zealand and CCAMLR (hoki etc)
- GADGET
  - Used in Iceland (cod, saithe, etc.)
- MULTIFAN
  - Used extensively for tuna, particularly in the Pacific
- Stock Synthesis
  - Used widely, but relatively few spatial applications at this point
- SPM
  - Under development, but spatially very complex.

Table 2
Summary of how recruitment is modelled. The symbols 'MFCL' and 'SS' refer to MULTIFAN-CL and Stock Synthesis, respectively.

Stock	S-R relationship	Stochastic deviations	Movement	Other
General approaches				
CASAL	Flexible	Annual by stock	Post-recruitment	All recruitment is to one area
GADGET	Flexible	Annual by area and stock	Post-recruitment	
MULTIFAN-CL	Constant	Annual deviations; mean proportion by area and spatial annual deviations	Post-recruitment	
SPM	Variable (local and block)	Annual	Post-recruitment	Allocation to area depends on user-specified variable
Stock Synthesis	Beverton-Holt, Ricker, Shepherd (annual)	Annual by area and stock	Post-recruitment	
Fishfishes				
Tunas and billfish				
Bluefin tuna[1]	None	Annual by area	VPA based with mixing.	
Bluefin tuna[2]	Beverton-Holt by stock	Annual by stock	Stock-specific density-dependence migration	
Bluefin tuna[3]	Beverton-Holt by stock	Quarterly by area	Post-recruitment	All recruitment to the Western North Pacific only
Swordfish (MFCL)[1]	Beverton-Holt (annual)	Annual by area	Post-recruitment	
Swordfish (SS)[2]	Beverton-Holt (annual)	Annual by area	Post-recruitment	All recruitment during quarter 1; movement post-recruitment was pre-specified to be low.
Albacore tuna (MFCL)	Beverton-Holt (annual)	Quarterly by area	Post-recruitment	
Bigeye tuna (MFCL)	Beverton-Holt (annual)	Quarterly by area	Post-recruitment	
Yellowfin tuna (MFCL)	Beverton-Holt (annual)	Quarterly by area	Post-recruitment	
Skipjack tuna (MFCL)	Beverton-Holt (annual)	Quarterly by area	Post-recruitment	
Other stocks				
European hake	None	Annual by area	Post-recruitment	
European eel	Recruitment auto-correlated (AR-1)	Dirichlet-Multinomial by zone; proportional to catchment area within zones		
Yellowtail flounder	Mean by stock	Annual by area	Post-recruitment	
Walleye pollock	Mean by area	Annual by area	Post-recruitment	
School shark	Pella-Tomlinson by stock	None	Post-recruitment	
Pink ling (SS)	Beverton-Holt	Annual (with/without area)		
Pacific halibut	None		Post-recruitment	VPA based with mixing
Hoki (CASAL)	Beverton-Holt by stock	Annual	Post-recruitment	All recruitment to nursery grounds
Snapper (CASAL)	Beverton-Holt by stock	Annual	Post-recruitment	Stock-recruitment parameters spatially
Gummy shark	Pella-Tomlinson by stock	Annual by stock	None	Stock-recruitment parameters spatially
Yelloweye rockfish (SS)	Beverton-Holt	Time-invariant spatial allocation	None	
Canary rockfish (SS)	Beverton-Holt	Annual by area	None	
Red snapper	Beverton-Holt by area	Annual by area	Post-recruitment	
Gag grouper	Beverton-Holt by area	Annual by area	Post-recruitment	
Cape hake	Beverton-Holt by stock	Annual	Post-recruitment	
Coral trout	Beverton-Holt by stock; fixed spatial allocation	Annual		Areas are MPA/fished areas
Red snapper (SS)	Beverton-Holt	Annual by area	None	
Invertebrates				
Rock lobster				
Southern rock lobster (New Zealand, South Australia)	Mean by area	Annual by area	Post-recruitment	
Western rock lobster	Mean by area	Annual by area	Post-recruitment	penalty on spatial differences in log-recruitment
American lobster	Beverton-Holt or Ricker by area	Annual by area		
Prawns and shrimp				
Nylon shrimp	Beverton-Holt (by area or spatially-aggregated)	Annual by area	Post-recruitment	
Tiger prawns	Ricker by area	Annual by area	None	Allowance for spatial correlation in deviations for projection
Eastern king prawns	Ricker by area	Annual by area	None	Allowance for spatial correlation in deviations for projection
Other stocks				
Abalone	Beverton-Holt by area	None	Post-recruitment	Inshore and offshore strata
Snow crab	Mean by area	Annual by area	Post-recruitment	
Marine mammals				
Minke whales[1]	Pella-Tomlinson by stock	None	Mixing matrices	Recruitment to an area not in the model
Minke whales[2]	Pella-Tomlinson by stock	None	Mixing matrices	Recruitment to an area not in the model
Minke whales[3]	Pella-Tomlinson by stock	Annual by stock	Mixing matrices	Recruitment to an area not in the model
Bryde's whales	Pella-Tomlinson by stock	None	Mixing matrices	Recruitment to an area not in the model
Fin whales	Pella-Tomlinson by stock	None	Mixing matrices	Recruitment to an area not in the model
Humpback whale[1]	Pella-Tomlinson by stock	None	Mixing matrices	Recruitment to an area not in the model
Humpback whale[2]	Schaefer by stock	None	Mixing matrices	Recruitment to an area not in the model

(continued on next page)

Table 1 (*continued*)

Species/stock	Key Reference	Notes
Bryde's whale, *Balaenoptera brydei* (Western North Pacific)	IWC (2008)	1 or 2 stocks (some with sub-stocks); two sub-areas
Fin whale, *Balaenoptera physalus* (North Atlantic)	IWC (2017)	3 or 4 stocks (some with sub-stocks); seven sub-areas
Humpback whale, *Megaptera novaeangliae* (North Atlantic)[1]	Punt et al. (2006)	2 stocks; 7 sub-areas
Humpback whale, *Megaptera novaeangliae* (Oceana)[2]	Ross-Gillespie et al. (2014, 2015)	3 stocks
Gray whale, *Eschrichtius robustus* (North Pacific)	Punt (2016)	1 or 2 stocks (some with sub-stocks); 13 sub-areas

Stock assessments are used:

- to provide management advice; and
- as the basis for Management Strategy Evaluation.

Spatial stock assessments have been developed for:

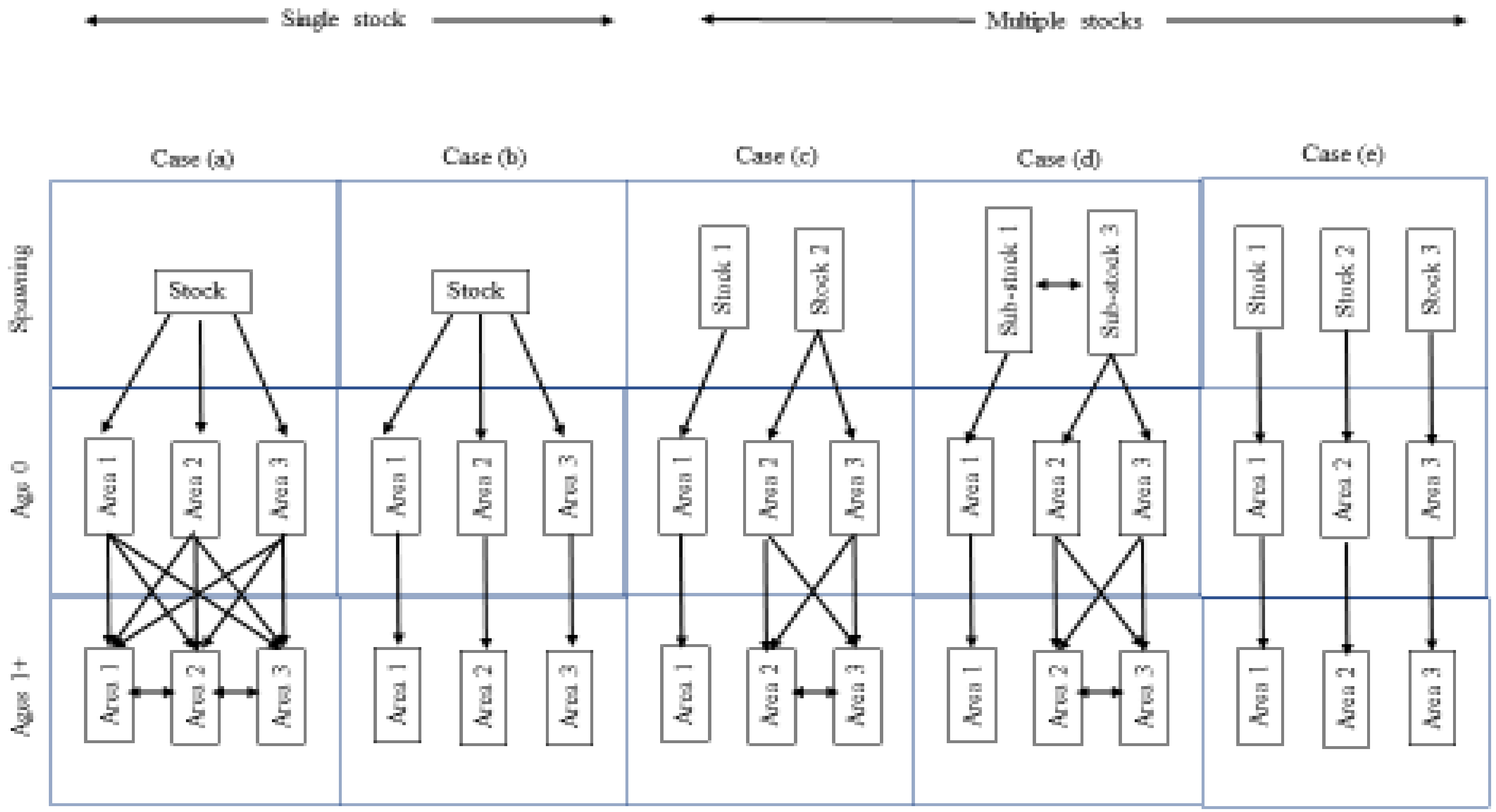
- finfish (including sharks);
- invertebrates; and
- marine mammals.

Assessments and Structure-I

Spatial structure means asking questions about population structure

- How many “stocks” (or “sub-stocks”) in the region to be assessed
  - **Stocks**: demographically-independent population units.
  - **Sub-stocks**: some dispersal among population units so the dynamics of one sub-stock are not independent on those of others.
- How are the population components in different areas linked:
  - Dispersal: Transfer of individuals **between stocks** (or sub-stocks)
  - Movement: Permanent (or non-permanent) movement of animals **within a stock**.

Assessments and Structure-II



Five alternative population structure hypotheses depending on:

- the number of stocks
- how animals in different areas are linked.

