Ecosystem models
A model of intermediate complexity for ecosystems for anchovy and sardine

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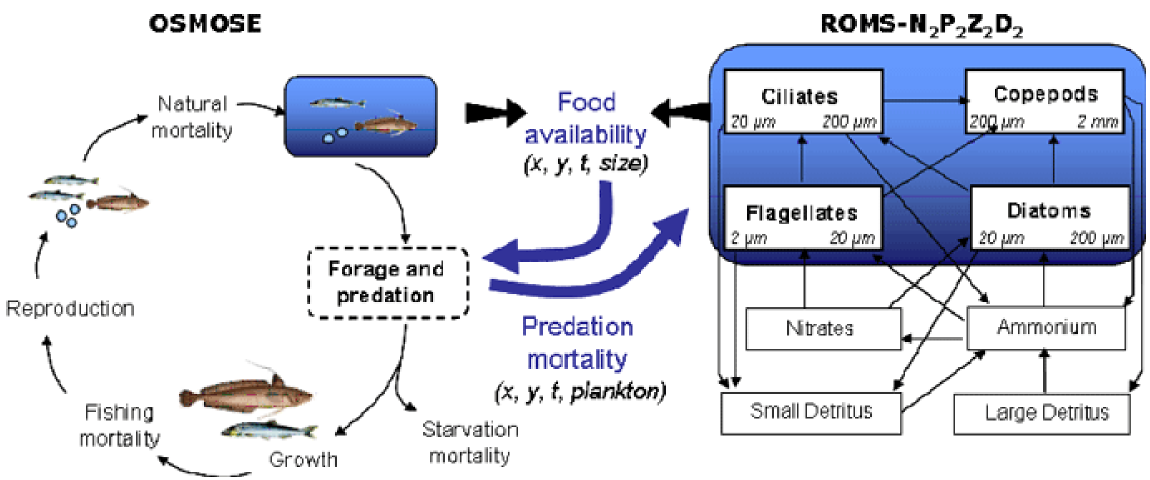
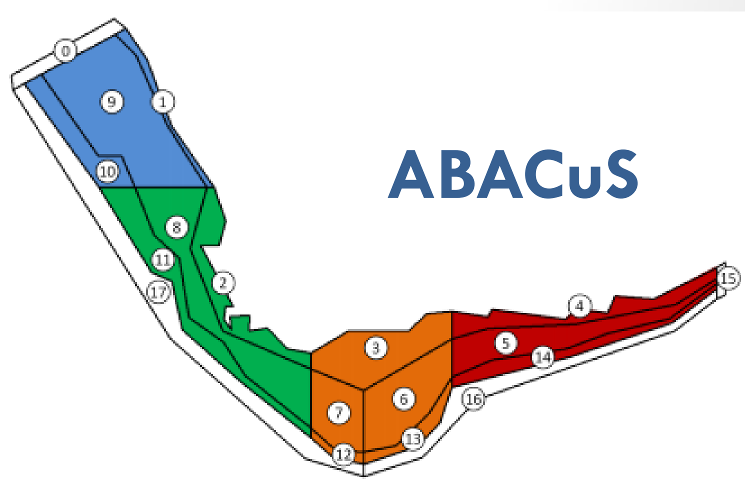
Ecosystem models

Ecopath with Ecosim

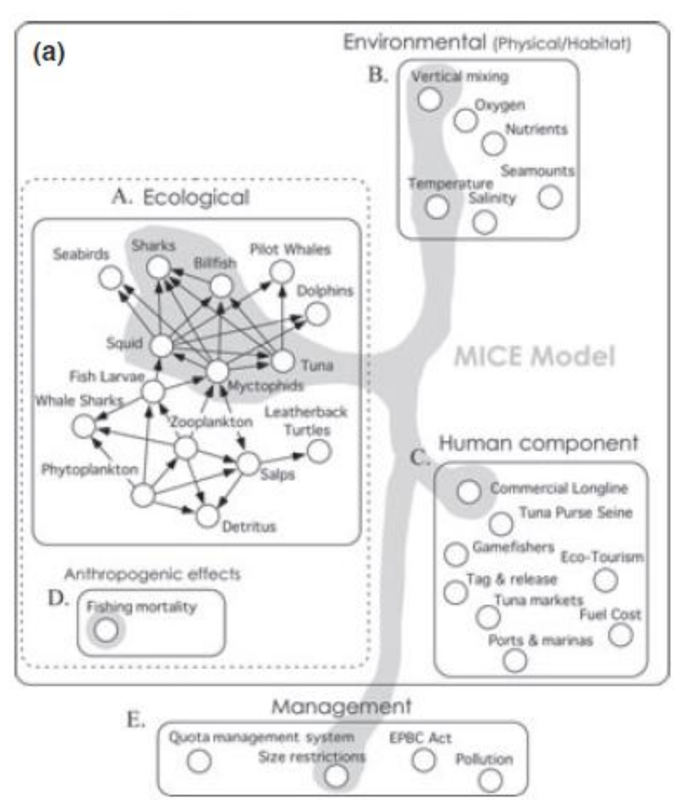
No fish is an island





Model of Intermediate Complexity for Ecosystems (MICE)

