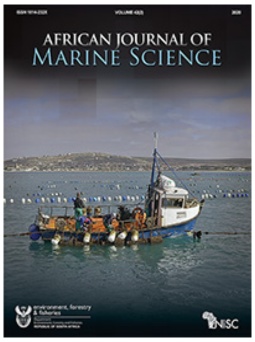

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Sustainable shellfish aquaculture in Saldanha Bay, South Africa

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The carrying capacity for bivalve shellfish culture in Saldanha Bay, South Africa, was analysed through the application of the well-tested EcoWin ecological model, in order to simulate key ecosystem variables. The model was set up using: (i) oceanographic and water-quality data collected from Saldanha Bay, and (ii) culture-practice information provided by local shellfish farmers. EcoWin successfully reproduced key ecological processes, simulating an annual mean phytoplankton biomass of 7.5 µg Chl *a* l^{-1} and an annual harvested shellfish biomass of about 3 000 tonnes (t) y^{-1}, in good agreement with reported yield. The maximum annual carrying capacity of Small Bay was estimated as 20 000 t live weight (LW) of oysters *Crassostrea gigas*, or alternatively 5 100 t LW of mussels *Mytilus galloprovincialis*, and for Big Bay as 100 000 t LW of oysters. Two production scenarios were investigated for Small Bay: a production of 4 000 t LW y^{-1} of mussels, and the most profitable scenario for oysters of 19 700 t LW y^{-1}. The main conclusions of this work are: (i) in 2015–2016, both Small Bay and Big Bay were below their maximum production capacity; (ii) the current production of shellfish potentially removes 85% of the human nitrogen inputs; (iii) a maximum-production scenario in both Big Bay and Small Bay would result in phytoplankton depletion in the farmed area; (iv) increasing the production intensity in Big Bay would probably impact the existing cultures in Small Bay; and (v) the production in Small Bay could be increased, resulting in higher income for farmers.

Keywords: blue mussel, carrying capacity, ecological model, EcoWin, Pacific oyster, phytoplankton biomass, production scenario, water quality

Introduction

The provision of a safe and acceptable diet to a population of 10 billion people by 2050 is a major global challenge (Cressey 2009; FAO 2016), and fish are a crucial source of energy, proteins, and micronutrients, all needed for an adequate human diet (Golden et al. 2016). However, many wild-fish stocks around the globe are currently overexploited (Halpern et al. 2012; Jayasinghe et al. 2016), and the consumption of aquatic products *per capita* has doubled over the past 50 years and is expected to keep increasing (Carlucci et al. 2015; FAO 2016). Aquaculture has been growing since the late 1970s; it currently represents over half of the supply of aquatic products for direct human consumption (FAO 2016) and is expected to play a major role in the future supply of aquatic products to the world population (Duarte et al. 2009).

In sub-Saharan Africa, 22.7% of the population suffered from undernourishment in 2015–2016, and many countries are still highly dependent on food imports to achieve an adequate dietary energy supply (FAO 2017). To address these challenges, the Malabo Declaration, the Declaration on Nutrition Security for Inclusive Economic Growth and Sustainable Development in Africa, and the African Union Agenda 2063 envision the end of hunger and poverty in Africa by increasing sustainable food production and creating employment (African Union Assembly 2014a, 2014b; African Union 2015). Achieving sustainable development of the still-underdeveloped African aquaculture sector would be in line with this vision (Brummett et al. 2008).

Filter-feeding shellfish are organic extractors and therefore do not need formulated feed, which makes them an especially attractive form of aquaculture. Furthermore, shellfish culture provides important ecosystem services, such as nutrient removal and habitat enhancement. Bivalves reduce water turbidity, thus potentially improving the condition of submerged aquatic vegetation, and remove nitrogen from eutrophic systems by incorporating a proportion of it in their tissues; this has gained attention in recent years as a measure to complement land-based actions for nutrient management (Petersen et al. 2014; Rose et al. 2014; Clements and Comeau 2019). Finally, bivalves may help to control or prevent harmful algal blooms (Brigolin et al. 2009; Costa-Pierce 2010; Kellogg et al. 2014; Rose et al. 2014; Saurel 2014).

However, bivalve aquaculture may also have some negative impacts, including phytoplankton depletion in the water column, biodiversity loss, and anoxic conditions in the sediment through the accelerated deposition of suspended materials (Stenton-Dozey et al. 1999; Chamberlain et al. 2001; Zhang et al. 2009). These impacts are generally low and, as a rule, are contingent on the dispersion of

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biodeposits, which varies with location (Kaspar et al. 1985; Stenton-Dozey et al. 1999; Souchu et al. 2001; Jiang and Gibbs 2005; Zhang et al. 2009; McKindsey et al. 2011).

Ecological models can support decision-making for aquaculture development through the simulation of production and environmental effects of shellfish culture. Models of this type have been implemented to analyse production and ecological carrying capacity (see review in McKindsey et al. 2006). These models have been applied to different sites and species: Bacher et al. (1997) compared the results for Marennes-Oléron Bay, France, to those obtained in Carlingford Lough, Ireland, using a similar model; Luo et al. (2001) estimated the system carrying capacity for menhaden fish stocks in Chesapeake Bay, USA, using a spatially-explicit approach; Ferreira et al. (2008) considered mussel and oyster culture in northern Irish loughs; Brigolin et al. (2009) analysed nutrient fluxes through an offshore mussel farm in the Adriatic Sea, Italy, using a simple population-dynamics model; Nobre et al. (2010) combined catchment and system-scale models to simulate finfish and shellfish culture in Xiangshan Gang Bay, China; Guyondet et al. (2010) investigated system- and local-scale interactions of a mussel farm in Grande-Entrée Lagoon, Canada; Nunes et al. (2011) used various system- and local-scale models in Killary Harbour, Ireland; and Filgueira et al. (2014) developed a system-scale model to analyse oyster carrying capacity for the Richibucto Estuary, Canada. There are a number of studies relevant to the estimation of shellfish production carrying capacity in Saldanha Bay, South Africa (Figure 1), including Henry et al. (1977), Monteiro and Brundrit (1990), Grant et al. (1998), Pitcher and Calder (1998), Pitcher et al. (2015), Probyn et al. (2015) and Smith and Pitcher (2015); however, this is the first study that simulates shellfish aquaculture in Saldanha Bay by means of a dynamic modelling approach that accounts for hydrodynamics, the transport of dissolved and suspended matter, nutrient loading and biogeochemistry, phytoplankton production, sediment diagenesis, and growth of farmed shellfish populations based on individual physiological models.

Most coastal-system modelling developed in Africa has focused either on water circulation and salinity (e.g. Markull et al. 2014; Biastoch et al. 2018) or on phytoplankton dynamics (e.g. Lamont et al. 2018). The central question addressed in this work is whether the farming activities of 2015–2016 were within the production and ecological carrying capacity of Saldanha Bay, and to consider alternative development scenarios.

This work has four main objectives: (i) to describe the main environmental variables and processes and their interactions with aquaculture activities in Saldanha Bay; (ii) to establish the carrying capacity for shellfish production at the scale of the bay; (iii) to develop different production scenarios; and (iv) to illustrate the use of ecological models in supporting management decisions for Saldanha Bay.

Methods

Study area

Saldanha Bay (Figure 1) is located on the west coast of South Africa, about 100 km northwest of Cape Town, and is connected to the shallow tidal Langebaan Lagoon. Saldanha Bay consists of an outer bay and a shallower inner bay, which was considerably altered in the 1970s with the construction of a causeway for iron ore and oil terminals; this divided the inner bay into two distinct areas: Big Bay and Small Bay (Clark et al. 2012; Pitcher et al. 2015) (Figure 1). The lagoon area is about 40 km^2 (Flemming 1977) and the bay area is about 45 km^2 (Grant et al. 1998)—both are considered areas of high biodiversity (Clark et al. 2012).

The prevailing winds on the west coast of South Africa tend to be towards the equator, parallel to the coast, and induce upwelling (Harris 1978). The Benguela upwelling season lasts about 10 months, from August to May, at which time Saldanha Bay is typically stratified. This process is very important for water renewal, and during upwelling events the residence time is half the normal time of 20 days (Monteiro and Largier 1999). Thus, nutrient input is largely dependent on the advection of cold NO_3^- rich bottom water into the bay and the turbulent vertical flux across the thermocline. The tidal regime in this area is semi-diurnal with relatively low amplitude. Table 1 shows the sampling stations used for each variable considered in this study.

Tools used

The well-tested ecological model EcoWin.Net (Ferreira 1995) was used, incorporating data collected during the studies of Monteiro and Largier (1999) and Smith and Pitcher (2015), as well as information about shellfish farming practices from local farmers, and was calibrated using the AquaShell individual growth model (e.g. Saurel et al. 2014; Bricker et al. 2018). Figure 2 shows the components of the study.