Example 1: Single stock

Yellowfin tuna in Indian Ocean

- Four areas
- Beverton-Holt (quarterly) recruitment
- Estimated post-recruitment movement rates

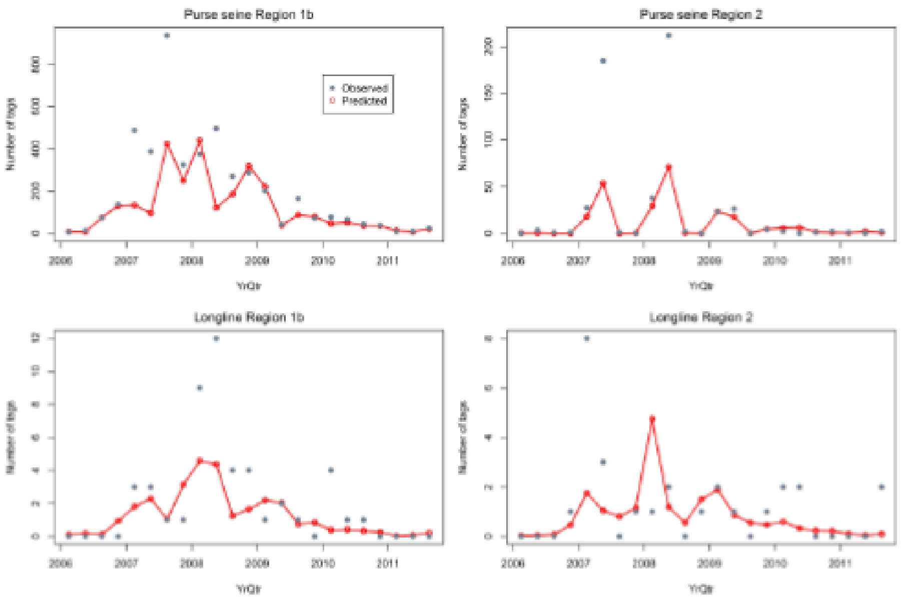
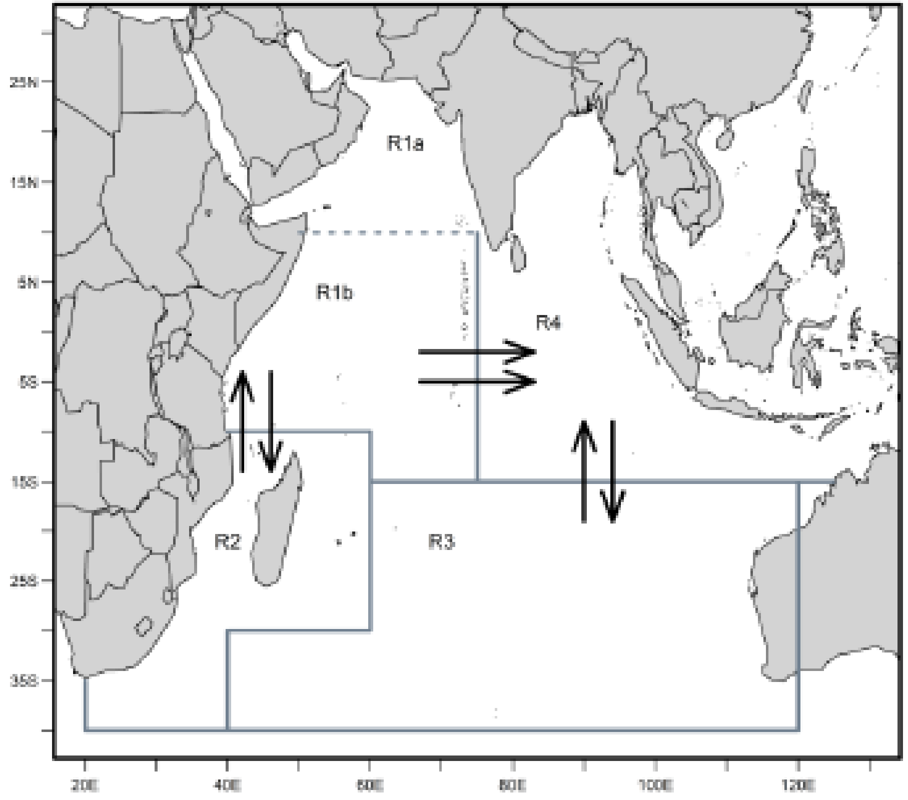


Figure 19. Observed and predicted number of tags recovered by quarter for the main method, region fisheries recovering tags. Only tags at liberty after the three quarter mixing period are included. Tag recoveries are aggregated from the regional purse seine free-school and log fisheries.



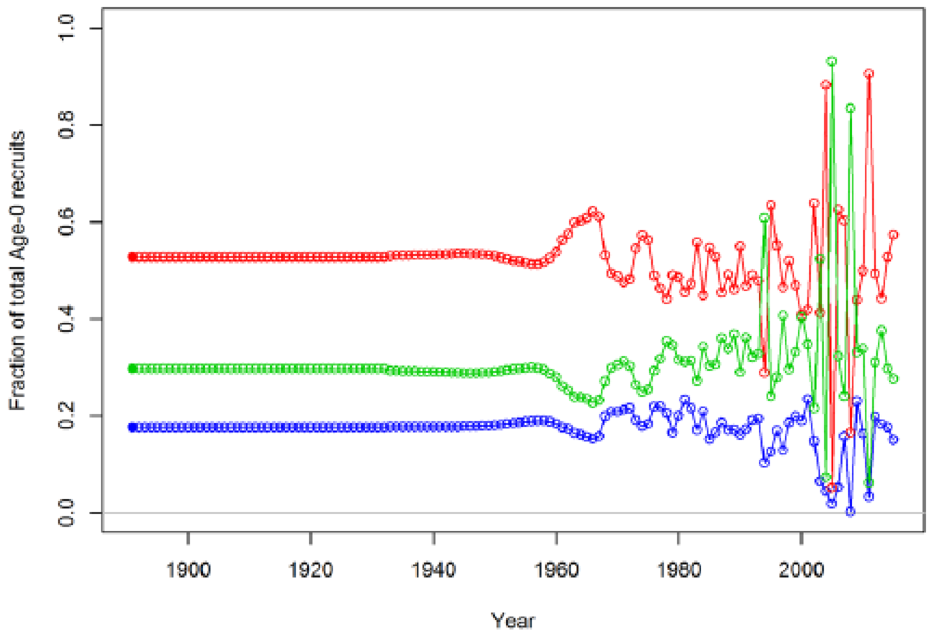
Langley et al. (2015)

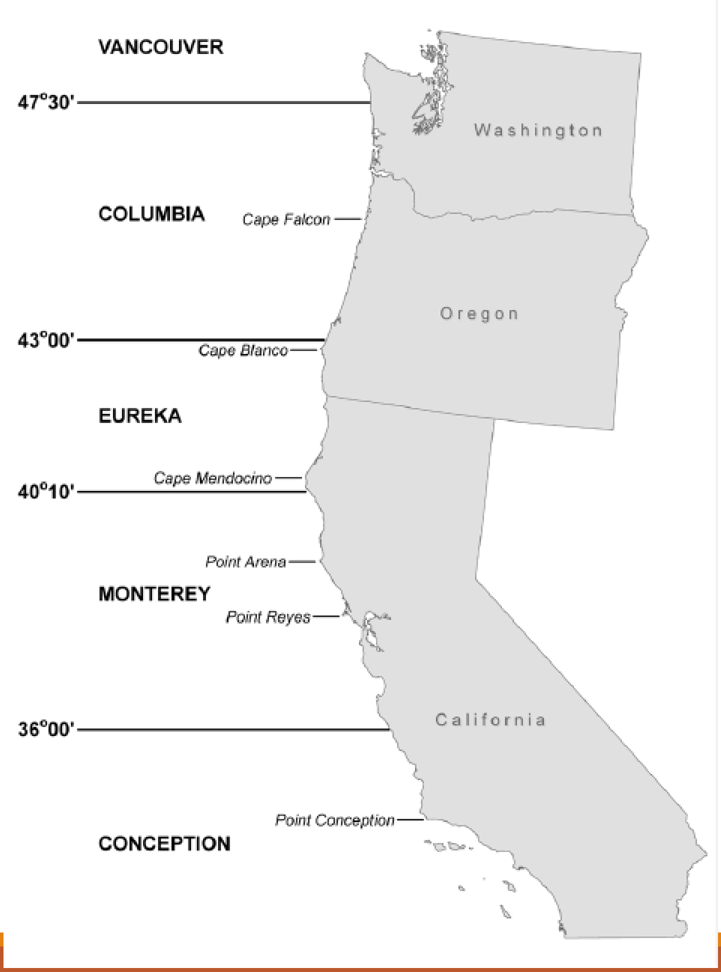
Example 2: Single stock

Canary rockfish off the US west coast

- Three areas
- Beverton-Holt recruitment
- No post-recruitment movement

Figure 109 – Fraction of recruitment distributed among states (blue: CA, red: OR, green: WA)

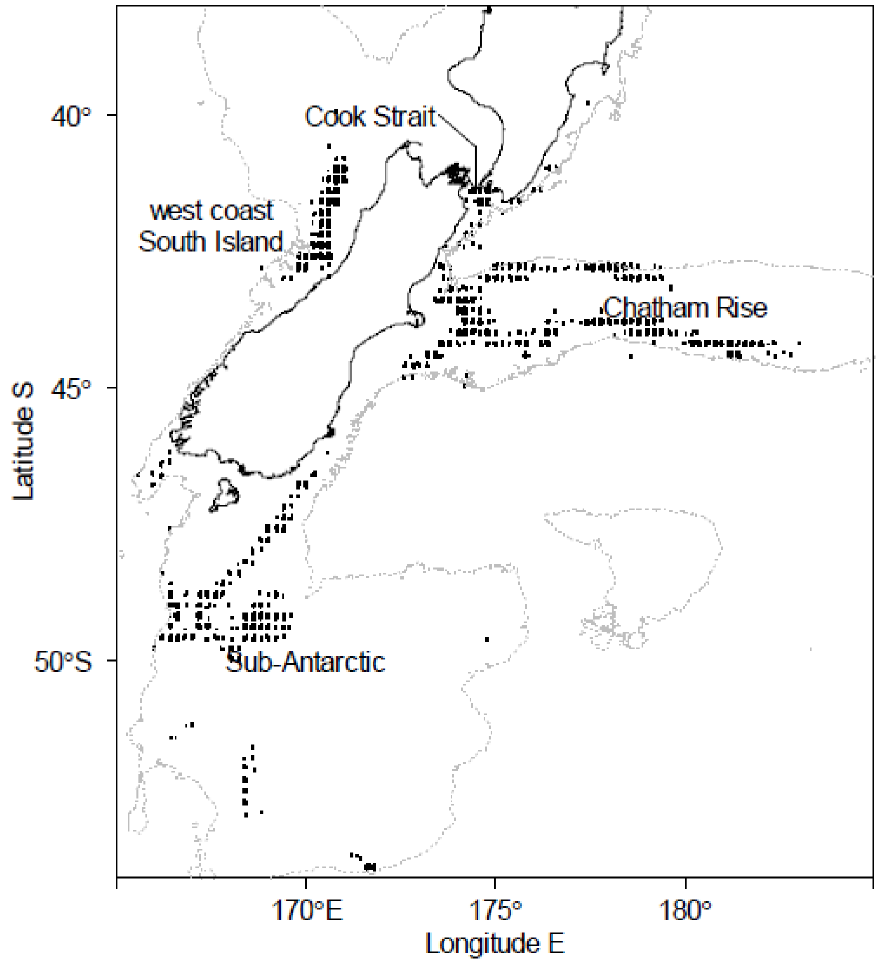




Example 3: Multiple stocks

Hoki off New Zealand

- Two stocks; four areas
- Migrations (West)
  - Oct-Dec: West Coast -> Sub-Antarctic
  - Dec-Mar: Recruitment to Chatham Rise
  - Apr-Jun: Chatham Rise -> Sub-Antarctic
  - End June: Sub-Antarctic -> West Coast
- Migrations (East)
  - Oct-Dec: Cook Strait -> Chatham Rise
  - Dec-Mar: Recruitment to Chatham Rise
  - End June: Chatham Rise -> Cook Strait
- No dispersal between stocks