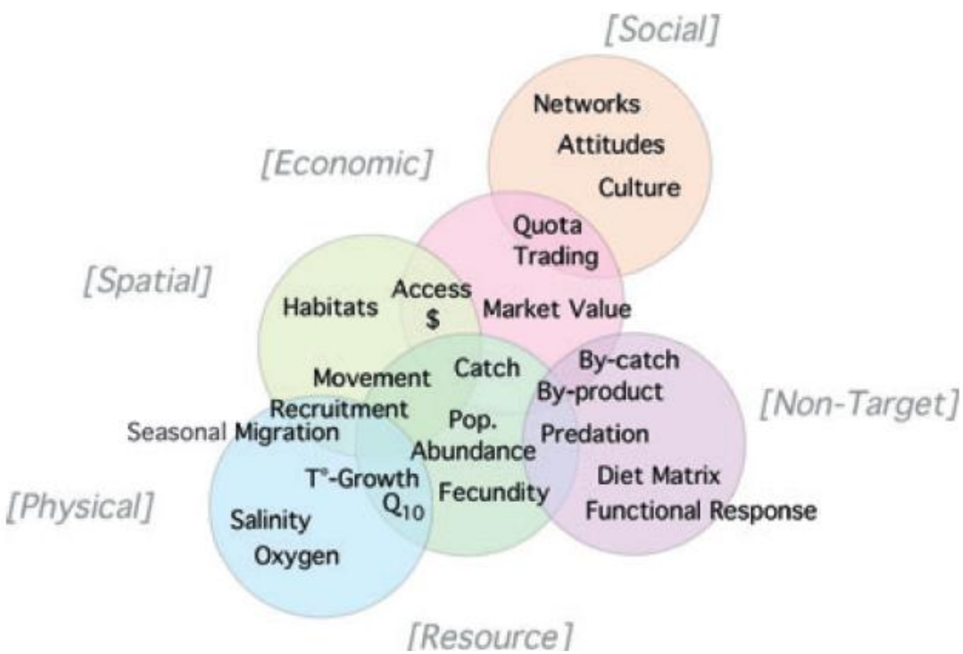
- Represent ecological processes for a limited group of species (typically <10) and include at least one explicit representation of an ecological process (e.g. interspecific interaction or spatial habitat use).
- MICE can have linked physical models.
- Provide the ability to address tactical questions. Strategic (what-if scenarios) purposes.



Plaganyi et al. (2014)

Model of Intermediate Complexity for Ecosystems (MICE)

- Designed based on data available to parameterize the model.
- Context and question-driven.
- Estimate parameters through fitting to data, use statistical diagnostic tools to evaluate model performance and account for uncertainty.



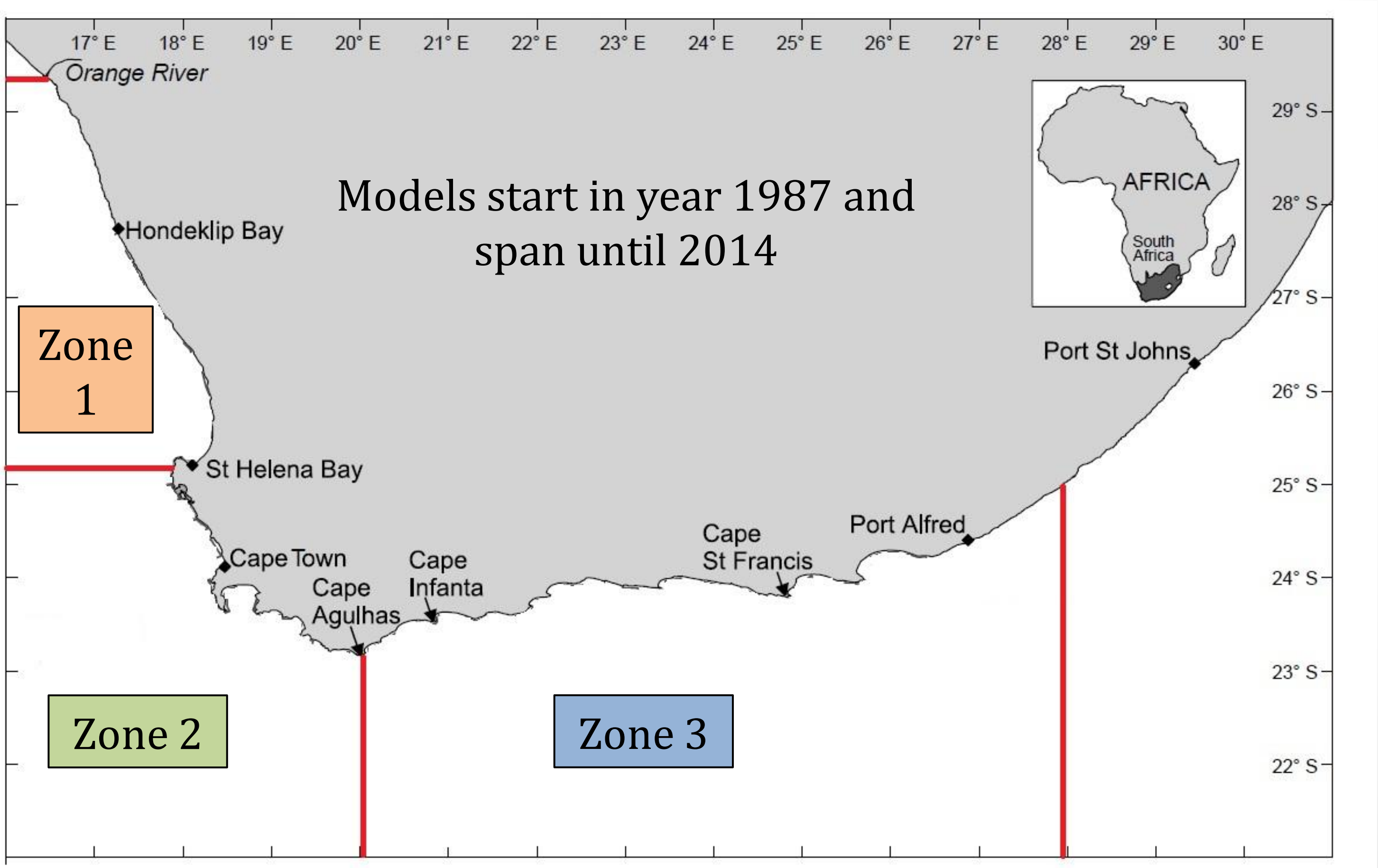
Plaganyi et al. (2014)

MICE - anchovy and sardine

- Explore the dynamics of anchovy and sardine in a spatially disaggregated model that would allow for consideration of the impacts of environmental variability and possible effects of climate change on movements between zones and on other key population dynamics processes.

MICE: anchovy and sardine

- Age-structured, biomass-based spatial model.
- Model equations account for juvenile and adult movement between zones, growth, recruitment, natural and fishing mortality.



Adapted from De Moor & Butterworth 2015

MICE: Catch data

- Monthly length frequencies from the commercial landings and monthly cut-off lengths (from de Moor *et al.*, 2012) were used to determine monthly catch of 0-year-olds and 1+ fish (in numbers).

