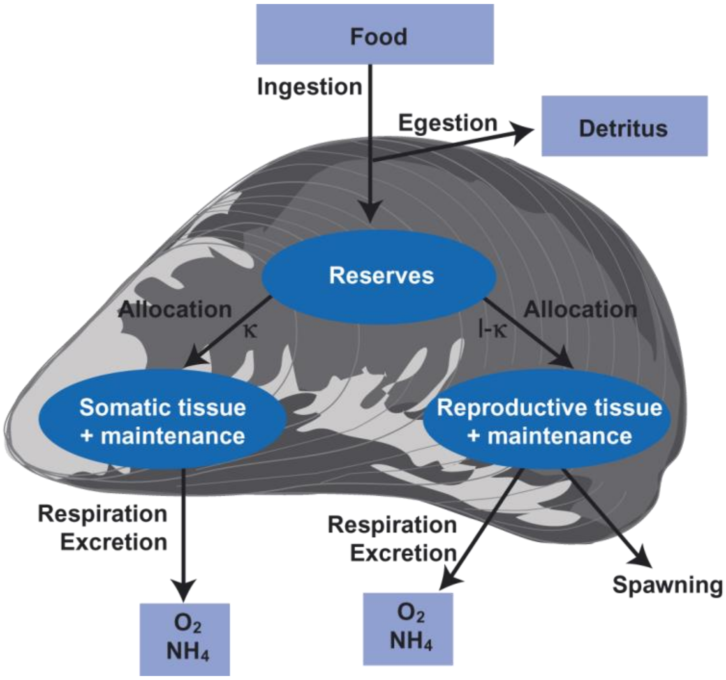
Supplementary Material

A.1. DEB Modelling



Supplementary Figure 1. Diagram of the Dynamic Energy Budget (DEB) model for blue mussels showing carbon flow (arrows), DEB state variables (spheres) and input/output variables (squares). From Maar et al. (2015).

Supplementary Table 1. Applied DEB parameters. The values are shown both for moles and joules using the conversion factor 6.97×105 J/mol-C (Saraiva et al. 2011).

Parameter	**Symbol**	**Value**	**Unit**	**Values in joules**	**Reference**
Maximum ingestion rate	J_{XM}	7×10^{-4}	mol-C cm^{-2} d^{-1}	488	Maar et al. 2015
Half saturation coefficient	X_K	0.8	mg-chl *a* m^{-3}	-	This study
Assimilation efficiency	K_A	0.80	-	-	Kiørboe et al. 1981
Fraction to growth and maintenance	κ	0.70	-	-	Van der Veer et al. 2006
Maximum storage capacity	E_M	2.06×10^{-3}	mol-C cm^{-3}	1438	Saraiva et al. 2011
Volume specific cost for growth	E_G	8.6×10^{-3}	mol-C cm^{-3}	5993	Saraiva et al. 2011
Volume specific maintenance cost	P_M	8.26×10^{-5}	mol-C cm^{-3} d^{-1}	57.6	This study
Maintenance cost osmoregulation	σ	2.9×10^{-5}	mol-C cm^{-2} d^{-1}	20.3	This study
Salinity threshold	S_R	16.2	-	-	Almada-Villeda et al. 1984
Chl *a* upper threshold	Chl_{ut}	17	mg m^{-3}	-	This study
Chl *a* lower threshold	Chl_{lt}	0.5	mg m^{-3}	-	Dolmer 2000
Chl *a* filtration response	D_r	-0.03	m^3 mg^{-1}	-	This study
Volume specific structural mass	*DVM*	7.93×10^{-3}	mol-C cm^{-3}	5527	Saraiva et al. 2011
Structural volume at sexual maturity	V_p	0.43	cm^3	-	Maar et al. 2018
Shape factor	δ_v	0.305	-	-	Maar et al. 2015
Reproductive efficiency	K_r	0.95	-	-	Kooijman 2010
Dry weight to wet weight ratio of structure		0.20	-	-	Maar et al. 2015
Gonado-somatic index	*GSI*	0.25	-	-	Saraiva et al. 2011
Minimum spawning temperature	T_{min}	9.6	°C	-	Pers. Obs.
Spawning rate		0.95	d^{-1}	-	Maar et al. 2018