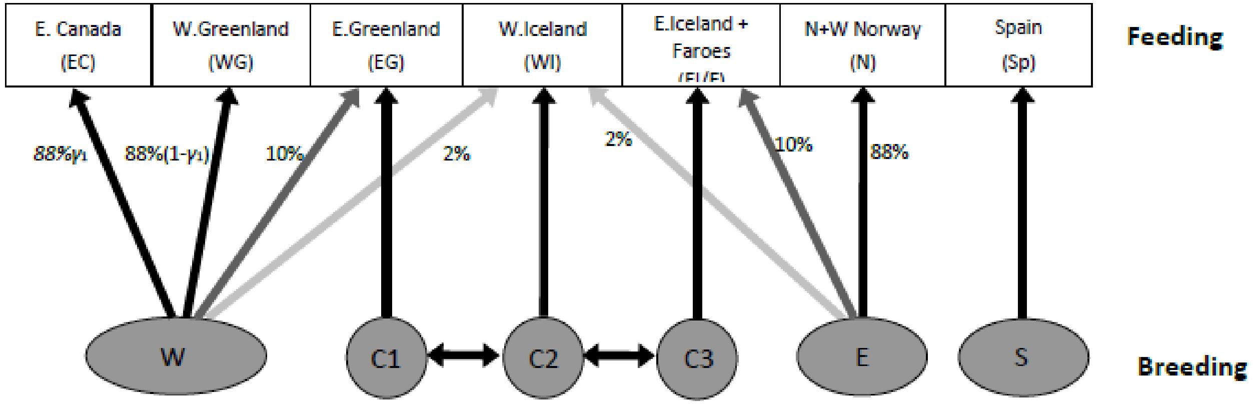


Example 4: Multiple stocks

Fin Whales in the North Atlantic

- Seven areas.
- Four stocks (one of which consists of three sub-stocks).
- Dispersal among sub-stocks estimated using tagging data.

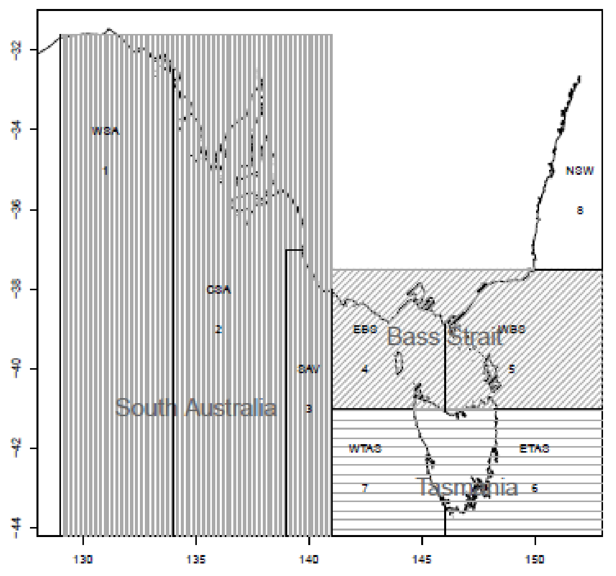
Hypothesis (II). 4 breeding stocks with the W and E stocks also feeding in the central sub-areas.

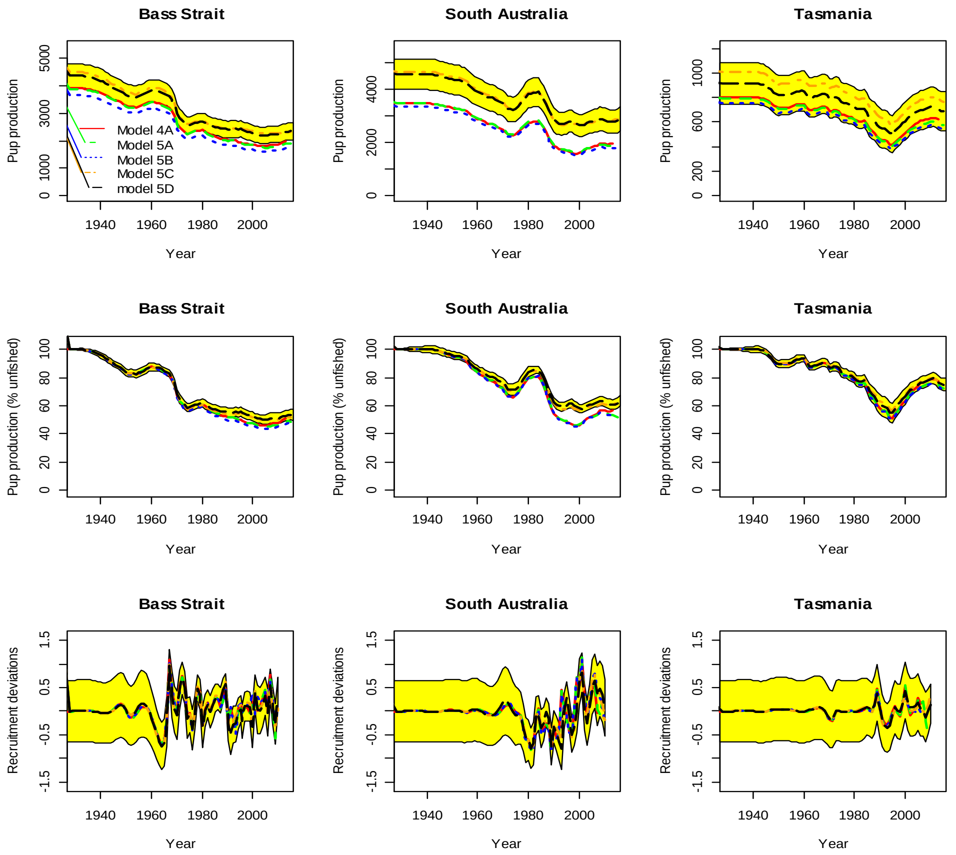


Example 5: Multiple stocks

Gummy Shark off southern Australia

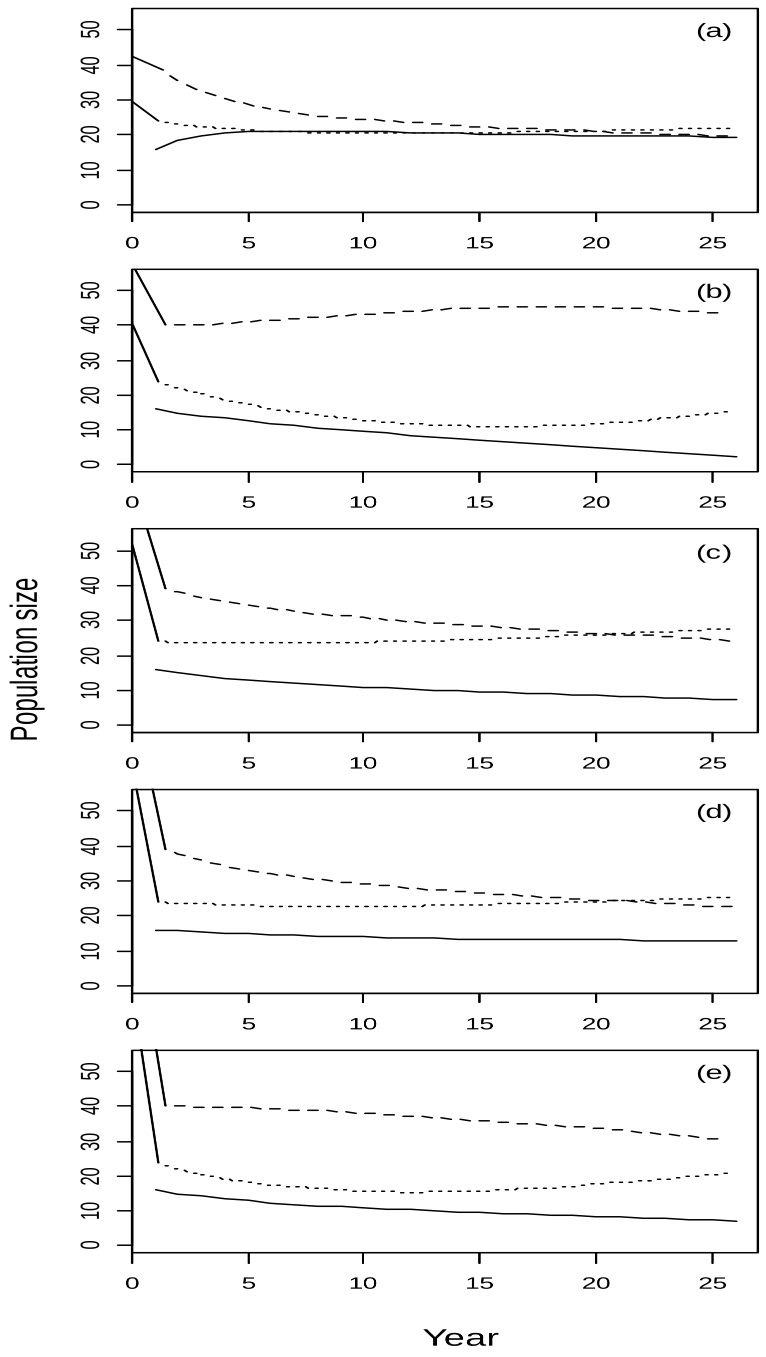
- Three areas and three stocks
- The stocks are independent
- Some of the parameters are shared among stocks.



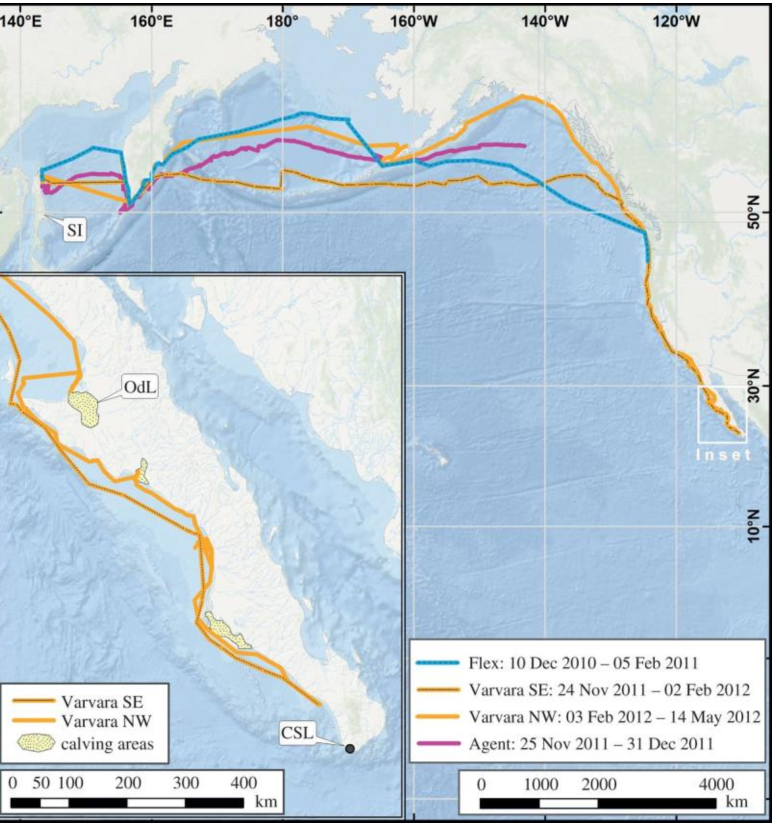


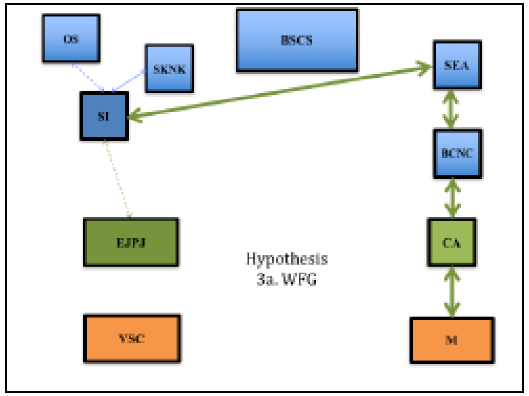
Does it matter?