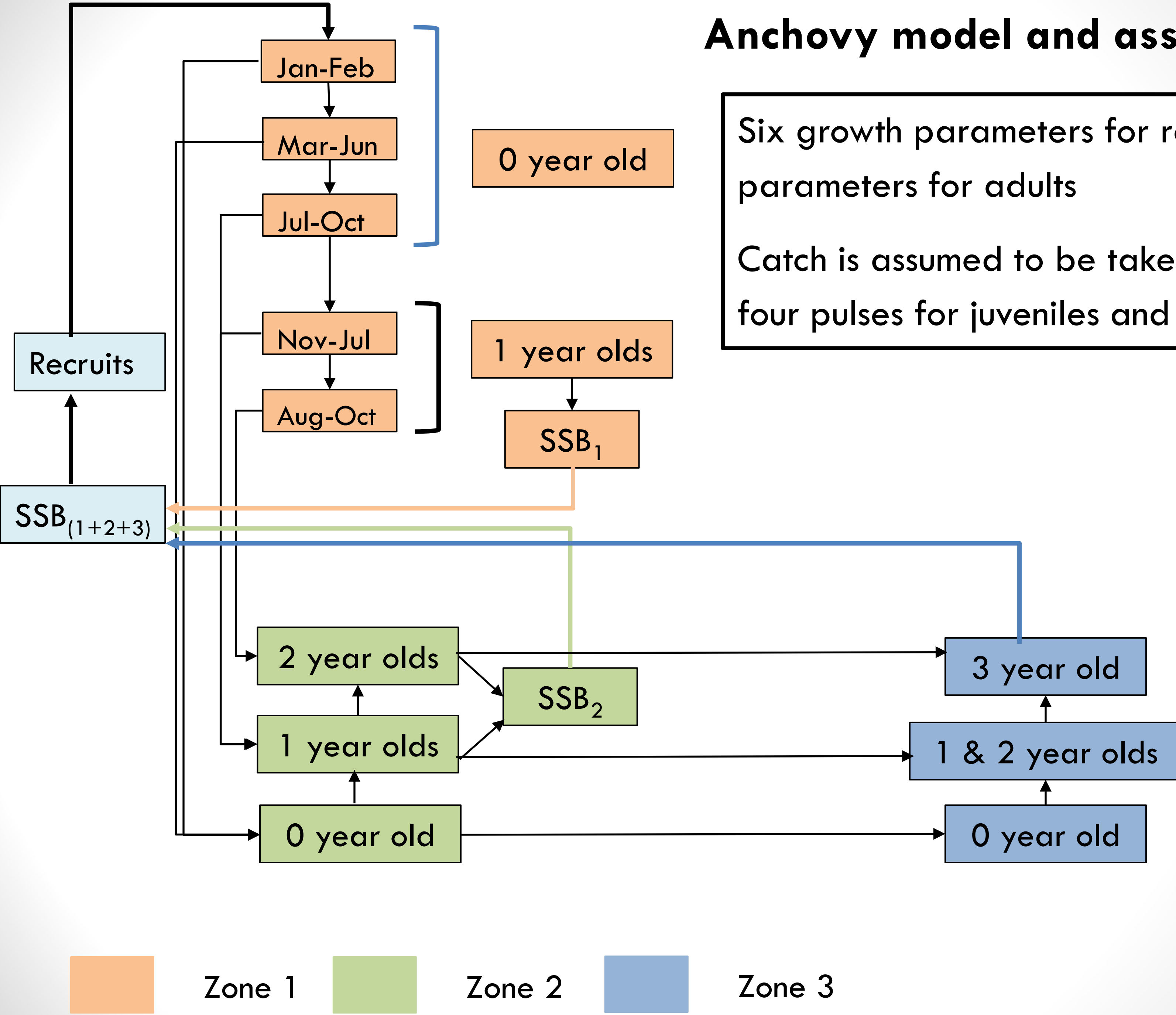
- The monthly catch (in tons) for juveniles and adults was determined using length-weight relationships for sardine and anchovy (de Moor & Butterworth, 2015a, 2015b).

- Both models assumed that these catches are taken in pulses throughout the year, monthly catch data were then grouped among months to fit the model structure.

Anchovy model and assumptions

Six growth parameters for recruits, six parameters for adults

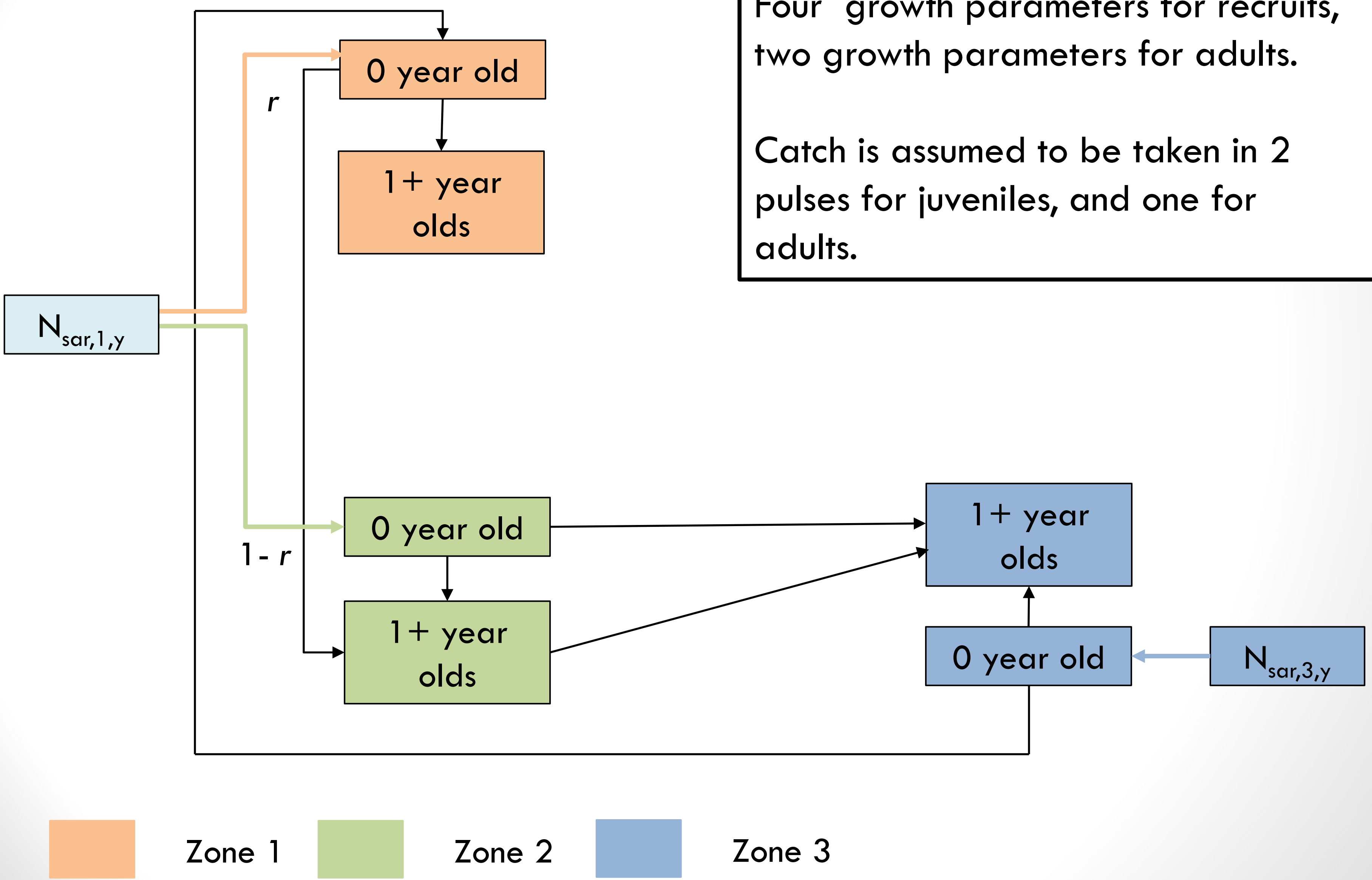
Catch is assumed to be taken in pulses, four pulses for juveniles and 2 for adults.