The modelling approach was implemented through the following steps:

1. Application of a circulation model for Saldanha Bay, using Delft3D-FLOW (Roelvink and Van Banning 1995).
2. Upscaling the hydrodynamic outputs from Delft3D-FLOW into EcoWin and verification of consistency.
3. Processing of ecological data and addition of the main ecological variables into the model, including salinity, temperature, dissolved nutrients, suspended particulate matter, phytoplankton and shellfish (mussels and oysters).
4. Collection, processing and addition of information relating to farm culture practices into the model.
5. Model calibration and validation.
6. Development of production scenarios, simulation, and analysis.

Data collection

Profiles for temperature, salinity, dissolved oxygen, chlorophyll and nutrients, as well as solar radiation data, were collected bimonthly over a period of one year, from seven stations transecting Saldanha Bay, as described by Smith and Pitcher (2015) (Figure 1b). Data on suspended particulate matter (SPM) and particulate organic matter (POM) were obtained from TA Probyn (formerly Department of Agriculture, Forestry and Fisheries, unpublished data); these data were collected at several stations in the bay (Figure 1c), between 25 February and 8 March 1997 (for methods of data collection see Monteiro and Largier 1999). Figure 3 shows the main interactions among variables in the system, and the system connection to the ocean boundary.

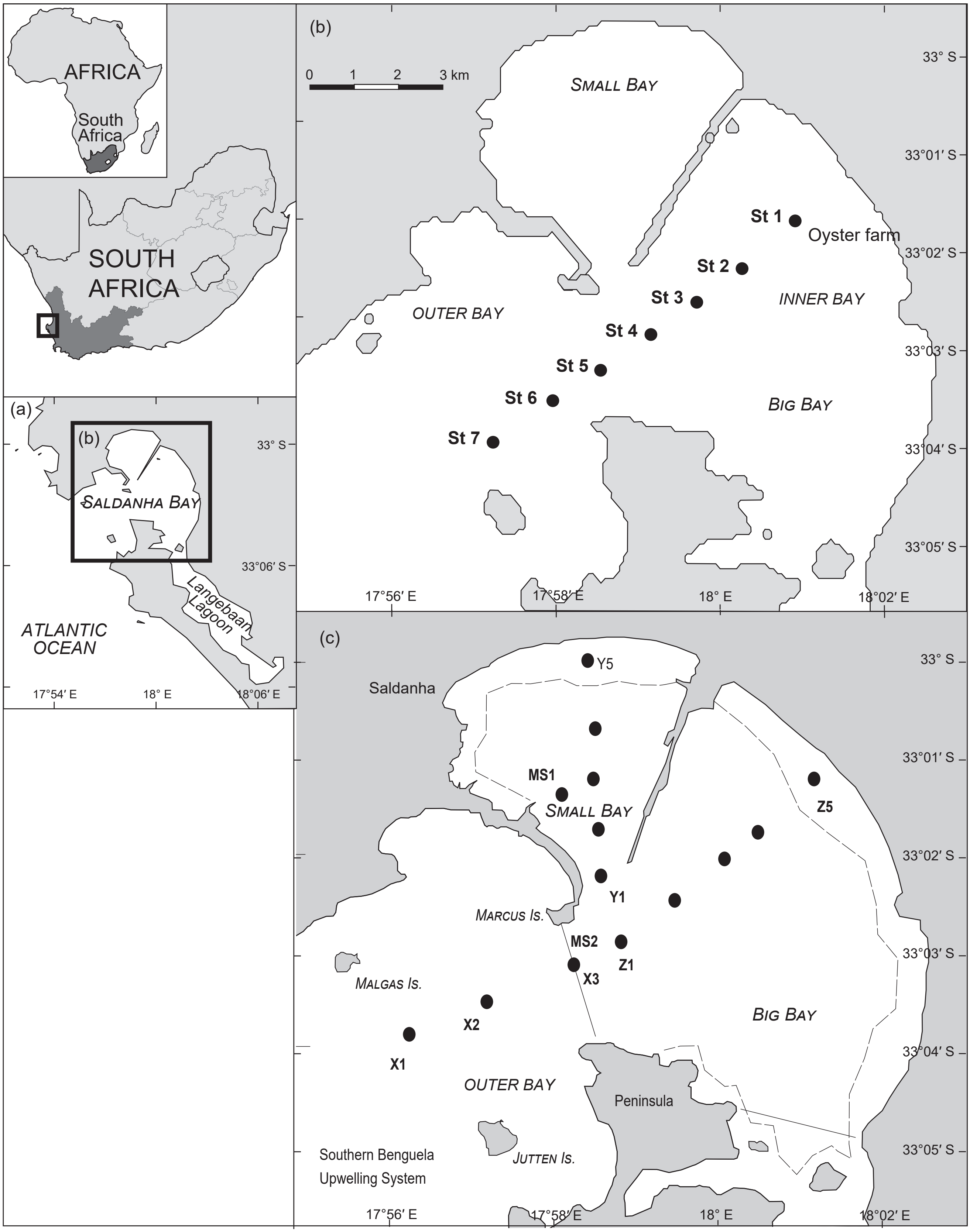

Figure 1: Maps showing locations of (a) Saldanha Bay; (b) spatial distribution of sampling stations of temperature, salinity, dissolved oxygen, chlorophyll, nutrients and light (after Smith and Pitcher [2015]); and (c) sampling stations for spatial distribution of particulate matter (after Monteiro and Largier [1999])

Table 1: The published study and the respective sampling stations used for each variable in the simulation of bivalve shellfish aquaculture in Saldanha Bay, South Africa. The locations of the sampling stations are shown in Figure 1

Source	Sampling station	Variable
Smith and Pitcher (2015)	7	Salinity
	1	Nutrients
	1	Phytoplankton
	1, 2, 3, 4, 5, 6, 7	Temperature, DO and light
TA Probyn (unpublished data), with methods described in Monteiro and Largier (1999)	X1, X2, X3	Suspended matter

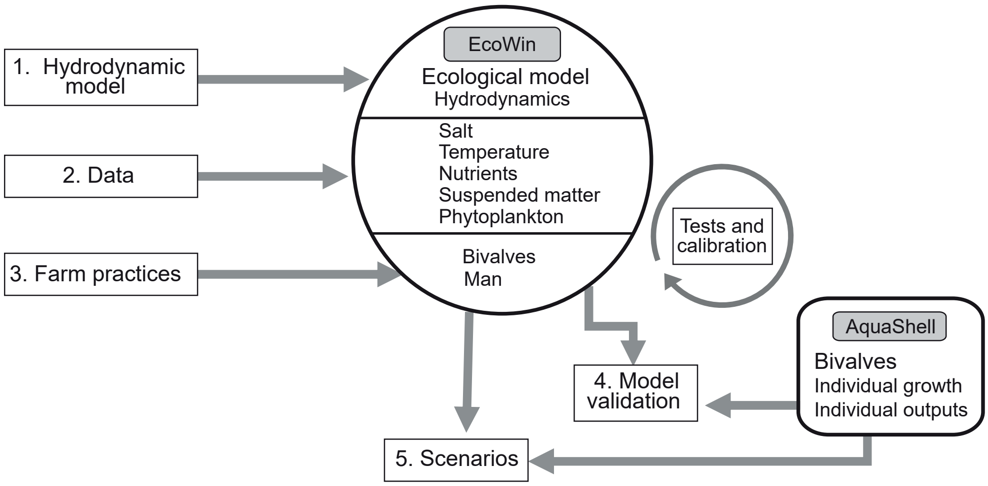

Figure 2: Diagram of components and interactions of the dynamic modelling approach used to simulate bivalve shellfish aquaculture in Saldanha Bay, South Africa

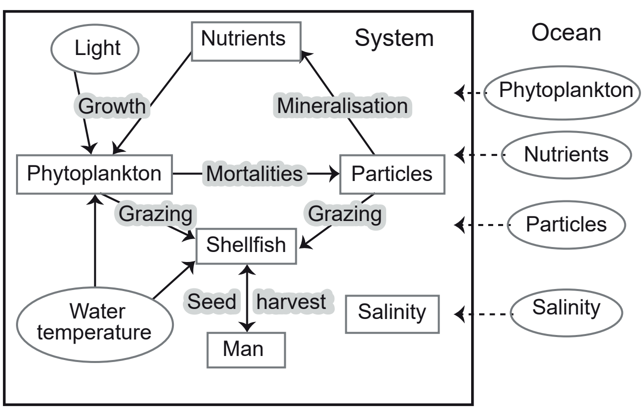

Figure 3: State variables (rectangles) and forcing functions (ovals) of the EcoWin ecological model used to simulate bivalve shellfish aquaculture in Saldanha Bay, South Africa

Hydrodynamic model

Water circulation was determined through application and upscaling of the Delft 3D-FLOW model (Roelvink and Van Banning 1995). Saldanha Bay was divided into eight boxes (four areas, each divided vertically into two), with a single boundary at the ocean interface. Only the Outer Bay (boxes 1 and 5) communicates directly with the ocean boundary, which was also divided into two layers (the upper and lower ocean) (Figure 4). Table 2 shows the sampling stations used for each box.