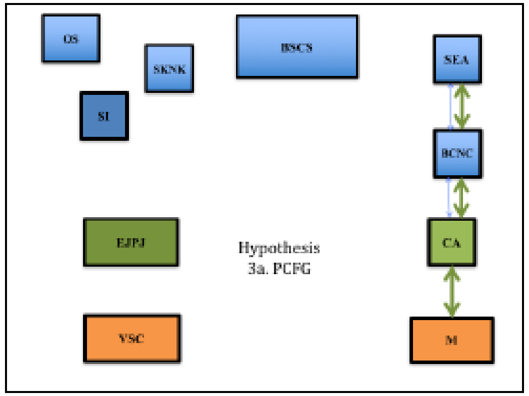
- Three areas and (a-b) one stock; and (c-e) two stocks
- Production model with r=0.2
- Areas 1 and 2 and 3 are initially 20%, 50% and 30% of K.
- Catches:
    - Constant in area 1
    - Increasing in area 2
    - Decreasing in area 3



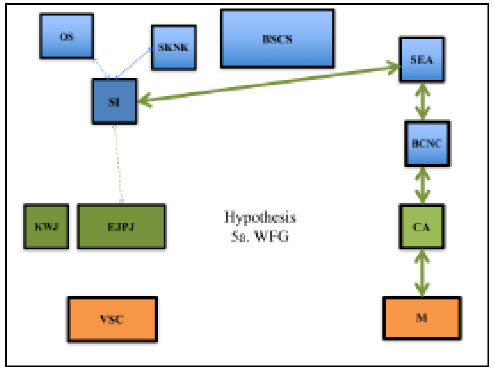
The Gray Whales (look out of window)

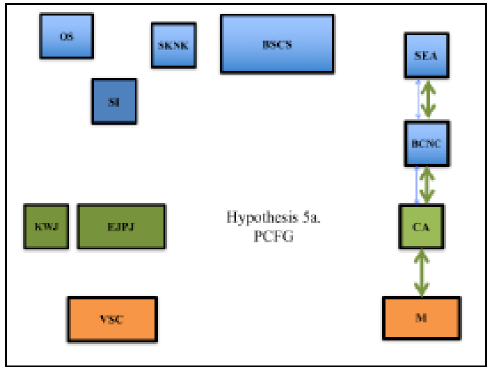


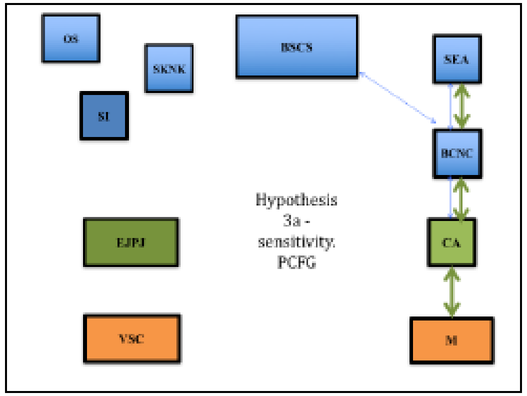


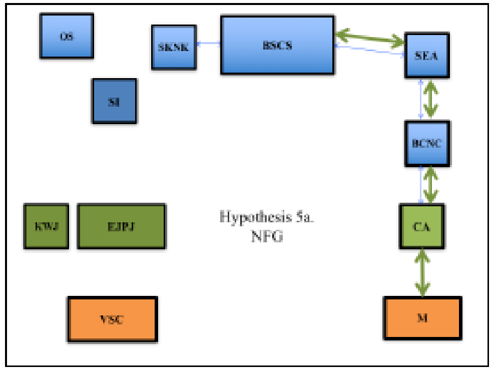


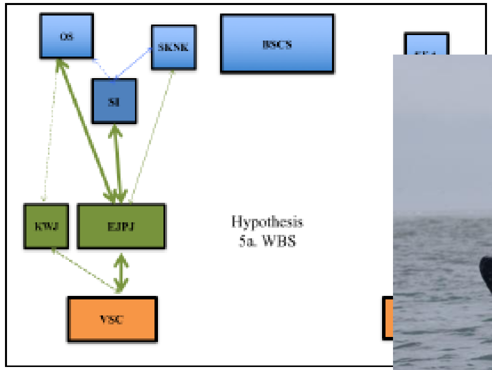
Hypothesis 5a:











The Gray Whales (look out of window)

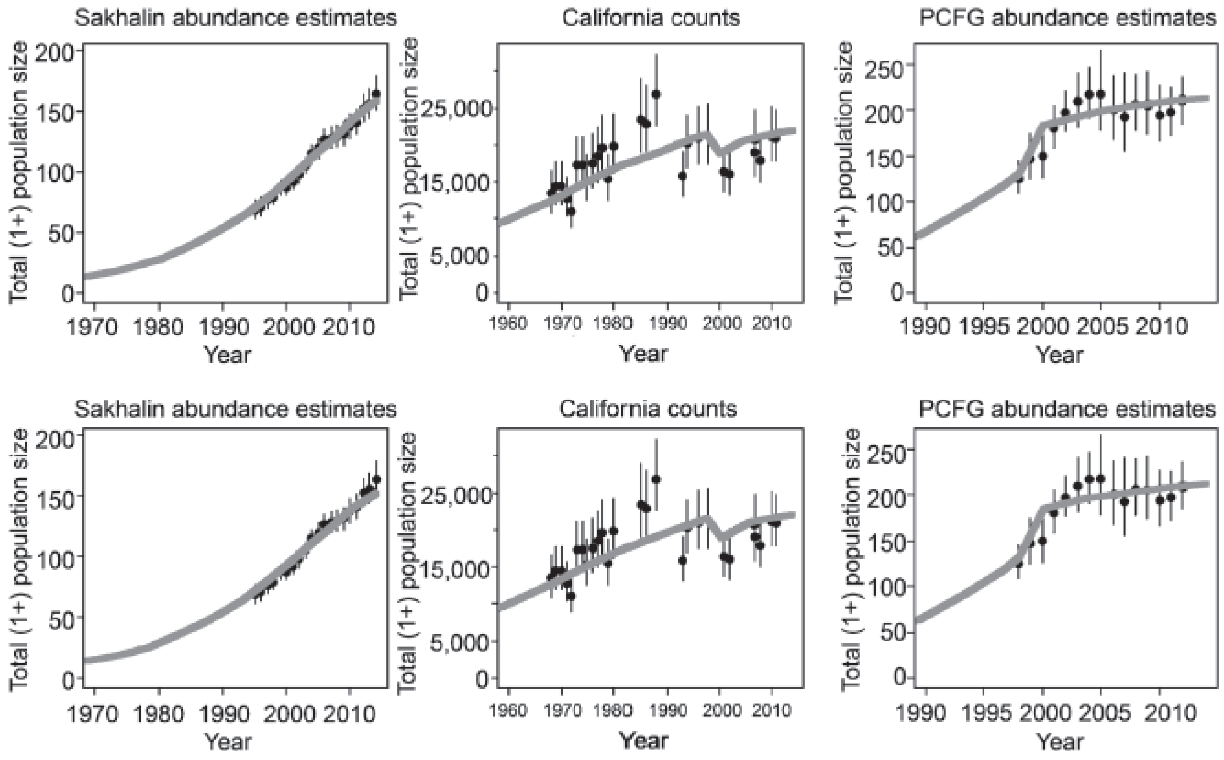


Table 1

The presence matrices for stock structure hypotheses 3a, 3b, 3c, 3e, 5a and 6b.

[a] Hypothesis 3a (no extant Western breeding stock)

Breeding stock/ Feeding Aggregation	Sub-area													
	VSC	KWJ	EJPJ	OS	SI	SKNK	BSCS	SEA (J-N)	SEA (D-M)	BCNC (J-N)	BCNC (D-M)	CA (J-N)	CA (D-M)	M
Eastern														
WFG			1	1	1	1			1		1		1	1
North			1			1	1	1	1	1	1	1	1	1
PCFG							1[A]	1	1	1	1	1	1	1

A: Sensitivity test (12) only

[b] Hypothesis 3b (extant Western breeding stock)

Breeding stock/ Feeding Aggregation	Sub-area													
	VSC	KWJ	EJPJ	OS	SI	SKNK	BSCS	SEA (J-N)	SEA (D-M)	BCNC (J-N)	BCNC (D-M)	CA (J-N)	CA (D-M)	M
Western	1	1	1	1		1								
Eastern														
WFG				1	1	1			1		1		1	1
North			1				1	1	1	1	1	1	1	1
PCFG								1	1	1	1	1	1	1

[c] Hypothesis 3c (no extant Western breeding stock; WFG in BSCS)

Breeding stock/ Feeding Aggregation	Sub-area													
	VSC	KWJ	EJPJ	OS	SI	SKNK	BSCS	SEA (J-N)	SEA (D-M)	BCNC (J-N)	BCNC (D-M)	CA (J-N)	CA (D-M)	M
Eastern														
WFG			1	1	1	1	1		1		1		1	1
North			1			1	1	1	1	1	1	1	1	1
PCFG								1	1	1	1	1	1	1

[d] Hypothesis 3e (extant Western breeding stock; WFG in EJPJ)

Breeding stock/ Feeding Aggregation	Sub-area													
	VSC	KWJ	EJPJ	OS	SI	SKNK	BSCS	SEA (J-N)	SEA (D-M)	BCNC (J-N)	BCNC (D-M)	CA (J-N)	CA (D-M)	M
Western	1	1	1	1		1								
Eastern														
WFG			1	1	1	1			1		1		1	1
North						1	1	1	1	1	1	1	1	1
PCFG								1	1	1	1	1	1	1

[e] Hypothesis 5a (Western breeding stock in SI)

Breeding stock/ Feeding Aggregation	Sub-area													
	VSC	KWJ	EJPJ	OS	SI	SKNK	BSCS	SEA (J-N)	SEA (D-M)	BCNC (J-N)	BCNC (D-M)	CA (J-N)	CA (D-M)	M
Western	1	1	1	1	1	1								
Eastern														
WFG			1	1	1	1			1		1		1	1
North						1	1	1	1	1	1	1	1	1
PCFG							1[A]	1	1	1	1	1	1	1