Sardine model and assumptions

Four growth parameters for recruits, two growth parameters for adults.

Catch is assumed to be taken in 2 pulses for juveniles, and one for adults.



Relationship with environmental parameters

- Investigate whether any relationships can currently be detected between model parameters and environmental indices.

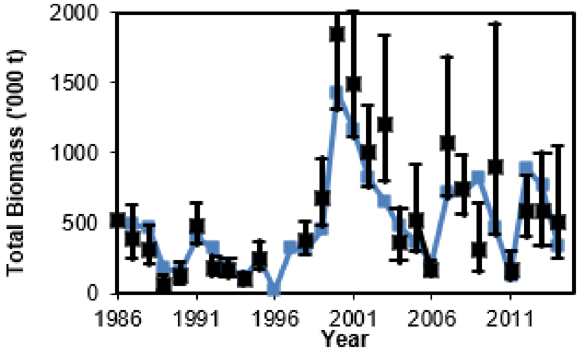
- Environmental indices spanning from 1980-2050 from the NEMO-MEDUSA 2.0 model: Sea surface salinity, temperature (SST) and pH, primary production (PP) and wind speed.

- Relationship between SST (seasonal averages)/PP and recruitment residuals for a given year has been analysed. Average of the monthly primary production from $\text{September}_{(y-1)}$ to $\text{April}_{(y)}$ was used. The relationship between $PP_{(y-1)}$ and recruitment residuals of year *y* was investigated.

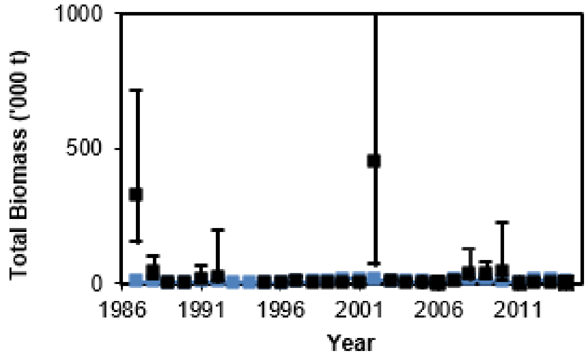
Results

Predicted biomass of anchovy recruits (right) and adults (left) fit to observations from 1987-2014