The hydrodynamic model deals with the transport of water and the water properties within the bay, providing EcoWin with flows (m^3 s^{-1}) across boundary interfaces for the eight boxes, as well as between the two outer boxes and the upper and lower ocean boundaries, using a time-step of two hours for a one-year cycle. The EcoWin 'hydrodynamics' object uses three variables: volume, salinity, and a conservative tracer to determine water residence time for intercalibration with the Delft3D-FLOW model outputs.

After validating the key variables, including the changes in box volume, number of tides per day, tidal amplitude, and the tidal synchronisation between boxes, the hydrodynamic model was coupled offline with EcoWin using a three-month set of outputs. Volume, salinity, and tracer outputs were obtained to validate water circulation in the upscaled model.

Ecological model

EcoWin.Net is an object-oriented ecological model that integrates hydrodynamics, biogeochemistry and the target aquaculture populations, where each object has its own properties (state variables, parameters, etc.) and methods (functions). EcoWin is appropriate for system-scale analysis

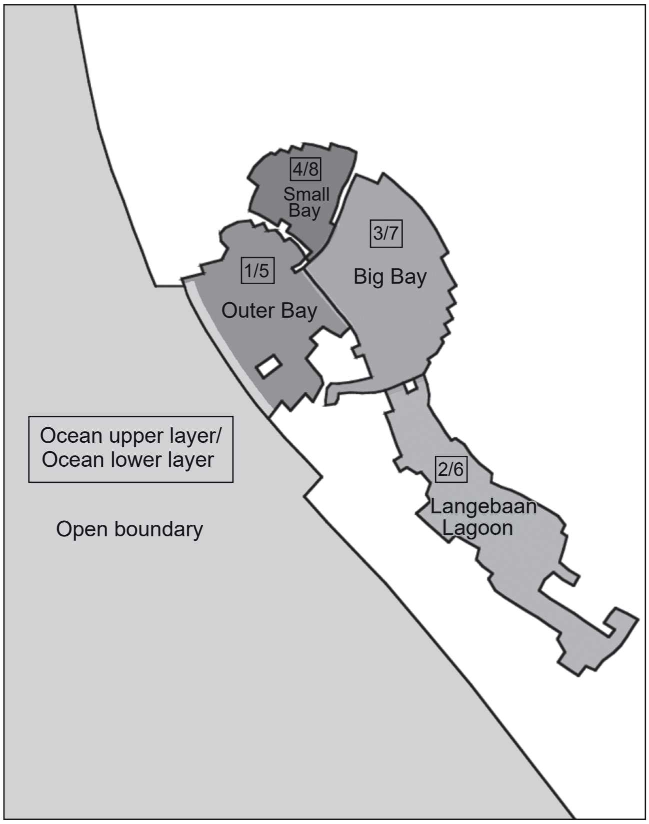

Figure 4: The eight boxes into which Saldanha Bay, South Africa, was divided for application of the EcoWin ecological model. Four areas were subdivided vertically into two layers

Table 2: Sampling stations used for each pair of boxes illustrated in Figure 4, for application of the EcoWin ecological model for Saldanha Bay, South Africa. For locations of the sampling stations, see Figure 1

Boxes	Stations
1/5	5, 6
3/7 and 4/8	2, 3, 4
2/6	1

and is typically used for multi-year simulations, dealing, for example, with multiple aquaculture cycles and species. The model concept can be found in Ferreira (1995), and examples of its application in Nobre et al. (2010), Nunes et al. (2011) and Bricker et al. (2018).

EcoWin uses a range of objects, including water temperature, salinity, light, suspended material (organic and inorganic), dissolved nutrients, phytoplankton and bivalve shellfish. These were inserted in two ways: either as state variables, or as forcing functions in each box and/or at the boundaries. Figure 5 shows the forcing functions used at the ocean boundaries for each parameter.

The AquaShell bivalve net-energy-balance model (Saurel et al. 2014) was used to calibrate the shellfish object by simulating the individual growth of oysters and mussels for site-specific ecological conditions. This code simulates how bivalve species will grow at a specific location based on environmental drivers such as water temperature, salinity, food (phytoplankton and non-phytoplankton organics) and suspended matter. The individual model is operated through the WinShell platform (Saurel et al. 2014), a workbench interface where environmental drivers and aquaculture practice are defined, and which provides outputs for analysis of model behaviour.

The ecological model was forced at the boundaries for the state variables, and internally through simulation of solar radiation and water temperature. Algorithms representing water temperature were developed for this study, and solar radiation at the surface was modelled after Brock (1981). This modelling approach follows previous work, such as by Bacher et al. (1997) and Ferreira et al. (2007, 2008). Table 3 shows the initial conditions used for each variable.

Water-temperature simulation

Water temperature is a critical variable for ecosystem models, since it is rate-limiting for key processes such as phytoplankton production and bivalve clearance and metabolic rates. In the present application of EcoWin, temperature was simulated by fitting a family of curves to measured data (see Figure 6). Since temperature distributions were not spatially homogenous, which is reasonable given the model framework of upper and lower boxes and the differences in circulation between the various bays and Langebaan Lagoon, data from different sampling stations were used to derive polynomial functions for each box. The water temperature was simulated in various parts of the bay over an annual cycle and iterated for multi-annual simulations.

The data available (Smith and Pitcher 2015) covered boxes 1, 3, 5 and 7 (Big Bay and Outer Bay). Based on information provided by Pitcher and Calder (1998), water temperature in Small Bay was considered identical to Big Bay and therefore the same curves were used. The temperature profile for station 1 was considered identical to Langebaan Lagoon, as both have relatively shallow water and higher temperatures (Henry et al. 1977); therefore, temperatures from this station were used to describe the profile inside the lagoon and to determine the curve for boxes 2 and 6. Figure 7 shows the equations used for each box.

The depths used for boxes 1 and 3 were 15.0 m and 6.6 m, respectively; box 2 was much shallower, with a depth of 1.9 m. The values for November, at all stations except station 1, had to be extrapolated. The similarities between curves allowed the use of results for station 1 (boxes 2 and 6) to guide the extrapolation for the remaining stations.

State variables

Pelagic state variables are forced at the ocean boundary, which means there is an independent flux from the ocean for each variable; the mass that enters across the ocean boundary is then transported, mixed, and produced or consumed within the system. The generic state variables are salinity, nutrients, phytoplankton, particulate matter (organic and inorganic) and bivalve shellfish (see 'Shellfish,' below).

'Salt' is part of the 'hydrodynamics' object, and the 'nutrients' object contains five state variables: ammonium, nitrite, nitrate, phosphate and silica. The 'phytoplankton'

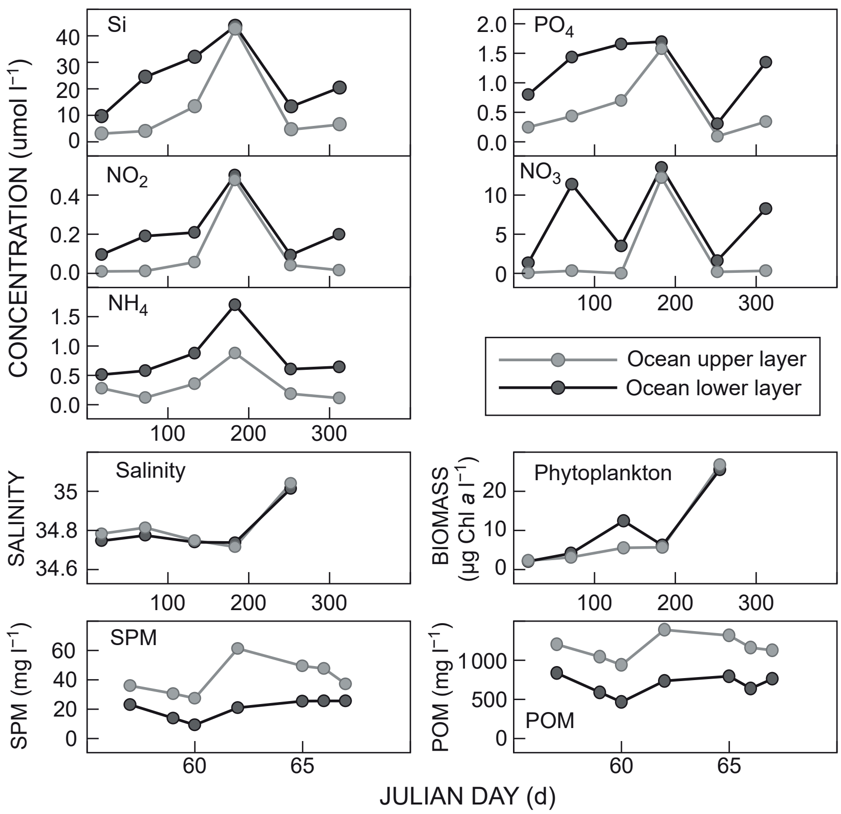

Figure 5: Ocean boundary condition curves (forcing functions) for silica (Si), phosphate (PO_4), nitrite (NO_2), nitrate (NO_3), ammonium (NH_4), salinity, phytoplankton biomass, suspended particulate matter (SPM), and particulate organic matter (POM), as used in the application of the EcoWin ecological model for Saldanha Bay, South Africa