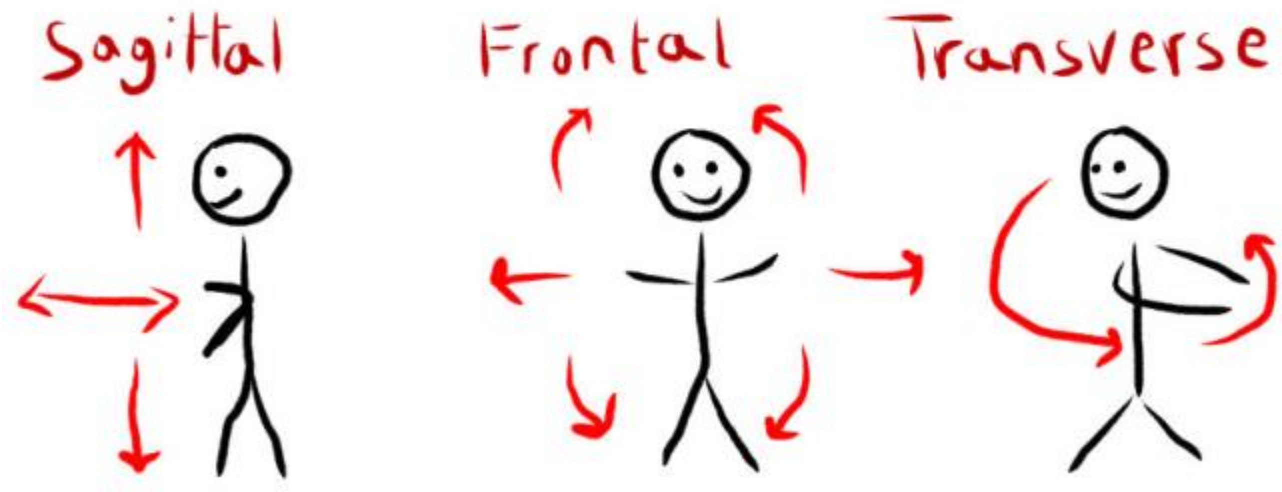
A: Sensitivity test (12) only

[f] Hypothesis 6b (no Western feeding group)

Breeding stock/ Feeding Aggregation	Sub-area													
	VSC	KWJ	EJPJ	OS	SI	SKNK	BSCS	SEA (J-N)	SEA (D-M)	BCNC (J-N)	BCNC (D-M)	CA (J-N)	CA (D-M)	M
Western	1	1	1	1	1	1			1		1		1	1
Eastern														
North						1	1	1	1	1	1	1	1	1
PCFG								1	1	1	1	1	1	1

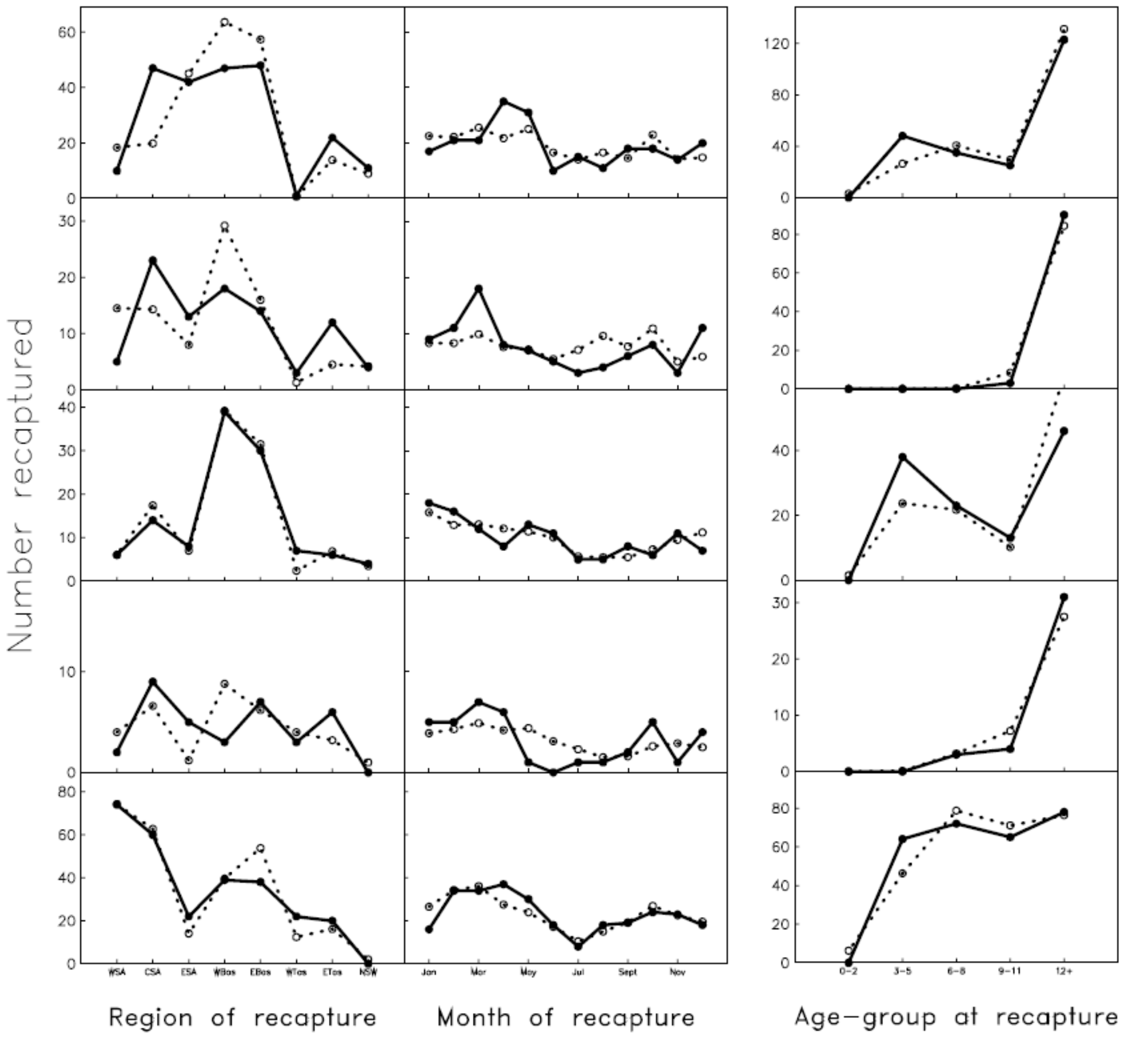
Modelling movement

- Diffusion / advection models, with most analyses (e.g. MULTIFAN-based assessments) based on diffusive movement.
- Models that specify where each age-class is at each time-step (i.e. the ”mixing matrix” approach).



Modelling movement-I

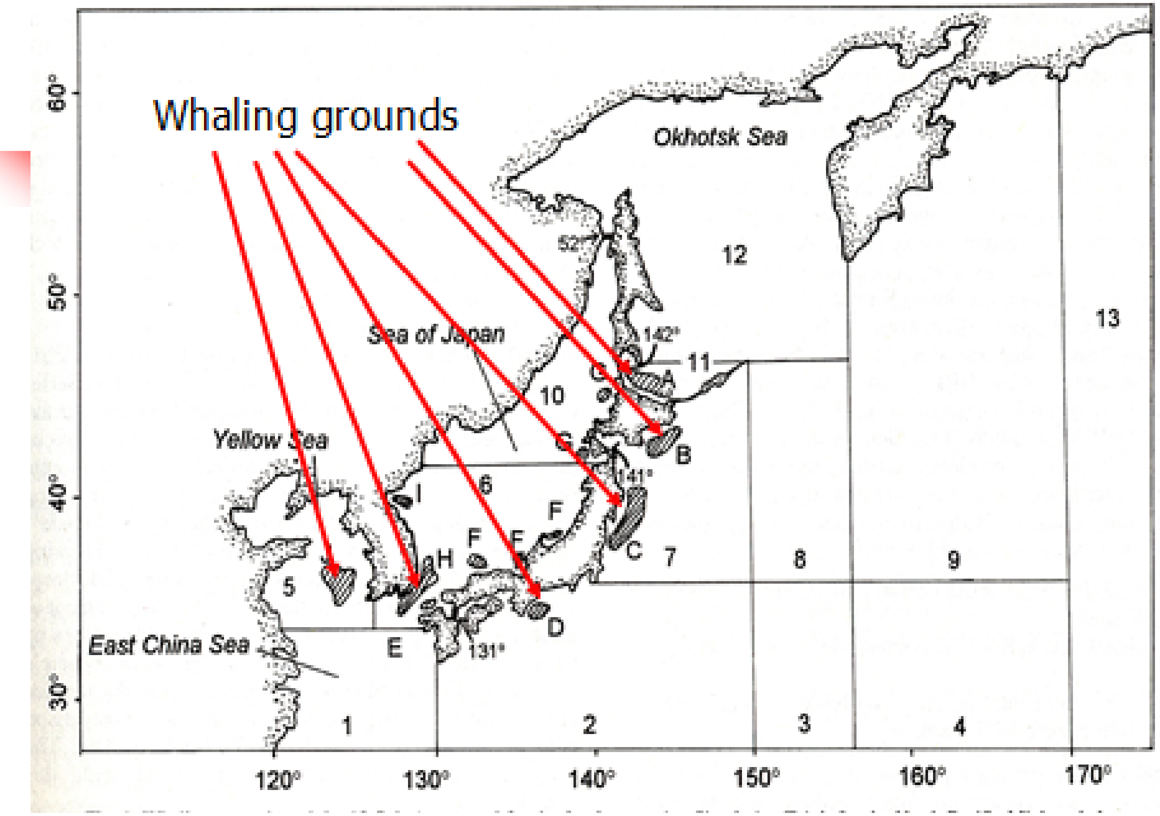
It is almost never possible to model the matrix **X** in its full generality (Punt et al. 2000 tried this because using a conceptual [and daily] model to determine an initial choice for **X** and then modifying **X**, which depended on month, based on fits to data, including tagging data).



Modelling movement-II

The model developed for minke whales in the NE Pacific “places” the whales by stock, age and sex in each cell.

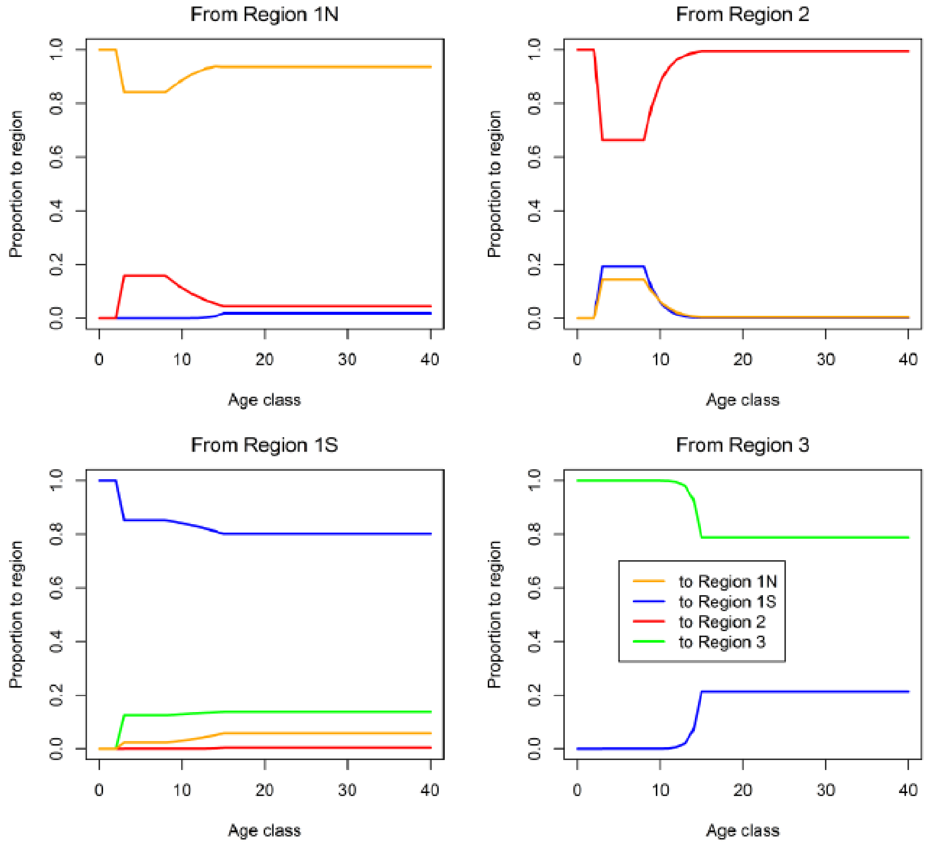
Note that this model was used as a spatial operating model for MSE work – where the management strategy is “non-spatial”