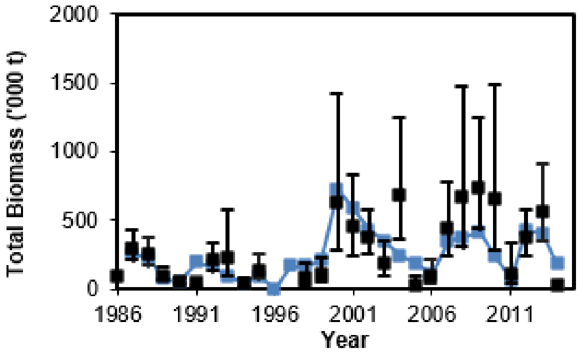
Zone 1



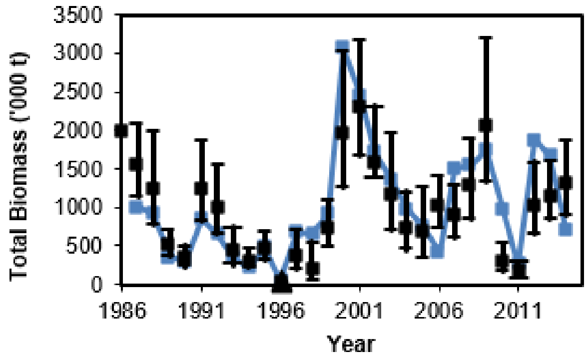
Zone 1



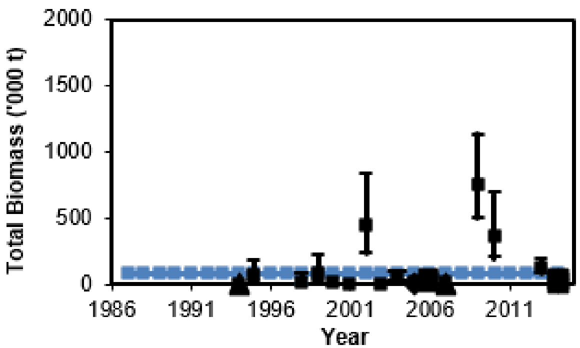
Zone 2



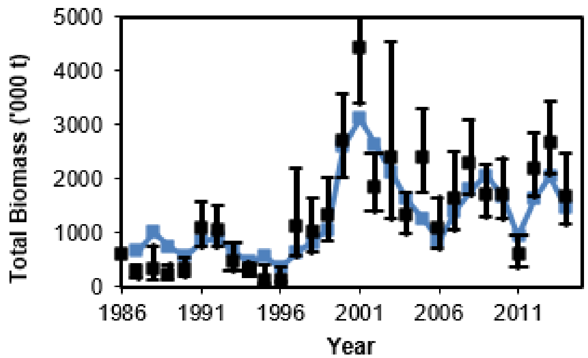
Zone 2

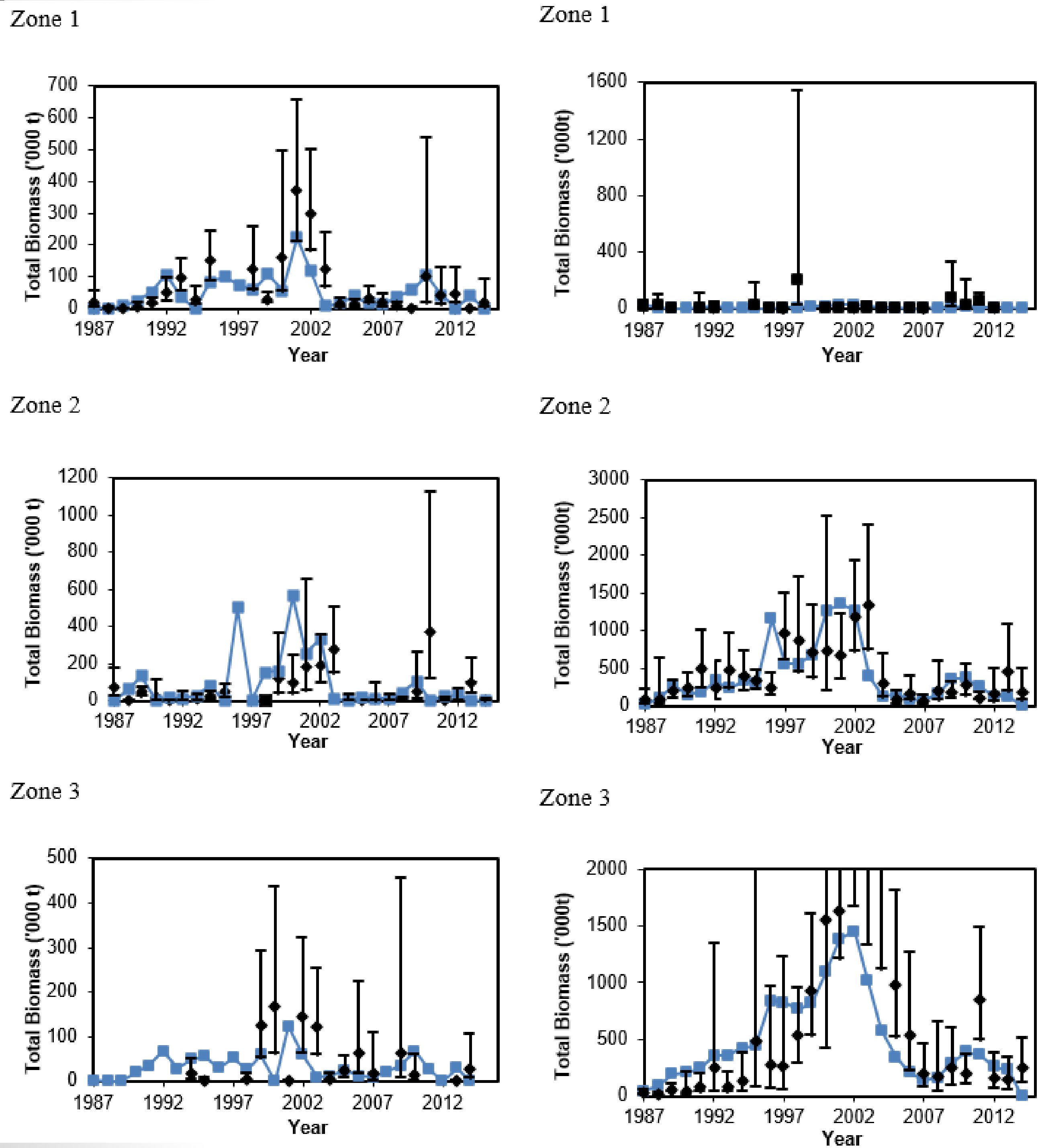


Zone 3



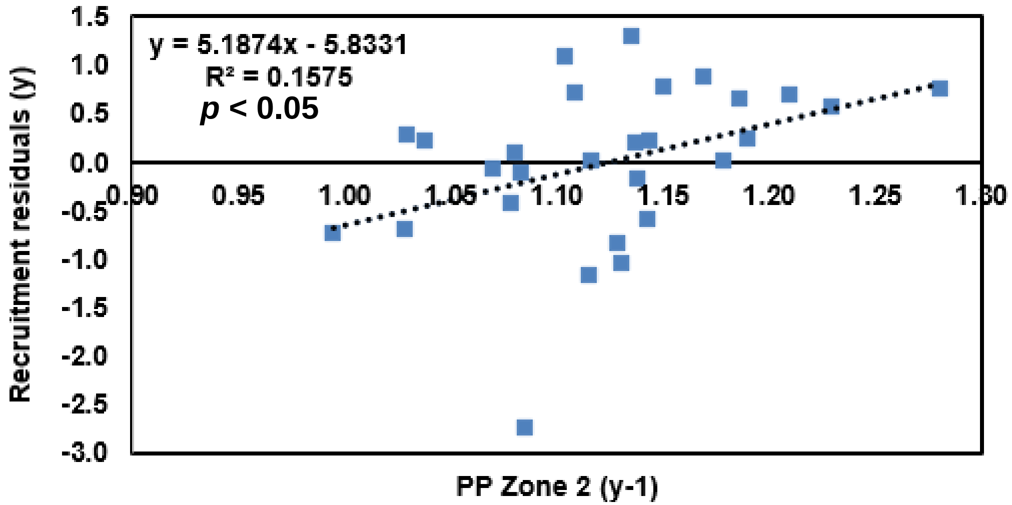
Zone 3





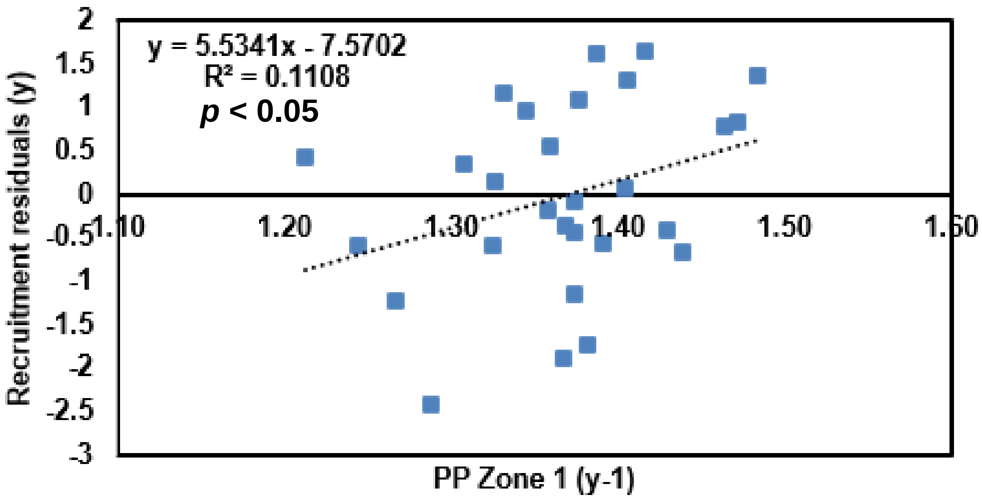
Predicted biomass of sardine recruits (right) and adults (left) fit to observations from 1987-2014

Zone 2



Recruitment residuals for the anchovy single stock and PP (g C m^2 d^{-1})

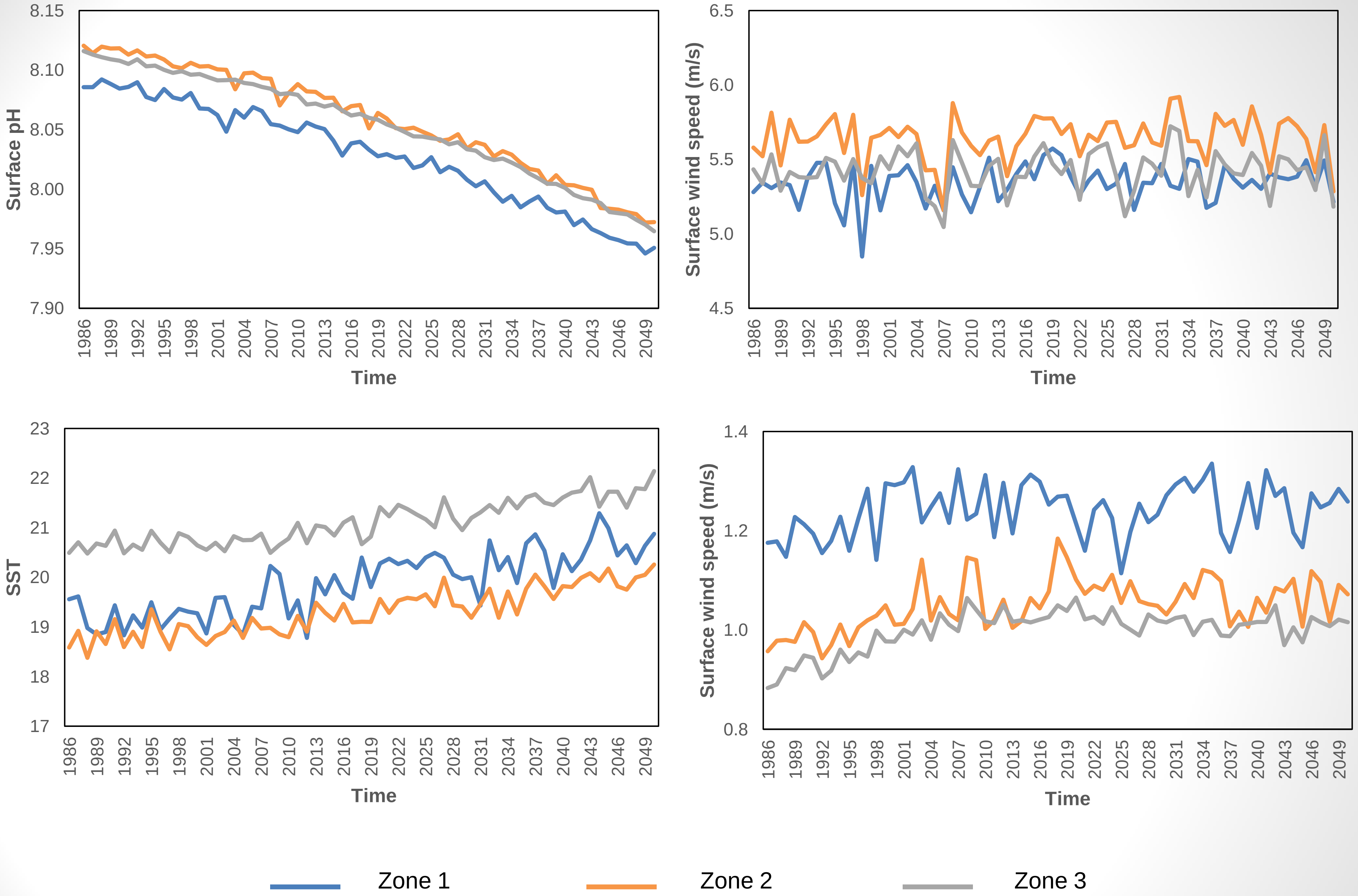
Zone 1



Recruitment residuals for the west stock of sardine and PP(g C m^2 d^{-1})

Future direction: what-if scenarios

- Estimate movement parameters annually, and link them to SST or PP in each zone.
- Link sardine and anchovy recruitment to variations in SST or PP.
- Use time series of environmental parameters to evaluate future changes in biomass, recruitment and movement of sardine and anchovy.
- Evaluate scenarios of increases or decreases in SST/upwelling accounting for spatial differences along the South African coast.



Surface pH
8.15
8.10
8.05
8.00
7.95
7.90
Time
Surface wind speed (m/s)
6.5
6.0
5.5
5.0
4.5
Time
SST
23
22
21
20
19
18
17
Time
Surface wind speed (m/s)
1.4
1.2
1.0
0.8
Time
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
2016
2019
2022
2025
2028
2031
2034
2037
2040
2043
2046
2049
Zone 1
Zone 2
Zone 3

Appendix: A1. Anchovy equations. Definitions of parameters and variables provided in Table A1.