Table 3: Initial conditions for state variables in each box defined for the application of the EcoWin ecological model for Saldanha Bay, South Africa. See Figure 4 for locations of boxes. POM = particulate organic matter; SPM = suspended particulate matter

Variable	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6	Box 7	Box 8
Salinity	34.79	34.86	34.80	34.80	34.74	34.78	34.76	34.76
NH_4^+ (µmol l^{-1})	0.28	0.28	0.28	0.28	0.52	0.52	0.52	0.52
NO_2^- (µmol l^{-1})	0.01	0.01	0.01	0.01	0.10	0.10	0.10	0.10
NO_3^- (µmol l^{-1})	0.07	0.07	0.07	0.07	1.35	1.35	1.35	1.35
PO_4^{3-} (µmol l^{-1})	0.24	0.24	0.24	0.24	0.80	0.80	0.80	0.80
Si^{2+} (µmol l^{-1})	3.27	3.27	3.27	3.27	9.80	9.80	9.80	9.80
POM (mg l^{-1})	4	4	4	4	4	4	4	4
SPM (mg l^{-1})	37	56	44	34	10	16	23	35
Phytoplankton (µg Chl *a* l^{-1})	8.6	2.3	5.5	5.5	3.9	2.1	11.0	11.0

object contains chlorophyll as a state variable, as well as derived variables such as phytoplankton carbon. The 'suspended matter' object contains two state variables: suspended particulate matter (SPM) and particulate organic matter (POM); internally, this object further subdivides the SPM variable into five subvariables predicated on granulometry, allowing for different sedimentation rates and the modelling of flocculation processes. Table 1 shows the source studies and the data used for each variable; the boundary curves for salinity, nutrients, particulate matter and phytoplankton are illustrated in Figure 5.

Initial conditions (Table 3) for salinity, nutrients, suspended matter and phytoplankton were determined for each box using the available data.

Parameters and equations

Standard parameterisation from other models, such as the Belfast Lough (Northern Ireland) model built by Ferreira et al. (2008), was used, and was tuned to this model system where applicable. The equations used for phytoplankton growth are a function of nutrient concentration in the Michaelis–Menten equation:

$$P = \frac{P_{max} \times [N]}{Ks + [N]} \tag{1}$$

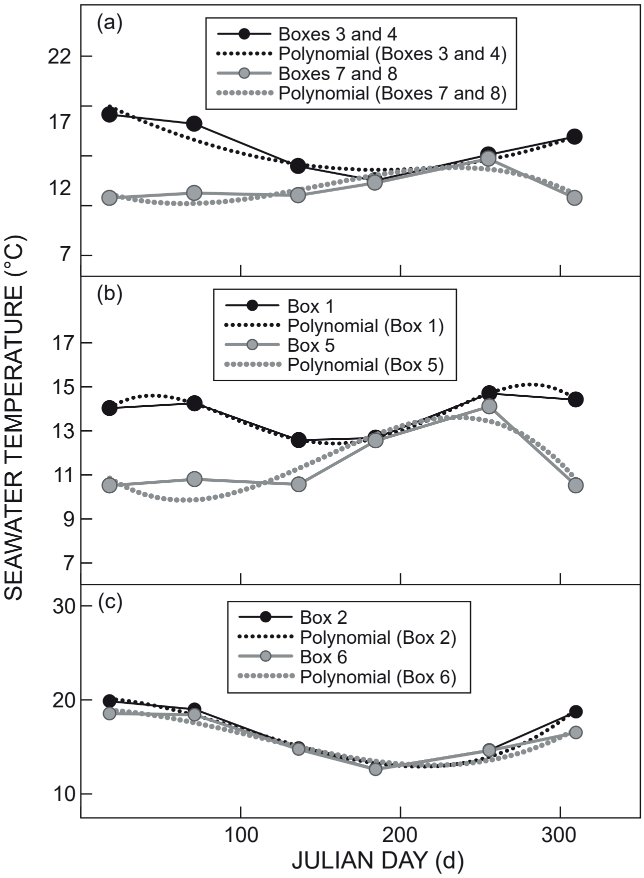

Figure 6: Water temperature curves (dashed lines) used for each box defined for the application of the EcoWin ecological model for Saldanha Bay, South Africa. See Figure 4 for box locations

where P_{max} is the maximum phytoplankton production, and Ks is the half-saturation constant; and a function of radiation intensity, as given in Steele (1962):

$$P_{pot} = \frac{P_{max} \times I}{I_{opt}} \times \exp(1 - \frac{I}{I_{opt}}) \tag{2}$$

where P_{pot} is the phytoplankton potential production, I is light energy at the depth of interest, and I_{opt} is the light energy at which maximum production (P_{max}) occurs. The parameters for phytoplankton and suspended matter are shown in Table 4. SPM resuspension and turbulence influence the vertical movement of SPM inside each box; the particulate organic carbon (POC) fraction defines the percentage of SPM that is POC; the POM mineralisation rate is the ratio that defines how much POM mineralises per day; and POM to nitrogen and POM to phosphorus define the POM mineralisation to N and P, respectively.

Shellfish

Information about the shellfish culture location, production areas, annual harvest and other aspects of culture practice was obtained through interviews with local growers in 2015–2016. At the time, mussels *Mytilus galloprovincialis* and oysters *Crassostrea gigas* were both farmed in Small Bay, whereas only oysters were farmed in Big Bay. Since farming takes place in a suspended culture, the farms are located in the upper model boxes (boxes 3 and 4).

Mussel production uses mostly natural seed, which, for modelling purposes, was considered to have a total fresh weight of 0.65 g per seed mussel. Based on the information provided by growers, a 10% annual mortality was used for both species.

The oyster and mussel growth potential were tested in WinShell, using temperature, SPM, POM, salinity and phytoplankton results from the EcoWin model. As WinShell does not consider competition and because shellfish growth is considered individually, these values were used only for calibration or for estimations of nutrient removal potential.

Box 1	$y = \begin{cases} -0.00000001229x^4 + 0.00000792921x^3 - 0.00157334324x^2 + 0.09711211252x + 12.75252362904, & 1 \le x \le 309 \\ -0.02810x + 23.10357, & 309 < x \le 365 \end{cases}$
Box 2	$y = \begin{cases} 0.000001568x^3 - 0.000502405x^2 + 0.001490460x + 20.230979965, & 1 \le x \le 309 \\ 0.02687x + 10.42470, & 309 < x \le 365 \end{cases}$
Boxes 3 and 4	$y = 0.0001672x^2 - 0.0625482x + 19.2913877, \quad 1 \le x \le 365$
Box 5	$y = \begin{cases} -0.000001538x^3 + 0.000689182x^2 - 0.069657333x + 11.893721175, & 1 \le x \le 309 \\ 0.02340x + 3.28452, & 309 < x \le 365 \end{cases}$
Box 6	$y = \begin{cases} 0.0000011501x^3 - 0.0003824031x^2 + 0.0016154650x + 18.9692831999, & 1 \le x \le 309 \\ 0.04400x + 2.90871, & 309 < x \le 365 \end{cases}$
Boxes 7 and 8	$y = \begin{cases} -0.000001101x^3 + 0.000494752x^2 - 0.050191880x + 12.376925798, & 1 \le x \le 309 \\ 0.01792x + 5.78498, & 309 < x \le 365 \end{cases}$

Figure 7: Seawater temperature forcing functions used for each box defined for application of the EcoWin ecological model for Saldanha Bay, South Africa

Table 4: Parameters used for phytoplankton and suspended particulate matter (SPM) in the EcoWin ecological model as applied to Saldanha Bay, South Africa. P_{max} = maximum phytoplankton production; Ks = half-saturation constant; I_{opt} = light energy at which P_{max} occurs; POC = particulate organic carbon; POM = particulate organic matter; DW = dry weight

Parameter	Value	Description
P_{max} (h^{-1})	0.3	Maximum phytoplankton production
Ks (µmol l^{-1})	2	Half-saturation constant
I_{opt} (W m^{-2})	200	Optimum light intensity
Dead loss (day^{-1})	0.01	Percentage of dead loss per day
Maintenance respiration (day^{-1})	0.4	Energy spent during low production (night)
Respiration coefficient (day^{-1})	0.3	Energy spending rate during production (day)
SPM resuspension (day^{-1})	0.50	Resuspension ratio to SPM
Turbulence (day^{-1})	0.10	Turbulence ratio
POC fraction (no units)	0.16	SPM fraction of POC
POM mineralisation rate (day^{-1})	0.060	POM mineralisation rate
POM to nitrogen (DW to N)	0.046	POM to nitrogen in mineralisation
POM to phosphorus (DW to P)	0.0034	POM to phosphorus in mineralisation

Oyster growth results obtained using WinShell for different POM scenarios are shown in Figure 8.