Modelling movement-III

Most models now model movement using transition matrices for which (for a given sex and age), the parameters are logit-transformed (and may depend on covariates, using age and sex)

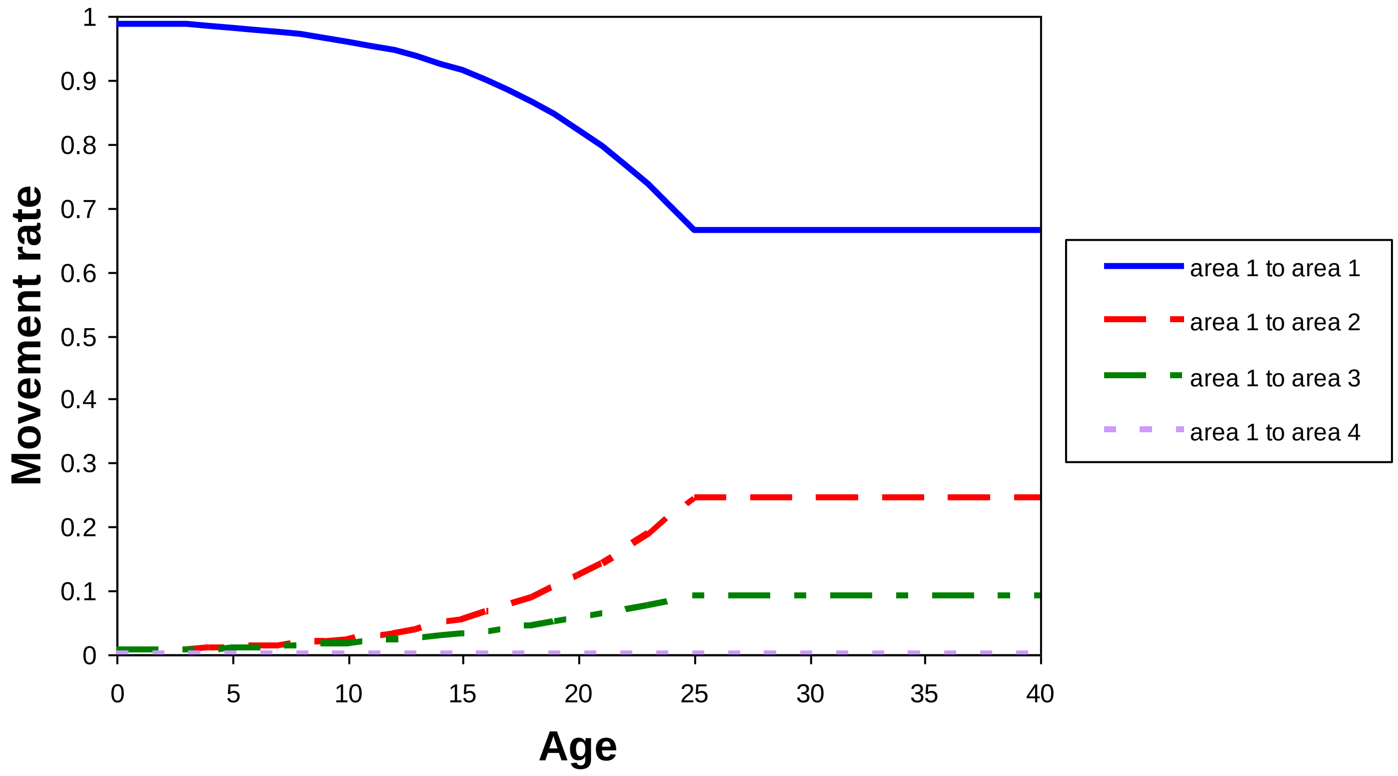
$$X_a^{C,D} = \begin{cases} 1 - \sum\limits_{A \neq C} X_a^{C,A} & \text{if } A \neq C \\ \dfrac{\exp(\delta_a^{C,D})}{1+\exp(\delta_a^{C,D})} & \text{otherwise} \end{cases}$$



Bigeye tuna – Langley (2016)

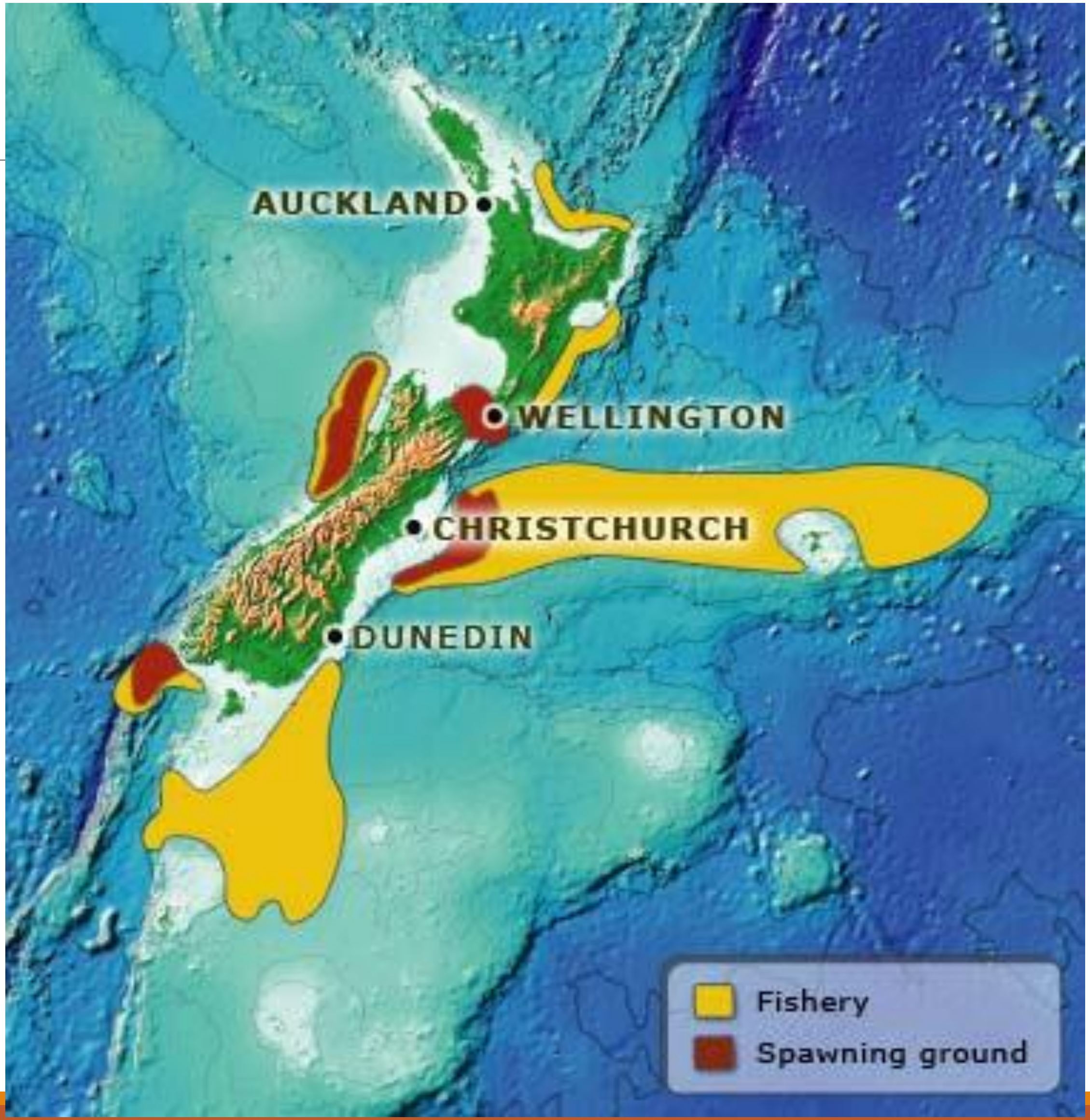
Modelling movement-IV

Stock Synthesis
Two parameters per movement definition to allow separate rates for young (A) and old (B) fish, with ramp in between (linear in log space)



Modelling movement-V

Step	Approx. Months	Processes	M fraction	Age fraction	Observations Label	Observations Prop. mort.
1	Oct-Nov	Migrations Wrtn: WC–>SA, Ertn: CS–>CR	0.17	0.25	–	
2	Dec-Mar	Recruitment at age 1+ to CR (for both stocks)	0.33	0.60		
		part1, non-spawning fisheries (Ensp1, Wnsp1)			SAsum	0.5
					CRsum	0.6
3	Apr-Jun	Migration Whome: CR–>SA	0.25	0.90		
		part2, non-spawning fisheries (Ensp2, Wnsp2)			SAaut	0.1
					pspawn	
4	End Jun	Migrations Wspmg: SA–>WC, Espmg: CR–>CS	0.00	0.90	–	
5	Jul-Sep	Increment ages	0.25	0.0	CSacous	0.5
		spawning fisheries (Esp, Wsp)			WCacous	0.5



Modelling Recruitment

A general stock-recruitment relationship:

$$R_{t,q,0}^{i,s} = f(SSB_t, t)\,g(s,q,t)\,h(s,i,q,t)\,k(q)$$

Recruitment for sex s in area i during quarter q of year t

Stock-recruitment relationship *(could depend on area)*

Sex ratio of recruitment

Spatial distribution of recruitment

Seasonal allocation of recruitment

$$R_{t,q,0}^{i,s} = f(SSB_{i,t}, t)$$

A general model of recruitment-II

Stochasticity in the recruitment about the stock-recruitment relationship could be:

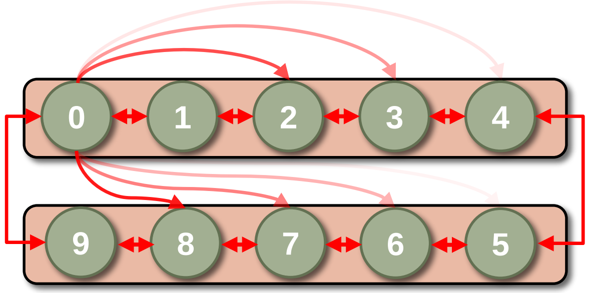
- annual, with a time-invariant proportion of total recruitment going to each area; or
- annual, but with a time-dependent proportion of total recruitment going to each area.