Dry weight to mol-C of tissue and gonads		25.22	g-DW mol-C^{-1}	-	Saraiva et al. 2011
Arrhenius temperature	T_A	5800	K	-	Van der Veer et al. 2006
Lower temperature boundary	T_L	275	K	-	Van der Veer et al. 2006
Upper temperature boundary	T_H	296	K	-	Van der Veer et al. 2006
Arrhenius temperature for rate of decrease at lower boundary	T_{TAL}	45430	K	-	Van der Veer et al. 2006
Arrhenius temperature for rate of decrease at upper boundary	T_{TAH}	31376	K	-	Van der Veer et al. 2006
Reference temperature	T_1	289	K	-	Van der Veer et al. 2006

Supplementary Table 2. DEB variables, symbols, equations and units. All physiological rates in the model depend on temperature (not shown in equations). Input data: T = temperature, X = Chl *a* concentration.

Variables	Symbol	Equation	Unit
Processes:			
Temperature function	T_{corr}	$T_{corr} = \exp\left(\frac{T_A}{T_r} - \frac{T_A}{T}\right) \times$ $(1 + \exp\left(\frac{T_{AL}}{T} - \frac{T_{AL}}{T_L}\right) + \exp\left(\frac{T_{AH}}{T_H} - \frac{T_{AH}}{T}\right))^{-1}$	ratio
Food function	f	$f = \begin{cases} 0 \; if \; X < CHL_{lt} \\ \frac{X}{(X+X_K)} \; if \; CHL_{lt} \geq X \leq CHL_{ut} \\ \frac{X}{X+X_K} \times \exp(D_r \times (X - CHL_{ut})) \; if \; X > CHL_{ut} \end{cases}$	ratio
Ingestion rate	J_X	$J_X = J_{XM} \times f \times V^{2/3}$	mol-C cm^{-2} d^{-1}
Assimilation rate	p_A	$p_A = K_A \times J_X$	mol-C d^{-1}
Maximum assimilation rate	p_{AM}	$p_{AM} = K_A \times J_{XM} \times V^{2/3}$	mol-C d^{-1}
Utilisation rate of reserves	p_C	$p_C = \frac{E}{\kappa \times E + E_G} \times \left(\frac{E_G \times p_{AM}}{E_M} + p_{MV} + p_S\right)$	mol-C d^{-1}
Maintenance rate of structural tissue	p_{MV}	$p_{MV} = P_M \times V$	mol-C d^{-1}
Maintenance cost osmoregulation	p_S	$p_S = \sigma \times V^{2/3} \times (S_R - S)$	mol-C d^{-1}
Maintenance rate of reproductive tissue	p_{MR}	$p_{MR} = \frac{(1-\kappa)}{\kappa} \times \min(V_p, V) \times P_M$	mol-C d^{-1}
State variables:			
Change in reserves (*E*)		$\frac{dE}{dt} = p_A - p_C$	mol-C d^{-1}
Change in structural volume (*V*)		$\frac{dV}{dt} = \frac{(\kappa \times p_C - p_{MV} - \kappa \times p_S)}{E_G}$	cm^3 d^{-1}
Change in reproductive tissue (*R*)		$\frac{dR}{dt} = (1-\kappa) \times p_C - p_{MR} - (1-\kappa) \times p_S$	mol-C d^{-1}
Maintenance payment in case of starvation		$\frac{dR}{dt} = \kappa \times p_C - p_{MV} - \kappa \times \mathrm{p_S}$	mol-C d^{-1}

Methodology to assess economic profitability

Krost et al. (2011) outlined the basic costs associated with producing 25 t and 100 t of mussels for human consumption (18 month grow out cycle) in the Kiel Fjord. They also mentioned a production of 30 to 50 tons per hectare. Based on this, we calculated the costs for running a one-hectare farm similar to the production of 25 tons of fresh mussels, as they cannot decrease below a certain threshold.