Two indices were used for the analysis of harvest in relation to seeding: average physical product (APP) and marginal physical product (MPP). APP was calculated for each run using the following equation:

$$APP_{x_1} = \frac{TPP_{x_1}}{x_1} \quad (3)$$

where x_1 is the initial stocking density of seed, considered the only variable input, and TPP_{x1} is the total physical product (harvest) for the initial stocking density.

MPP is the first-order derivative from the production function (Ferreira et al. 2007). Considering a constant input seeding price (P_x) and output price (P_y), the farmer's maximum profit will occur when the value of marginal product (VMP) equals P_x:

$$VMP = MPP \times P_y = P_x \quad (4)$$

This is based on the following assumptions: (i) inputs are unlimited; (ii) input purchases and output sales are made in a perfectly competitive market situation; (iii) the farm sells only this product; and (iv) seed is the only variable input (the remaining outlays are fixed costs).

Results and discussion

Ecological model calibration and validation

Water temperature and salinity

Confidence limits for temperature curves were determined after Sokal and Rohlf (1995), as $p_{0.05}$ = 0.811. All areas except the lagoon (boxes 2 and 6) were thermally stratified during summer (Figure 6), which is in agreement with Monteiro and Largier (1999). Water temperature in the upper boxes was higher during the summer; the lower boxes showed higher values during the winter as a result of weakening of the thermocline. Both seasonal temperature variation and the temperature range in each box are in agreement with previous observations in the bay.

Salinity showed an identical profile in all boxes, with the lowest values in winter (minimum of 34.7) and the highest values in spring (maximum of 35). These results fall within the observed range of variation.

Biogeochemical variables

The 'nutrients'-object-derived state variable used for primary production is dissolved inorganic nitrogen (DIN), namely $NH_4^+ + NO_2^- + NO_3^-$. The results showed a similar DIN profile in all boxes, with a higher peak in winter and two smaller peaks during summer; the results for boxes 3 and 4 are shown in Figure 9. The average DIN was 4 µmol l^{-1}, the maximum was 14 µmol l^{-1}, and the minimum value was close to 0 µmol l^{-1}. The results were considered acceptable after comparison with field data.

The results obtained for phosphate showed an identical curve for all boxes, with a major peak in winter and a lower point at the beginning of summer. The average PO_4^{3-} was 1 µmol l^{-1}, the maximum value was 1.7 µmol l^{-1}, and the minimum value was 0.3 µmol l^{-1}. The results were close to the measured concentrations.

The SPM curve showed four small peaks occurring approximately every three months and an average value of 26 mg l^{-1}. The lower boxes showed higher POM of ~1.8 mg l^{-1}, except in box 5. The upper boxes and box 5 had a lower average value of 1 mg l^{-1}. The results for both SPM and POM were within the measured values.

Phytoplankton biomass results were highest in September, with a peak of 16 µg Chl *a* l^{-1}, and an additional small peak in March. Only box 2 showed a slightly different pattern, with higher values during January and February, a higher peak during winter, and lower values in September. The average biomass was 7.5 µg Chl *a* l^{-1} and the minimum approximately 2 µg Chl *a* l^{-1}.

The phytoplankton biomass was strongly correlated (r > 0.919) with boundary values, suggesting that most of the biomass in the system originated from the ocean, which corresponds with what is known about the system: the bay has a short residence time of 20 days and an ocean boundary with the southern Benguela upwelling system—consequently, its phytoplankton supply is mainly driven by upwelling events (Monteiro and Largier 1999).

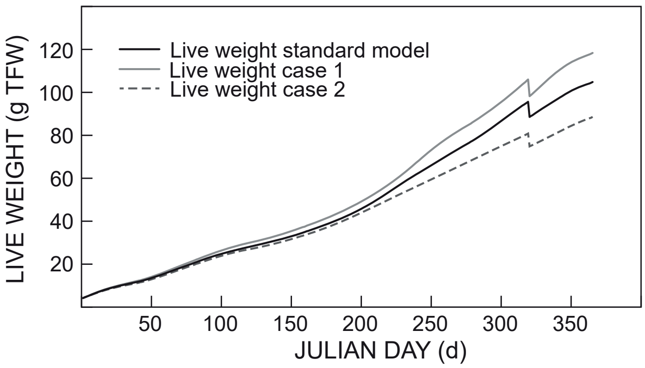

Figure 8: Individual growth curves of oysters obtained for three different scenarios in Saldanha Bay: the standard model (mean 1.1 mg l^{-1} POM), case 1 (mean 1.3 mg l^{-1} POM), and case 2 (mean 0.9 mg l^{-1} POM). POM = particulate organic matter; TFW = total fresh weight or total live weight

The mean phytoplankton results for each box before and after adding the shellfish farms to the model are shown in Figure 10.

Several studies have reported phytoplankton biomass in Saldanha Bay: Henry et al. (1977) and Pitcher et al. (2015) found values between 5 and 32 µg Chl *a* l^{-1}, with means of 12.1 µg Chl *a* l^{-1} and 15.5 µg Chl *a* l^{-1}, respectively; and Smith and Pitcher (2015) and Pitcher and Calder (1998) found a mean of 8.6 µg Chl *a* l^{-1}. When compared with those studies, the phytoplankton results appear acceptable, with the mean of 7.5 µg Chl *a* l^{-1} slightly lower than those given by Smith and Pitcher (2015) and Pitcher and Calder (1998).

Smith and Pitcher (2015) describe the phytoplankton biomass in Saldanha Bay as being lower during the winter months and increasing during the summer, reaching maximum values in April. Our results for phytoplankton biomass have a minimum in January, a similar reduction during the winter months, and a small peak in April, but the maximum biomass occurs in September. Pitcher and Calder (1998) also reported two similar peaks, one in April and another in September, although the September peak was not the highest biomass for the year. Henry et al. (1977) found a similar profile, with one peak in April and another in October. The modelled phytoplankton concentration agrees in general with these studies and shows similar peaks on a seasonal, and in some cases on a monthly, basis.

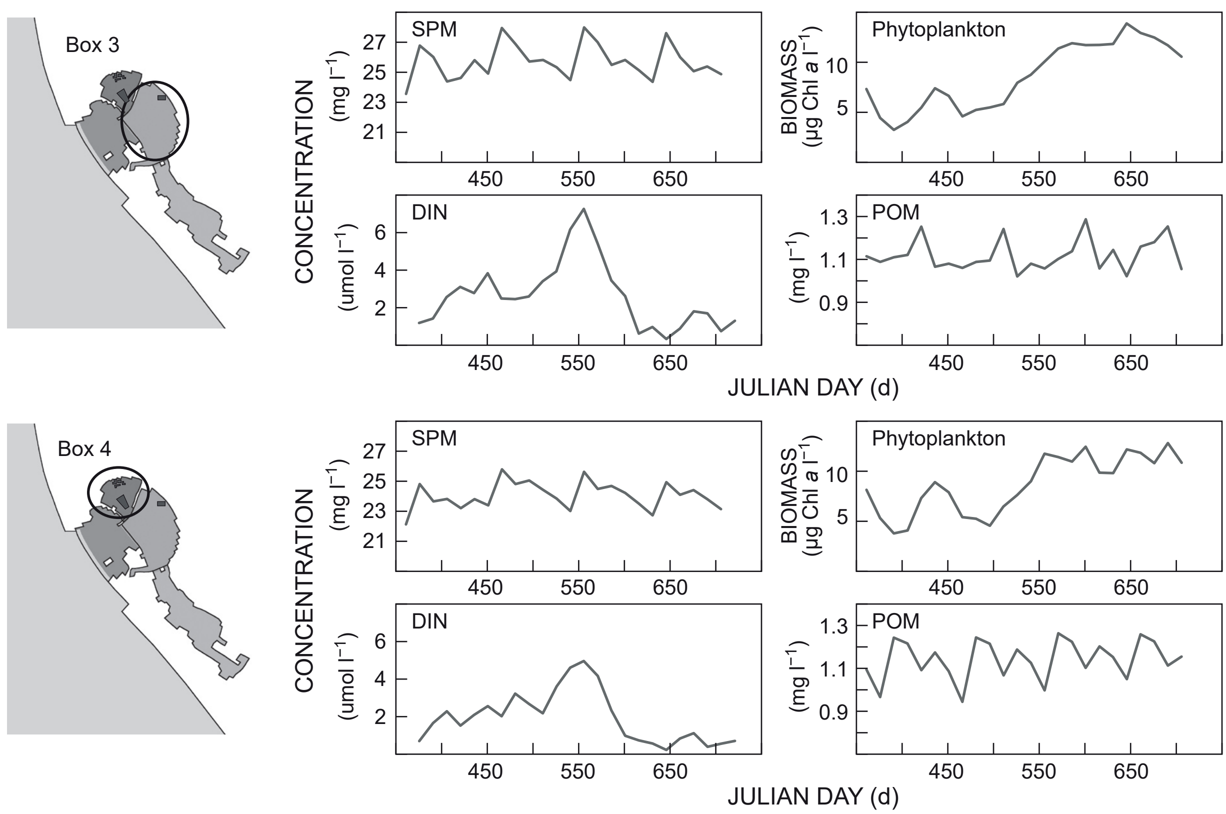

Figure 9: EcoWin results for boxes 3 and 4, for suspended particulate matter (SPM), phytoplankton biomass, dissolved inorganic nitrogen (DIN) and particulate organic matter (POM), in Saldanha Bay, South Africa