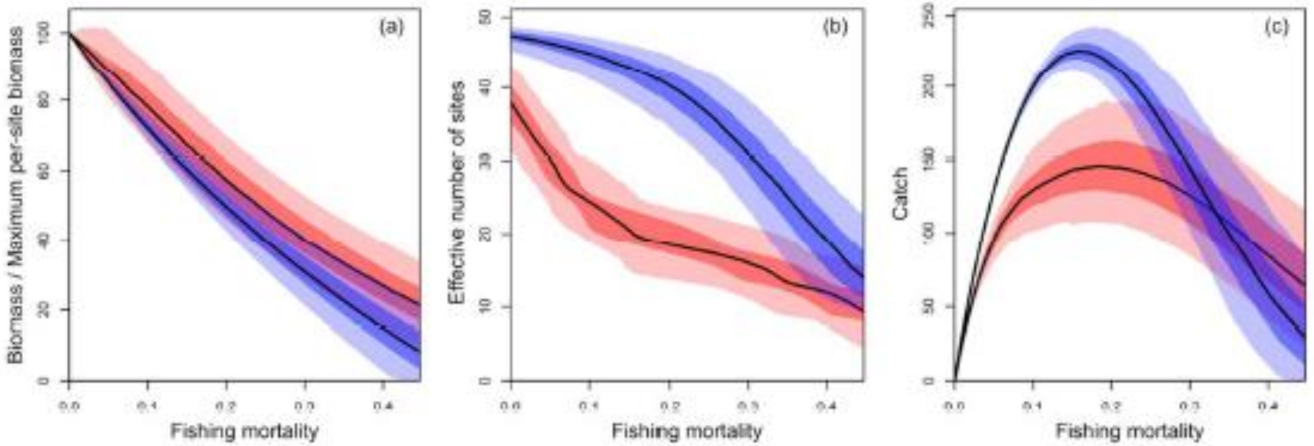
Annual deviations in recruitment are usually log-normal (with a bias-correction factor) while the allocation of recruitments can be Dirichlet, or a logit-transformed random variable. The annual deviations could be correlated spatially (as is the case in reality for salmon, cod, etc.)

In Stock Synthesis, recruitment is computed globally and allocated to sex and growth morphs, settlement events (temporal allocations) and areas.

An alternative recruitment model

MacCall *et al*. (ICES J. mar Sci.) consider an alternative recruitment model in which recruitment depends on following spawners (The "Go with the Old Fish" hypothesis)





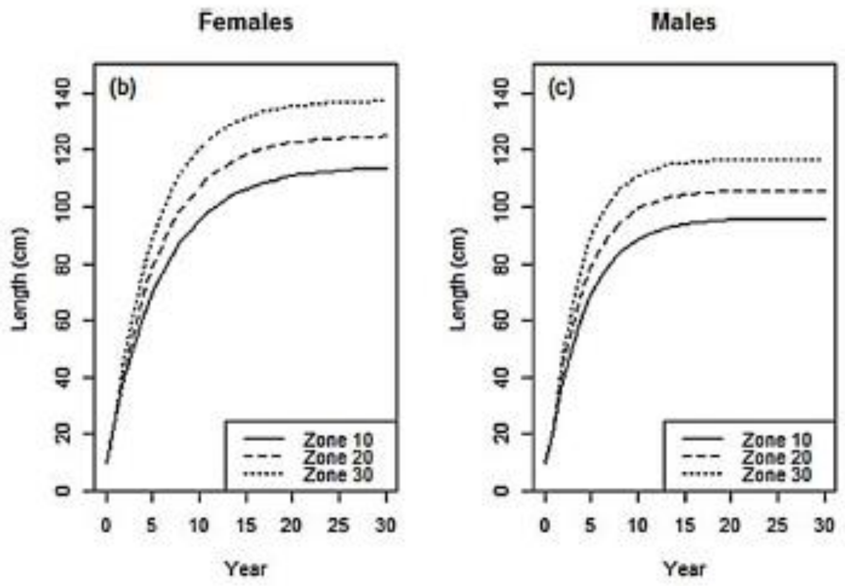
Modelling growth and natural mortality-I

Growth rates may differ spatially:

- If ignored, this can lead to bias when models are fitted to length data.
- Growth increments can be modelled spatially:

$$I_{l+1,i} = (\ell_{\infty,i} - I_l)(1 - e^{-\kappa_i})$$

  where *i* denotes area
- This approach performs adequately when animals do not move. What happens if animals move post-recruitment and growth differs spatially?



Pink ling (Punt et al. Fish Res. 2015)

Modelling growth and natural mortality-II

Rick's suggestions:

- Extend to area-specific natural mortality (but this has computational implications).
- As fish move between areas update mean length-at-age (and allow for sex-/area-specific growth parameters), but this may have huge computational implications.
- Assume length-at-age is unaffected my migrating animals.

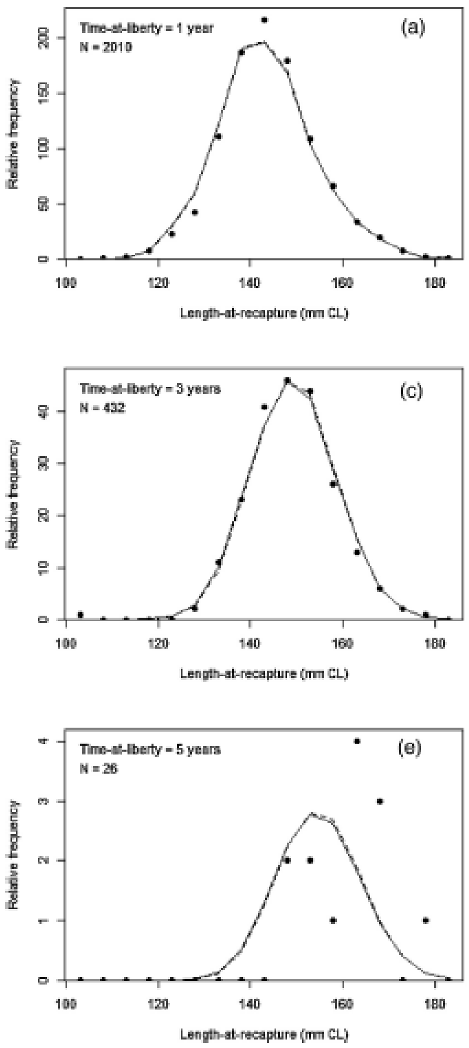
Parameter estimation

Consider a (typical) SS assessment with 20 years of data, 3 areas and 2 fleets in each area

Parameter	Areas-as-fleets	Spatial
Log(R_0)	1	**3** (1 plus 2 offsets)
Rec_devs	20	20
Spatial rec_devs	0	**20**
Selectivity	$\geq$ 12	$\geq$ 12 (unless shared)
Movement	0	> 12 (with post-recruitment movement)
Growth	~4	~4 (unless growth is spatial)

Tagging data-I

- Tagging data can be included in an assessment to estimate movement and perhaps also growth and fishing mortality rates – examples exist for:
    - tunas, rock lobster, sharks, and cetaceans
- Care needs not to overweight the tagging data (each tagging data point may not be independent as assumed by, for example, a Poisson recapture process)



Tagging data

- The "Hilborn" approach can be used to include tagging data in assessment, but this can be challenging when:
  - there are multiple stocks; and
  - the lengths of animals are available, not ages, and selectivity depends on age.
- In SS, tags released in area, p, at time, t, at age, a, are distributed proportionally among all biology morphs according to the current distribution of morphs.

Determination of Fish Movement Patterns from Tag Recoveries using Maximum Likelihood Estimators

Ray Hilborn

Fisheries Research Institute WH-10, University of Washington, Seattle, WA. 98195 U.S.A.

Hilborn, R. 1990. Determination of fish movement patterns from tag recoveries using maximum likelihood estimators. Can. J. Fish. Aquat. Sci. 47: 635–643.

A general method for analysis of movement data from tag returns is proposed which has four major components: (1) a population dynamics and movement model that describes how the number of tagged individuals in each spatial location changes over time; (2) an observation model which describes how the tags are recovered and reported; (3) a likelihood function that specifies the likelihood of observing a specific number of recoveries in each space/time stratum as a function of the number thought to be there under a specific set of parameters of the population dynamics, movement and observation models, and (4) a nonlinear function minimization computer algorithm. This approach is applied to movements of skipjack tuna (*Euthynnus pelamis*). When tagging and recapture take place in each spatial stratum, reliable estimates of movement rates can be obtained. The approach described is completely general and can be used in cases where movement takes place continuously, or only once in the life history. Methods for determining confidence limits and evaluation of residuals are presented and extensions that include tagging mortality, tag shedding, and size specific vulnerability are discussed.

Une méthode générale d'analyse des données portant sur les déplacements à partir des bagues retournées est proposée : cette méthode compte quatre éléments importants : (1) un modèle de mouvement et de dynamique des populations qui décrit comment la population constituée par le nombre de sujets marqués dans chaque emplacement spatial, se transforme avec le temps; (2) un modèle d'observation qui décrit comment les bagues sont récupérées et rapportées; (3) une fonction de vraisemblance qui détermine la vraisemblance de l'observation d'un nombre donné de récupérations dans chaque strate spatiale-temporelle en fonction du nombre qu'on estime être présent en vertu d'un ensemble précis de paramètres retenus pour les modèles de la dynamiques des populations, des mouvements et des observations; enfin, (4) un algorithme de minimisation de la fonction non linéaire. Cette approche est appliquée aux déplacements de la thonine (*Euthynnus pelamis*) à ventre rayé. Avec le marquage et le recapture dans chaque strate spatiale, il est possible d'obtenir des évaluations fiables des taux de déplacement. L'approche décrite est on ne peut plus générale et peut s'appliquer aux cas de déplacements continuels ou aux cas d'un seul déplacement dans la vie. Les méthodes utilisées pour déterminer les limites de confiance et l'évaluation des résidus sont présentées; il est question aussi de la mortalité par marquage, de la perte des bagues et de la vulnérabilité associée à chaque taille.

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(J9227)

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Tricks that might help

- The amount of data is “increased” by disaggregating data (but usually not more than in an areas-as-fleets assessment).
- To date, most spatial assessments are based on limited (or no) tagging data -
  - This should be fine for cases when animals do not move post-settlement (e.g. canary rockfish), and perhaps even when there is post-settlement movement.
- Some key parameters (e.g. selectivity, productivity, *M*) can be shared among areas and stocks to reduce the number of estimable parameters).
- Moving to a random effects structure may improve estimation performance given most “additional” parameters are what amount to random effects.

Decision process in a spatial assessment

Select stock structure (and time-step) → One stock, multiple stocks

↓

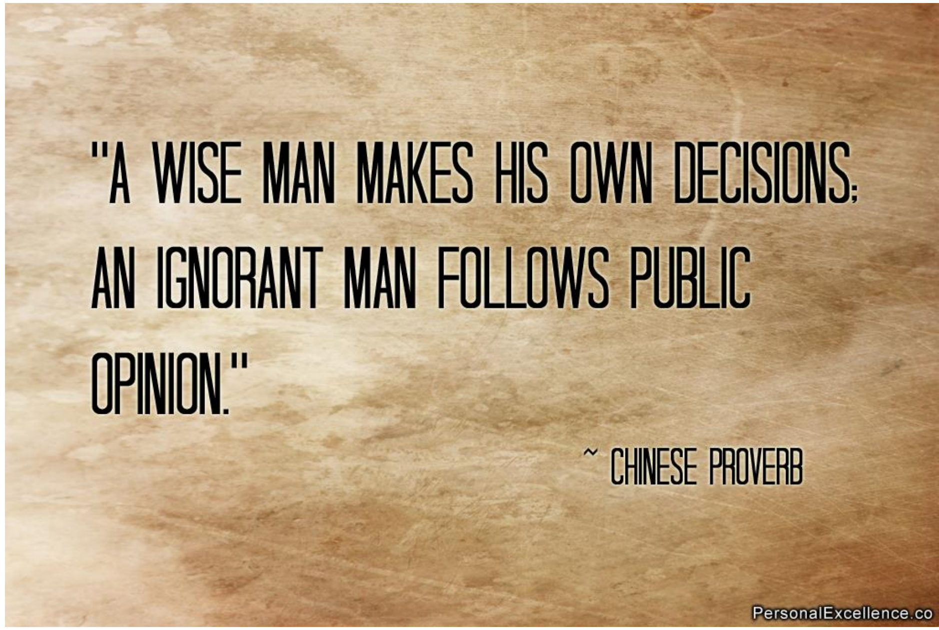
Identify spatial strata (and alternative strata) → 2,3, …

↓

Basic model structure → Age-structured, size-structured

↓

Key management outputs → Total biomass, area biomass, catch limits… ???