0-year-old biomass at the time of the survey (1 June)

$$B^{anSURVEY}_{y,0,1} = (1-move_S^{0-1})(((f^{1}(SSB^{an}_{y-1,1}+SSB^{an}_{y-1,2}))G_0^1 e^{-2M_0^{an}/12} - C^{anJF}_{y,0,1})G_0^3 e^{-3M_0^{an}/12} - C^{anMM}_{y,0,1}$$

$$B^{anSURVEY}_{y,0,2} = (1-move_S^{0-4})move_S^{0-1}((f^{1}(SSB^{an}_{y-1,1}+SSB^{an}_{y-1,2}))G_0^1 e^{-2M_0^{an}/12} - C^{anJF}_{y,0,1})G_0^3 e^{-3M_0^{an}/12} - C^{anMM}_{y,0,2}$$

$$B^{anSURVEY}_{y,0,3} = move_S^{0-4}\, move_S^{0-1}((f^{1}(SSB^{an}_{y-1,1}+SSB^{an}_{y-1,2}))G_0^1 e^{-2M_0^{an}/12} - C^{anJF}_{y,0,3})G_0^3 e^{-3M_0^{an}/12} - C^{anMM}_{y,0,3}$$

1-year-old biomass in November

$$B^{an}_{y,1,1} = (1-move_S^{0-3})(((1-move_S^{0-2})(B^{anSURVEY}_{y,0,1}G_0^5 e^{-M_0^{an}/12} - C^{anJJ}_{y,0,1})G_0^6 e^{-M_0^{an}/12})G_0^7 e^{-M_0^{an}/12} - C^{anAO}_{y,0,1})G_0^8 e^{-2M_0^{an}/12}$$

$$\begin{aligned} B^{an}_{y,1,2} = {} & (((move_S^{0-2}(B^{anSURVEY}_{y,0,1}G_0^5 e^{-M_0^{an}/12} - C^{anJJ}_{y,0,1})G_0^6 e^{-M_0^{an}/12} + (B^{anSURVEY}_{y,0,2}G_0^5 e^{-M_0^{an}/12} - C^{anJJ}_{y,0,2})G_0^6 e^{-M_0^{an}/12}))G_0^7 e^{-M_0^{an}/12} - C^{anAO}_{y,0,2})G_0^8 e^{-2M_0^{an}/12} \\ & + move_S^{0-3}(((1-move_S^{0-2})(B^{anSURVEY}_{y,0,1}G_0^5 e^{-M_0^{an}/12} - C^{anJJ}_{y,0,1})G_0^6 e^{-M_0^{an}/12})G_0^7 e^{-M_0^{an}/12} - C^{anAO}_{y,0,1})G_0^8 e^{-2M_0^{an}/12} \end{aligned}$$

$$B^{an}_{y,1,3} = (((B^{anSURVEY}_{y,0,3}G_0^5 e^{-M_0^{an}/12} - C^{anJJ}_{y,0,3})G_0^6 e^{-M_0^{an}/12})G_0^7 e^{-M_0^{an}/12} - C^{anAO}_{y,0,3})G_0^8 e^{-2M_0^{an}/12}$$

2-year-old biomass in November

$$B^{an}_{y,2,1} = 0$$

$$\begin{aligned} B^{an}_{y,2,2} = {} & (((1-move_S^1)(B^{an}_{y,1,1}G_1^1 e^{-5M_{1+}^{an}/12} - C^{anNJ}_{y,1,1})G_1^2 e^{-4M_{1+}^{an}/12})G_1^3 e^{-M_{1+}^{an}/12} - C^{anAO}_{y,1,1})G_1^4 e^{-2M_{1+}^{an}/12} \\ & + (1-move_E)(move_S^1((B^{an}_{y,1,1}G_1^1 e^{-5M_{1+}^{an}/12} - C^{anNJ}_{y,1,1})G_1^2 e^{-4M_{1+}^{an}/12})G_1^3 e^{-M_{1+}^{an}/12} + ((B^{an}_{y,1,2}G_1^1 e^{-5M_{1+}^{an}/12} - C^{anNJ}_{y,1,2})G_1^2 e^{-4M_{1+}^{an}/12})G_1^3 e^{-M_{1+}^{an}/12} - C^{anAO}_{y,1,2})G_1^4 e^{-2M_{1+}^{an}/12} \end{aligned}$$

$$\begin{aligned} B^{an}_{y,2,3} = {} & move_E(move_S^1((B^{an}_{y,1,1}G_1^1 e^{-5M_{1+}^{an}/12} - C^{anNJ}_{y,1,1})G_1^2 e^{-4M_{1+}^{an}/12})G_1^3 e^{-M_{1+}^{an}/12} + ((B^{an}_{y,1,2}G_1^1 e^{-5M_{1+}^{an}/12} - C^{anNJ}_{y,1,2})G_1^2 e^{-4M_{1+}^{an}/12})G_1^3 e^{-M_{1+}^{an}/12} - C^{anAO}_{y,1,2})G_1^4 e^{-2M_{1+}^{an}/12} \\ & + ((B^{an}_{y,1,3}G_1^1 e^{-5M_{1+}^{an}/12} - C^{anNJ}_{y,1,3})G_1^2 e^{-4M_{1+}^{an}/12}G_1^3 e^{-M_{1+}^{an}/12} - C^{anAO}_{y,1,3})G_1^4 e^{-2M_{1+}^{an}/12} \end{aligned}$$

3+ biomass in November

$$B^{an}_{y,3+,1} = 0$$

$$B^{an}_{y,3+,2} = 0$$

$$B^{an}_{y,3+,3} = \left(B^{an}_{y-1,2,2} + B^{an}_{y-1,2,3}\right)G_2 e^{-M^{an}_{1+}} + B^{an}_{y-1,3+,3} G^1_{3+} e^{-M^{an}_{1+}}$$