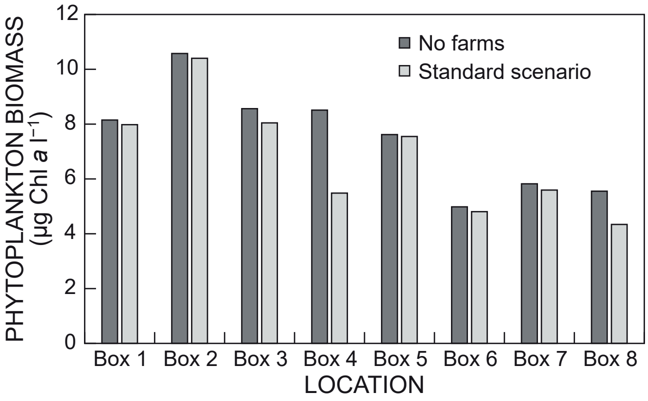

Figure 10: Mean phytoplankton for each box, before (no farms) and after (standard scenario) adding shellfish farms to the EcoWin model as applied for Saldanha Bay, South Africa. For box locations see Figure 4

Ecological variables in boxes 3 and 4

As the farms are located in boxes 3 and 4 (Big Bay and Small Bay, respectively), their results were analysed in more detail (Figure 9). The two boxes had very similar curves and an average phytoplankton biomass of 8.6 µg Chl *a* l^{-1}. The conditions shown in Figure 9 were validated in AquaShell, where individual oyster and mussel weights grew to (or above) the estimated mean weight for both boxes in one year (Figure 11).

Standard scenario

The estimated harvest was based on information provided by local farmers (Tables 5 and 6); the model was calibrated by tuning the different parameters to obtain harvest results close to these estimates (Figure 12). These results are summarised in Table 7, and the modelled harvest compares well with the expected harvest.

Box 4 produced larger oysters (130 g) than box 3 (125 g) (Figure 11a, b). The modelled individual weight of mussels was approximately 37 g after 13 months (Figure 11c). Individual mussel weights were within values estimated by local farmers (25–40 g live weight [LW]), whereas individual oyster weights were higher than the estimated mean (70 g). The WinShell simulation for Small Bay yielded slightly higher phytoplankton biomass than Big Bay, and therefore the modelled growth of oysters was better in Small Bay. The characteristics of the oyster and mussel farms in Saldanha Bay are summarised in Table 6.

WinShell focuses only on individual growth, and does not consider competition or other population interactions, although EcoWin can do so, since this can be an important factor in partitioning the food resource (Heasman 1996; Boyd and Heasman 1998). As a result, the smaller dimensions and higher seeding in Small Bay in comparison with Big Bay are not considered in AquaShell. The AquaShell results were simply used to test whether the conditions inside the bay allow the shellfish to grow to the expected individual weight. Changing a parameter such as POM mineralisation in the EcoWin model alters the POM outputs, which are then used as environmental inputs into AquaShell and change the bivalve growth rate results. The sensitivity analysis in

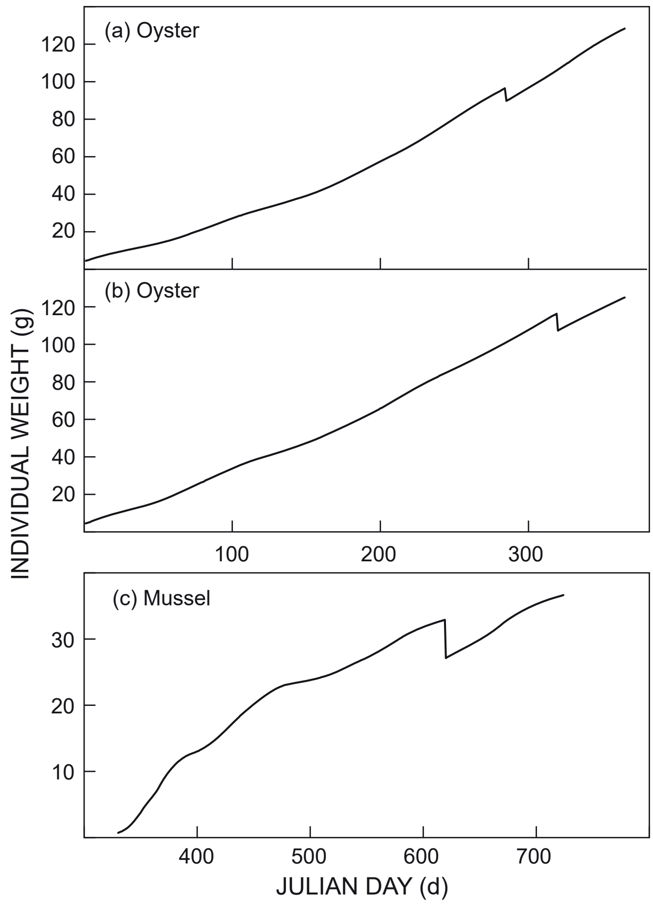

Figure 11: Oyster individual growth curves, as simulated using the AquaShell model in (a) box 3 and (b) box 4; (c) mussel individual growth curve in box 4, in Saldanha Bay, South Africa. Box locations are given in Figure 4

Figure 8 shows the variation in oyster growth: the standard model with a mean POM concentration of 1.1 mg l^{-1}, case 1 with 1.3 mg l^{-1}, and case 3 with 0.9 mg l^{-1}, which demonstrates how further calibration could more closely approximate the modelled individual weight to the real values. Figure 13 illustrates the variation in oyster production in Big Bay with different stocking densities.

As illustrated in Figure 10, the introduction of shellfish impacts the phytoplankton biomass as a result of top-down control. Boxes 4 and 8 showed the greatest differences, followed by boxes 3 and 7. The impact in the remaining boxes was not significant. The average difference in phytoplankton biomass was 3 µg Chl *a* l^{-1} (35%) in box 4, and 1.2 µg Chl *a* l^{-1} (21%) in box 8, but in boxes 1 and 7 it was only 0.5 µg Chl *a* l^{-1} (6%) and 0.2 µg Chl *a* l^{-1} (4%), respectively.

The farms are located in boxes 3 and 4, but box 3 has triple the volume and 20% of the production, indicating that box 4 is under greater filter-feeding pressure than box 3. Consequently, shellfish farms have a greater impact on phytoplankton biomass in box 4 and the underlying box 8.

Most of the literature reviewed, such as Pitcher and Calder (1998), Pitcher et al. (2015), and Smith and Pitcher

Table 5: Bivalve shellfish aquaculture companies working in Saldanha Bay, South Africa, the size of the area in which they are licenced to operate, and their annual production

Product	Company	Location	Area (ha)	Annual production (tonnes)
Oysters	Saldanha Bay Oyster Company	Small Bay and Big Bay	10 + 25	525
	West Coast	Big Bay	5	140
	Blue Safire Pearls	Small Bay	5	40
Total			45	705
Mussels	Imbaza Mussels	Small Bay	30	1 000
	Blue Ocean Mussels	Small Bay	50	1 000
Total			80	2 000

Table 6: Mussel and oyster production, number of seeds, farm area, seed and harvested shellfish weight in Saldanha Bay, South Africa

Shellfish	Parameters	Box 3 (Big Bay)	Box 4 (Small Bay)
Mussel	Farm area (ha)	–	80
	Number of seed mussels	–	50 million
	Seed weight (g)	–	0.65
	Harvested weight (g)	–	25–40
Oyster	Farm area (ha)	30	15
	Number of seed oysters	5 million	2 million
	Seed weight (g)	4.3	4.3
	Harvested weight (g)	70	70

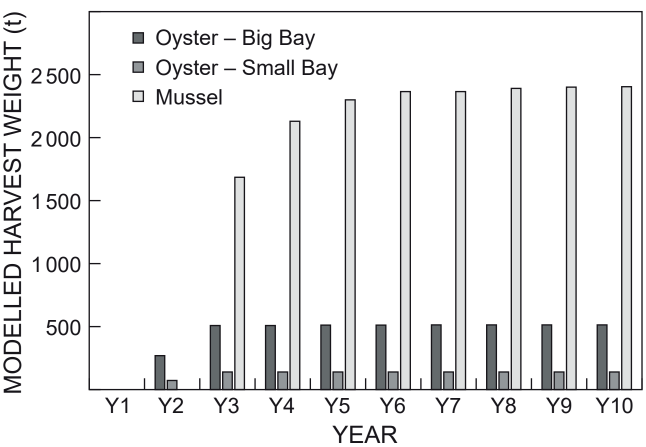

Figure 12: The harvested shellfish weight for each aquaculture species and location in Saldanha Bay, estimated for the standard scenario (i.e. with shellfish farms present) using the EcoWin model

(2015), reports on similar conditions to those simulated in the standard scenario (i.e. with top-down control from shellfish farms). The modelled phytoplankton biomass obtained for Small Bay was low, which is consistent with Pitcher and Calder (1998).