Decision process in a spatial assessment

Spatial allocation of recruitment → One area, multiple areas, time-dependent?

↓

Movement directions / age-structure → Are all areas connected? How does movement and dispersal depend on age

↓

Selection of fleets (and selectivity patterns) → Consider mirroring among areas; asymptotic selectivity by area (instead of dome-shaped, ignoring space)

Decision process in a spatial assessment

Spatial variation in growth and fecundity → Causes problems when animals move?

↓

Spatial variation in natural mortality → Causes problems when animals move?

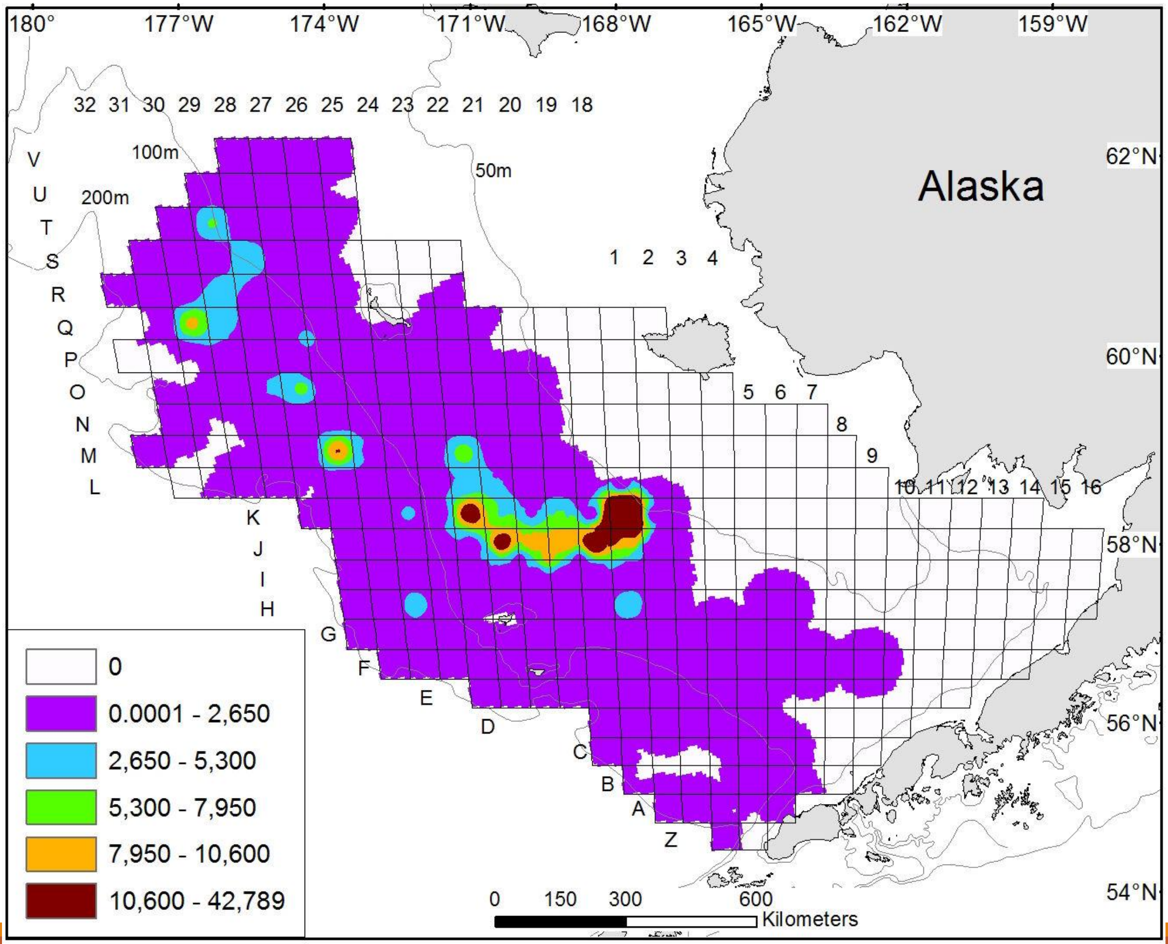
↓

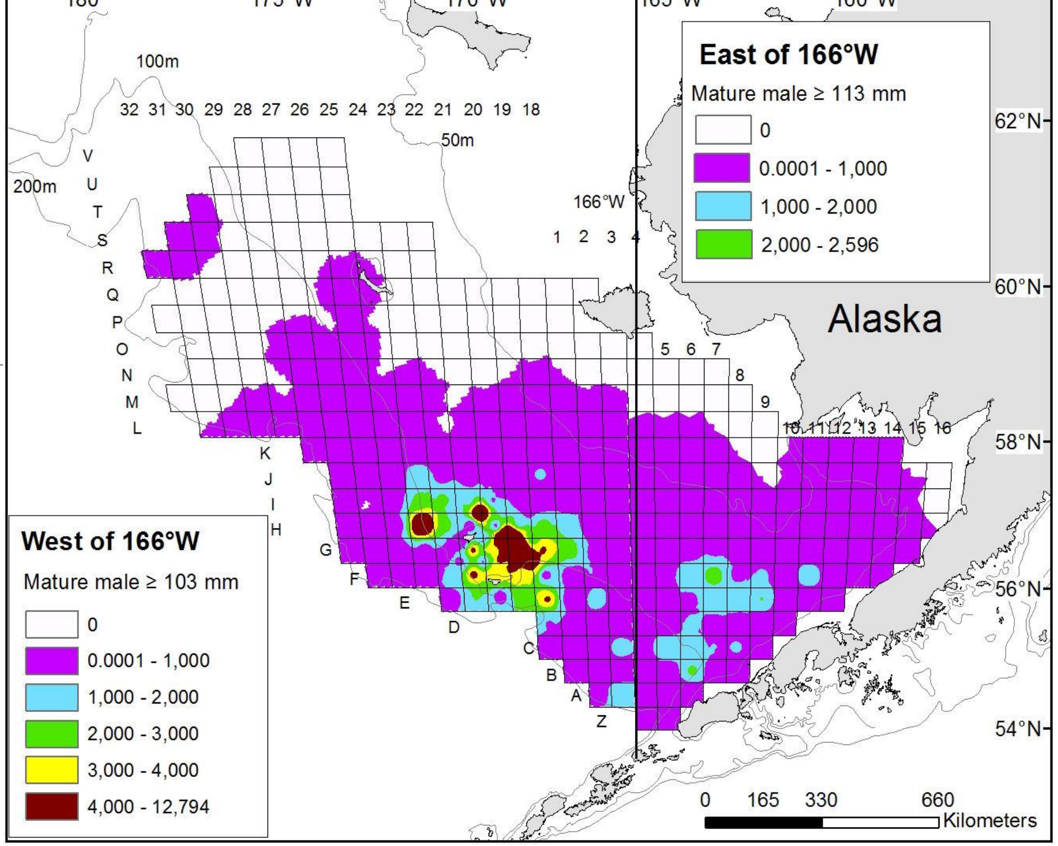
Data and the likelihood functions → Are all data sources spatial? Do we have data on tagging / movement?

Multi-species spatial models-I

Spatial models add many parameters to a model (e.g. fishing mortality rates by area and year). The number of parameters can be reduced by analysing multiple species simultaneously, i.e. the Robin Hood method.

Multi-species spatial models-II



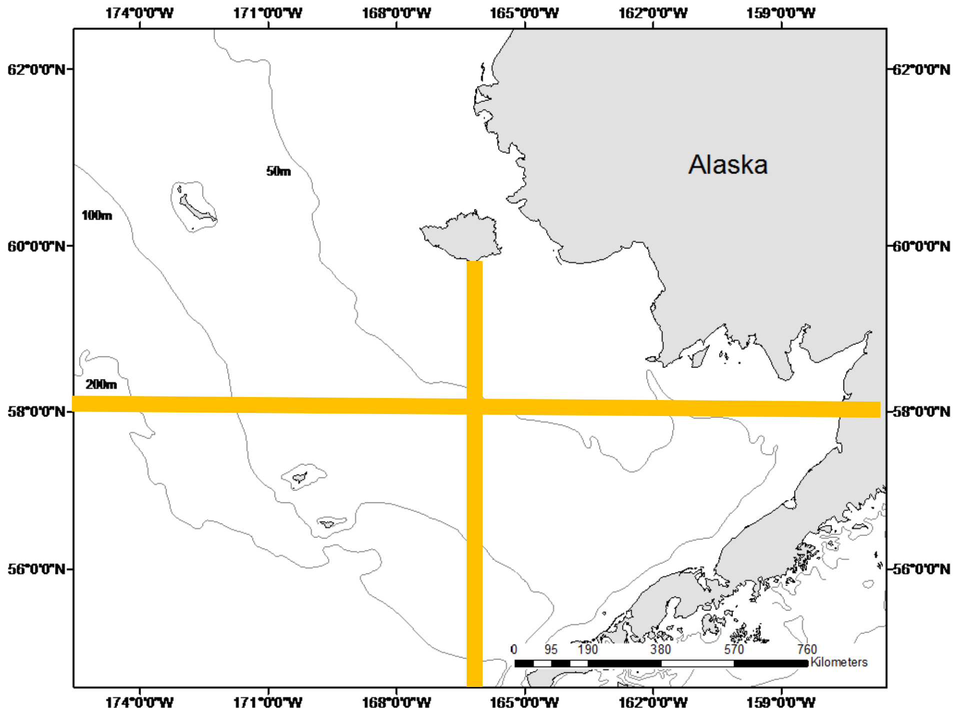


Survey estimates of abundance of snow (left) and Tanner (above) crab

Multi-species spatial models-III

Snow and Tanner crab in the Bering Sea are modelled (using areas-as-fleets) in four areas.

Data are available on (a) landed catches of Tanner crab in the snow crab fishery and vice versa [by area] and (b) the total catch of Tanner crab in the snow crab fishery (some of which is discarded)



Multi-species spatial models-III

Fully-selected fishing mortality is modelled as:

$$F_y^{f,s,A} = F_y^{f,A} e^{\phi^{f,A,s}}$$

where $F_y^{f,s,A}$ is the fully-selected fishing mortality for fishery *f* in area *A* during year *y* on species *s*.

Fishermen's news

Final thoughts

- Why have spatial assessments not been adopted widely?
  - Complexity?
  - Lack of general package?
  - Inertia?
- Assessment platforms need to include multiple (and flexible) formulations regarding stock structure
- Movement modeling – deterministic vs stochastic vs non-stationary.
- Ensure that that the assessment platform has been simulated tested, including the ability of model selection methods (including fit diagnostics) to select among alternative configurations.
- Attempts should be made to estimate migration rates within spatially-structured stock assessments even if it is recognized that the estimates of migration rate parameters may be poorly determined (a role for spatial random effects).



Questions?