SSB in November

$$SSB^{an}_{y,1} = p_1 B^{an}_{y,1+,1}$$

$$SSB^{an}_{y,2} = p_2 B^{an}_{y,1+,2}$$

$$SSB^{an}_{y,3} = p_3 B^{an}_{y,1+,3}$$

Recruitment in January

$$f^1\left(SSB^{an}_{y-1,1} + SSB^{an}_{y-1,2}\right) = \begin{cases} a^{an}_1 e^{\varepsilon^{an}_{y,1} - 0.5\left(\sigma^{an}_1\right)^2} & \text{if } SSB^{an}_{y-1,1} + SSB^{an}_{y-1,2} \geq b^{an}_1 \\ a^{an}_1 \dfrac{SSB^{an}_{y-1,1} + SSB^{an}_{y-1,2}}{b^{an}_1} e^{\varepsilon^{an}_{y,1} - 0.5\left(\sigma^{an}_1\right)^2} & \text{if } SSB^{an}_{y-1,1} + SSB^{an}_{y-1,2} < b^{an}_1 \end{cases}$$

Fitting the Model to Available Data

$$-\ln L = 0.5 \sum_{y=1987}^{2014} \sum_{z=1}^{3} \ln\left(2\pi\left(\sigma^{anMAY}_{y,z}\right)^2\right) + \left(\frac{\ln\left(B^{anMAY}_{y,z}\right) - \ln\left(k^{san}_{MAY,z} B^{anSURVEY}_{y,0,z}\right)}{\sigma^{anMAY}_{y,z}}\right)^2$$

$$+ 0.5 \sum_{y=1986}^{2014} \sum_{z=1}^{3} \ln\left(2\pi\left(\sigma^{anNOV}_{y,z}\right)^2\right) + \left(\frac{\ln\left(B^{anNOV}_{y,z}\right) - \ln\left(k^{an}_{NOV,z} \sum_{a=1}^{3+} B^{an}_{y,a,z}\right)}{\sigma^{anNOV}_{y,z}}\right)^2$$

$$+ 0.5 \sum_{y=1987}^{2014} \ln\left(2\pi\left(\sigma^{an}_1\right)^2\right) + \left(\frac{\varepsilon^{an}_{y,1}}{\sigma^{an}_1}\right)^2$$

Sardine equations.

0+ biomass at the time of the survey (1 June)

$$B^{sarSURVEY}_{y,0,1} = \left(\left(r_y\left(e^{Nsar1,y}\right) + \left(move_w e^{Nsar3,y}\right)\right)G^1_0 e^{-3M^{sar}_0/12} - C^{sarBS}_{y,0,1}\right)G^2_0 e^{-2M^{sar}_0/12}$$

$$B^{sarSURVEY}_{y,0,2} = \left(\left(\left(1-r\right)\left(e^{Nsar1,y}\right)\right)G^1_0 e^{-3M^{sar}_0/12} - C^{sarBS}_{y,0,2}\right)G^2_0 e^{-2M^{sar}_0/12}$$

$$B^{sarSURVEY}_{y,0,3} = \left(\left(\left(1-move_w\right)\left(e^{Nsar3,y}\right)\right)G^1_0 e^{-3M^{sar}_0/12} - C^{sarBS}_{y,0,3}\right)G^2_0 e^{-2M^{sar}_0/12}$$

1+ biomass in November

$$B^{sar}_{y,1+,1} = \left(1-move_S\right)\left(B^{sarSURVEY}_{y,0,1}G^3_0 e^{-2M^{sar}_0/12} - C^{sarAS}_{y,0,1}\right)G^4_0 e^{-3M^{sar}_0/12} + \left(B^{sar}_{y-1,1+,1}G^1_{1+}e^{-0.5M^{sar}_{1+}} - C^{sar}_{y,1+,1}\right)e^{-0.5M^{sar}_{1+}}$$

$$B^{sar}_{y,1+,2} = move_S\left(B^{sarSURVEY}_{y,0,1}G^3_0 e^{-2M^{sar}_0/12} - C^{sarAS}_{y,0,1}\right)G^4_0 e^{-3M^{sar}_0/12} + \left(1-move_E\right)\left(B^{sarSURVEY}_{y,0,2}G^3_0 e^{-2M^{sar}_0/12} - C^{sarAS}_{y,0,2}\right)G^4_0 e^{-3M^{sar}_0/12}$$
$$+ move_A\left(1-move_E\right)\left(B^{sar}_{y-1,1+,2}G^1_{1+}e^{-0.5M^{sar}_{1+}} - C^{sar}_{y,1+,2}\right)G^2_{1+}e^{-0.5M^{sar}_{1+}}$$

$$B^{sar}_{y,1+,3} = move_E\left(B^{sarSURVEY}_{y,0,2}G^3_0 e^{-2M^{sar}_0/12} - C^{sarAS}_{y,0,2}\right)G^4_0 e^{-3M^{sar}_0/12} + \left(B^{sarSURVEY}_{y,0,3}G^3_0 e^{-2M^{sar}_0/12} - C^{sarAS}_{y,0,3}\right)G^4_0 e^{-3M^{sar}_0/12}$$
$$+ move_A move_E\left(B^{sar}_{y-1,1+,2}G^1_{1+}e^{-0.5M^{sar}_{1+}} - C^{sar}_{y,1+,2}\right)G^2_{1+}e^{-0.5M^{sar}_{1+}} + \left(B^{sar}_{y-1,1+,3}G^1_{1+}e^{-0.5M^{sar}_{1+}} - C^{sar}_{y,1+,3}\right)G^2_{1+}e^{-0.5M^{sar}_{1+}}$$

Fitting the Model to Available Data

$$-\ln L = 0.5\sum_{y=1987}^{2014}\sum_{z=1}^{3}\ln\left(2\pi\left(\sigma^{sarMAY}_{y,z}\right)^2\right) + \left(\frac{\ln\left(B^{sarMAY}_{y,z}\right) - \ln\left(k^{sar}_{MAY,z}B^{sarSURVEY}_{y,0,z}\right)}{\sigma^{sarMAY}_{y,z}}\right)^2$$
$$+ 0.5\sum_{y=1986}^{2014}\sum_{z=1}^{3}\ln\left(2\pi\left(\sigma^{sarNOV}_{y,z}\right)^2\right) + \left(\frac{\ln\left(B^{sarNOV}_{y,z}\right) - \ln\left(k^{sar}_{NOV,z}B^{sar}_{y,1+,z}\right)}{\sigma^{sarNOV}_{y,z}}\right)^2$$