The standard scenario was then validated, and the modelled and estimated harvest are a good match (Table 7). The tested mussel size matches the actual farmed size, and the oyster size is acceptable for modelling purposes. Phytoplankton biomass is also realistic when compared with measured values.

The model provides results on the influence of the farms on the ecosystem and allows an estimation of ecosystem services and possible impacts created by the present-day farming activity. The present aquaculture activities remove approximately 38 tonnes (t) of Chl *a*, 126 t of nitrogen, and 6 500 t of POM. This improves water quality and compensates for human nutrient inputs. Considering an annual generation of ~5 kg N per capita (Van Drecht et al. 2003), and a population of 21 600 people in the town of Saldanha and 8 000 in Langebaan, this would represent an annual discharge of 148 t of N into the bay and lagoon area. The present cultivation of shellfish potentially removes about 85% of human nitrogen inputs.

Production carrying capacity

Local stakeholders requested the model results for Small Bay, mentioning their interest in increasing aquaculture production here, but production carrying capacity was determined for both Small Bay and Big Bay. Due to the bay morphology, farming activities in Big Bay significantly influence phytoplankton availability in Small Bay.

Small Bay

The carrying capacity for Small Bay was calculated by iteratively increasing the stocking density of both mussels and oysters. For the mussel carrying-capacity scenario, as mussel production was increased, the production of oyster farms was not altered from the standard seeding scenario. Similarly, for the oyster carrying-capacity scenario, the production in mussel farms was also the same as in the standard scenario. Figure 14 illustrates the harvest obtained for different seed-stocking densities for both species. The maximum production achieved was ~5 100 t live weight of

Table 7: Modelled and estimated annual production for each box and shellfish species farmed in Saldanha Bay, South Africa, in 2015

Shellfish annual production		Box 3 (Big Bay)	Box 4 (Small Bay)
Mussel production (t y^{-1})	Estimated	–	2 400
	Modelled	–	2 400
Oyster production (t y^{-1})	Estimated	520	150
	Modelled	500	140

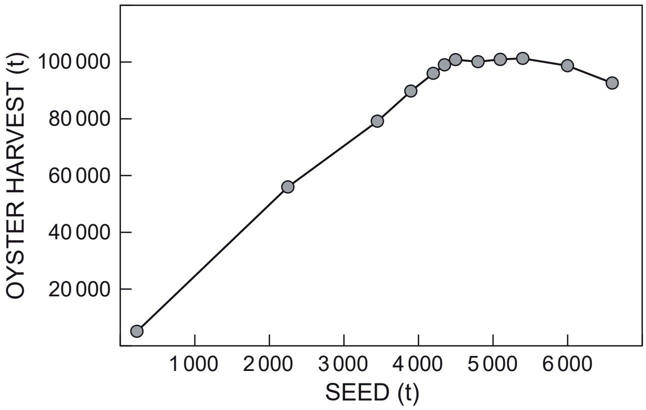

Figure 13: Modelled oyster harvest for different seeding densities in the Big Bay portion of Saldanha Bay, South Africa, using the EcoWin model

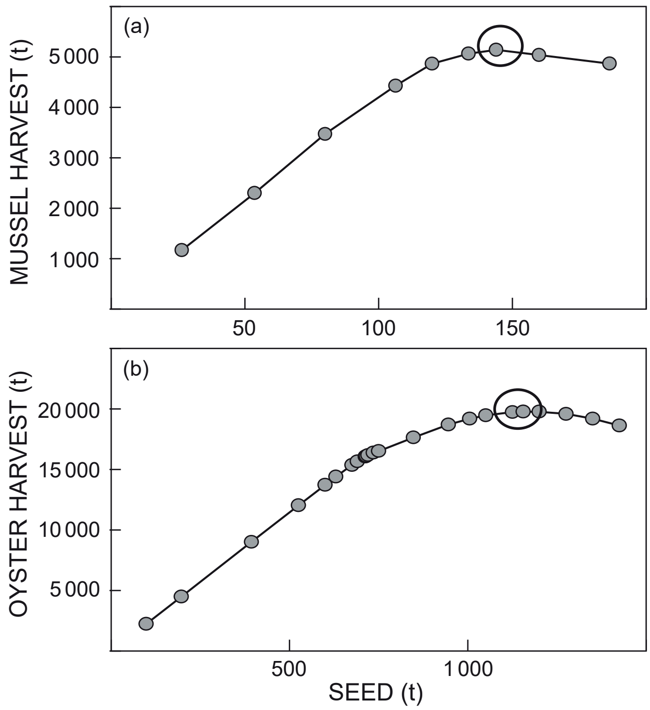

Figure 14: The modelled harvest for different seeding densities of (a) mussels and (b) oysters inside the Small Bay portion of Saldanha Bay, South Africa; the maximum production capacity for each species is circled. t = tonnes

mussels with seeding of ~145 t, and ~20 000 t live weight of oysters with seeding of ~1 200 t. Small Bay's carrying capacity for oyster production is about four-times higher than for mussel production.

The production carrying capacity maximises income but not necessarily profit, due to diminishing returns. At higher stocking densities, growth rates are typically lower (Figure 15) as a consequence of food depletion—and smaller shellfish have a lower market value; in parallel, higher seeding density has greater costs associated with seed purchase and farm maintenance (Ferreira et al. 2007).

Big Bay

The maximum production capacity for oyster production in Big Bay was calculated by maximising the production of oysters, the only species produced; the seeding density was gradually increased in this box, and the remaining farms (i.e. those in Small Bay) were kept at the standard-scenario stocking density. The maximum production for Big Bay would be 100 000 t of oysters (Figure 13) using a stocking density of 4 500 t.

The calculated oyster production capacity is about five-times higher in Big Bay than in Small Bay, which is reasonable since Big Bay is about three-times greater in volume and has higher food availability. Big Bay is also more exposed to the ocean, where most phytoplankton originates, and hence feed renewal and availability for shellfish are higher.

Impacts of shellfish farming on Small Bay and Big Bay

The scenario results for production carrying capacity in Small Bay suggest there are significant impacts of farming on phytoplankton concentration. When compared with the standard scenario (Figure 16), the phytoplankton biomass is considerably lower in boxes 4 and 8, and remains almost unchanged in the remaining boxes (i.e. elsewhere in the Saldanha Bay system), which means the impact would be mostly in Small Bay.

The Big Bay carrying-capacity scenario shows that the phytoplankton concentration is affected in the entire Saldanha Bay system. This is explained by two main factors: (i) most phytoplankton is supplied across the ocean boundary (rather than through internal primary production); and (ii) the morphology of Saldanha Bay is such that Big Bay is the connection between the main phytoplankton source and the remaining areas. As a result, the greater uptake in Big Bay means that less is available in the other areas. The carrying-capacity scenario increases the annual oyster production from 520 t to 100 000 t, significantly increasing the grazing pressure on the phytoplankton biomass. The consequences of this for natural communities of benthic filter-feeders would warrant examination.

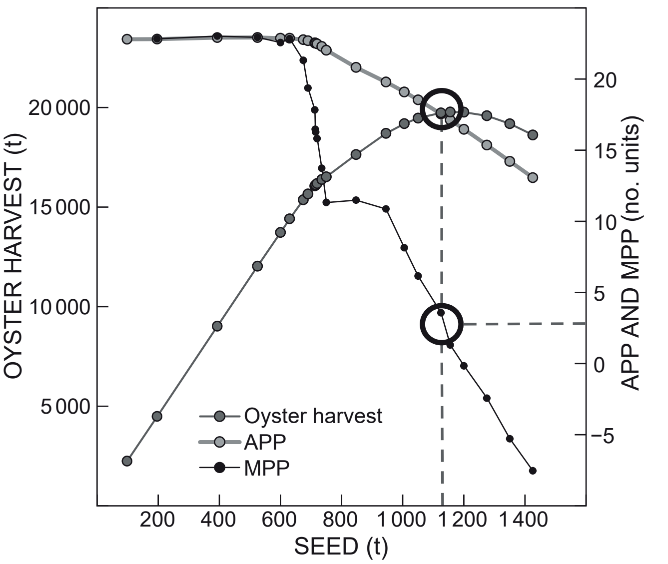

Figure 15: Harvest, average physical product (APP), and marginal physical product (MPP) for different seeding densities. Circles denote the point with the most profitable scenario in Small Bay (top) and the corresponding MPP (bottom). t = tonnes

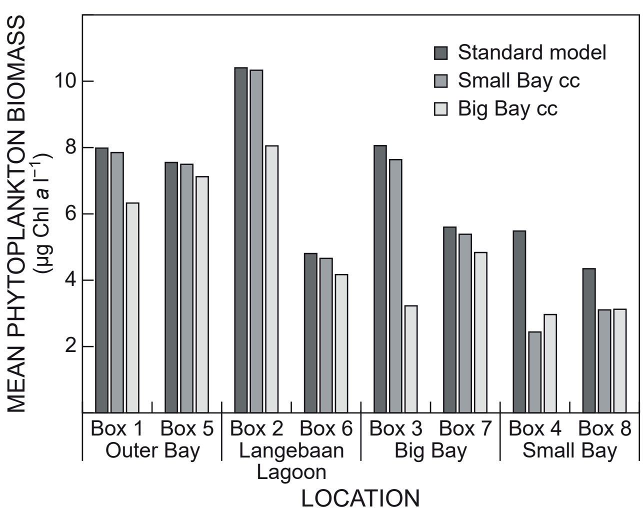

Figure 16: Average phytoplankton biomass for each box in the standard model, in Small Bay at maximum production capacity, and in Big Bay at maximum production capacity. cc = carrying capacity. Box locations are given in Figure 4

Sequeira et al. (2008) suggest that overstocking of cultivated bivalves might affect benthic biodiversity through food competition. Given that the two carrying-capacity scenarios would result in a large reduction in phytoplankton biomass in the water column, they would probably have considerable effects on wild benthic filter-feeders. Hence, further research is necessary to assess the impact of different seeding intensities on natural benthic populations. The impact of biodeposition under the farms could also be significant under certain conditions; this is an important potential impact, which should be investigated by means of a different research approach that combines field measurements with local-scale deposition models. Such impacts have been modelled by, for example, Guyondet et al. (2015) for a bay in Canada that is used for shellfish culture.

Production scenarios

Local stakeholders showed greater interest in the expansion of farming operations in Small Bay than in Big Bay. Therefore, two scenarios were developed and analysed for Small Bay: (i) increasing oyster production to maximum profitability through analysis of the marginal physical product (MPP), and (ii) increasing mussel production to 4 000 t LW y^{-1}.

Scenario 1

A mussel production curve (Figure 14) was used to determine the stocking density needed to achieve an increased mussel harvest of 4 000 t LW y^{-1}, a number proposed by the local aquaculture industry. As shown in Figure 14, the required seed stock would be ~90 t, which is still considerably less than the seed stock required to achieve the production carrying capacity for mussels in Small Bay (Figure 14).

Scenario 2

An input seeding price (P_x) of €12 000 and an output price of €4 600 were considered, for which the maximum marginal profit would be achieved with an MPP of ~2.6. Figure 15 shows that the maximum profit is achieved with approximately 1 130 t of seed, and corresponds to a harvest of ~19 700 t, which is slightly below the amount required for maximum production capacity, at 1 200 t.

Impacts under scenarios 1 and 2

Production under scenario 2 would translate into a farmgate revenue of about €90 million, with clear positive social impacts for the local community. According to Olivier et al. (2013) there is a ratio of 89 employees for each 1 000 t shellfish produced, meaning that this level of production could employ 1 753 people, about 1 463 more than were employed in 2015–2016.

In the future, policymakers and marine shellfish farmers could consider developing a nutrient credit-trading market, as occurs in parts of the United States (Bricker et al. 2018), which could represent an added income from regulating ecosystem services. EcoWin scenario 1 has the potential to remove ~310 t of N, representing an annual income of between €3 million and €86 million. This revenue would be between 20% and 670% of the estimated income, a significant potential increase for the industry. Further analysis would be necessary to determine whether these scenarios would have other user conflicts or impacts on local activities such as fisheries. User conflicts could affect both the social and physical carrying capacity, and could reduce the carrying capacity for Small Bay.

Both scenarios have impacts on phytoplankton availability in the water column (Figure 17), mainly in Small Bay (where the modelled farming activities were intensified), and no relevant impacts on the remaining boxes. Scenario 2 has the biggest impacts, in which box 4 has approximately half the phytoplankton biomass of scenario 1. The observed

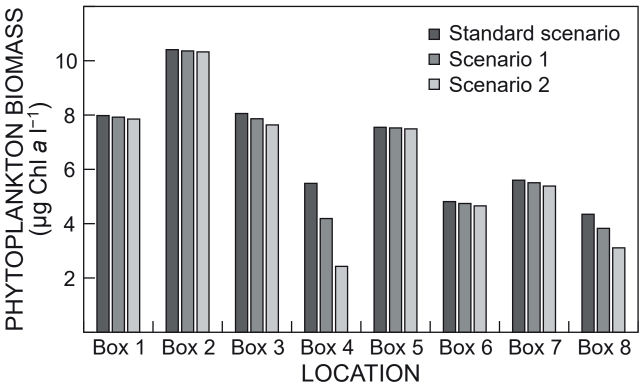

Figure 17: Comparison of average phytoplankton biomass in each box, under the standard model, scenario 1 (a mussel harvest of 4 000 t LW y^{-1} in Small Bay), and scenario 2 (a seeding density of ~1 130 t and a harvest of ~19 700 t in Small Bay). Box locations are given in Figure 4

phytoplankton depletion might contribute positively by increasing underwater light availability and promoting the growth of submerged aquatic vegetation, which might enhance fish nursery areas. However, phytoplankton depletion could negatively impact both the naturally occurring benthic filter-feeders and the pelagic food web.

Conclusions

This work implemented and applied a model that successfully describes the main interactions in the aquatic ecosystem of Saldanha Bay and that can simulate the response of the ecosystem to different inputs. It produced several production scenarios and is the first study to determine the production carrying capacity for shellfish in Saldanha Bay using an ecological model.

Production carrying capacity was determined separately for the Small Bay and Big Bay areas, showing that both areas in 2015–2016 were below their carrying capacity. The carrying capacity of Small Bay was calculated separately for oysters and mussels and showed a higher capacity for oysters (20 000 t y^{-1}) than for mussels (5 100 t y^{-1}). The Big Bay area had the biggest production potential, with ~100 000 t y^{-1} of oysters. The maximum-production scenarios are normally not the most profitable option for farmers, as the increased costs of seeding are not matched by proportionally higher harvests. The Big Bay production-capacity scenario exemplifies the ecological model's potential for studying the spatial influence of input changes, as the increase of seeding density in this area affects phytoplankton availability in all the remaining boxes.

In response to the interest shown by local farmers in increasing production inside Small Bay, two production scenarios were developed: scenario 1 simulated an increase in mussel harvest in Small Bay from 2 400 t y^{-1} to 4 000 t y^{-1} (a number suggested by local farmers); scenario 2 raised oyster harvest in the same area from 150 t y^{-1} up to the most profitable scenario, using the MPP of 19 700 t y^{-1}. This suggests that bivalve aquaculture in Saldanha Bay still has substantial growth potential. In both scenarios, the phytoplankton biomass is reduced, mainly in Small Bay where the modelled production is intensified.

It is difficult to analyse whether the chlorophyll depletion in any of the scenarios would have negative impacts on wild filter-feeders or on zooplankton biomass without a baseline study to determine the abundance, diversity and needs of naturally occurring benthic filter-feeders.

Better data for boundary conditions for water temperature, dissolved nutrients, suspended matter and phytoplankton would improve the model's accuracy and value; the present work relied on available data from different studies, which did not cover the full temporal and spatial range. The development of a finer-grid hydrodynamic model would also significantly improve model accuracy.

Data collection for the introduction of naturally occurring benthic filter-feeders and zooplankton in the model would increase its power with regard to ecological impact assessment; adding these variables would incorporate resource partitioning between wild and cultivated organisms, making it possible to analyse the farming impacts on the benthic environment. The addition of zooplankton would further allow an indirect analysis of aquaculture impacts on higher trophic levels in the ecosystem and consequently on the fishing industry.

The EcoWin model is a powerful management framework for aquaculture that can be used by decisionmakers to maximise social, economic, and environmental benefits of bivalve shellfish aquaculture in Saldanha Bay by making it possible to predict ecological and productivity outcomes of different production and expansion strategies.

By using system-scale tools in conjunction with local-scale models such as FARM (Ferreira et al. 2007; Bricker et al. 2018), policymakers can test the impact of system-level changes to drivers and pressures on the performance of individual farms. Shellfish farm managers could also use this toolset for marginal analysis at the scale of a set of rafts or longlines, to optimise seeding for profit maximisation.

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