The cultivation depth in Kiel Fjord was 4 m, resulting in a total cultivation volume of 40,000 m^3 for a one-hectare farm. The cost for running a 40,000 m^3 (1 ha) mussel farm was 125,000 €. With the exception of socks, which need to be replaced after each harvest (yearly), the total investment had a 5-year lifespan (Krost et al., 2011). The investment was amortized over 5 years. Including the yearly labor and rent costs (100,000 € and 20,000 €, respectively), the yearly running costs sum up to 146,000 €. For a mussel farm with a cultivation volume of 160,000 m^3 (4 ha), the investment was 225,900 € and yearly labor and rent costs were 125,000 € and 20,000 €, respectively. This resulted in yearly running costs of 192,500 €. Establishing a mussel farm also required upfront costs, to conceptualize and develop the farm. This included, for example, the labor costs of a biologist and technician, who would design the farm. According to Krost et al. (2011), this work can take about two years and cost between 100,000 € and 120,000 € per year. To keep results conservative, high-end estimates were applied to the studied farms and an initial farm development cost of 240,000 € (two-year total) was assumed. In this analysis, these costs were amortized within the first five years of the farms productive lifetime. This resulted in two separate yearly running cost estimates: one with upfront investment costs (first five years) and a second without upfront investment costs (post 5 years).

Based on the future mussel usage and production cycle, the production costs were adjusted. For example, the production cycle for animal feed mussels was one third (6 instead of 18 months) of the time to produce human consumption mussels and pre-harvest processes such as grading, thinning, and socking was unnecessary (Haas et al., 2015; Krost et al., 2011). Additionally, machinery and labor costs were scaled down by half when considering mussel farming for feed mussels. Although the production cycle for feed mussels was 6 months, they can only be harvested once per year, because mussel spawning occurs mainly in spring/early summer. The farm scenarios of this study were coastal and near to harbors. As a result, any costs associated with traveling between the harbor and farm were absorbed into the labor costs. Due to varying mussel yield per cultivation volume [$kg\ m^{-3}$] between the farms, the pre-determined cost associated with running a mussel farm (outlined above) resulted in different production costs [$€\ kg^{-1}$].

The cost estimates from Krost et al. (2011) were selected because their study also took place in the Kiel Fjord and therefore, these estimates were the best available parallel to the scenarios of this study. Production costs were based on the farm cultivation area (40,000 m^3 for a 1 ha farm and 160,000 m^3 for a 4 ha farm). The cost estimates from Krost et al. (2011) for a cultivation volume of 40,000 m^3 were directly applied to the studied farms with the same cultivation area (Flensburg, Eckernförde, Kiel, Lübeck, Nienhagen, and Rostock), as labor and material cost will be similar across Germany. For the remaining farms (Salzhaff, Darss-Zingst-Bodden-Chain, Strelasund, Wieker Bay, Greifswald Bay, and Usedom), the cultivation area was either 20,000 m^3 or 30,000 m^3 for one hectare surface area. However, while an increase in farm size can result in a decrease of marginal costs, reducing farm size will not cut costs below a minimum required to establish a farm. Many of the costs outlined by Krost et al. (2011) for a 40,000 m^3 farm were already at the minimum. For example, while it will be necessary to purchase a boat and hire at least one employee at any farm size, the costs for longlines, mussel collectors, and mussel socks would reduce linearly.

Market prices for human consumption mussels were drawn from two sources: a low end estimate from Schleswig Holstein and the North Sea, where an existing commercial farm earned 2.19 € kg^{-1} wet weight in 2018[1], and a high end estimate from KielerMeeresfarm, where mussels were sold for 11 € kg^{-1} wet weight in 2018[2]. KielerMeeresfarm sold their mussels as an eco-certified, regional specialty to achieve these prices.

Mussel meal as a fishmeal replacement or substitute for fish aquaculture or agricultural feeding (e.g., poultry) could bring up to 2 € kg^{-1} (Nguyen et al., 2013). However, before sale, the mussels must be processed. In addition to the cost of processing, which is about 0.5-1 € kg^{-1} (Nguyen et al., 2013), the final product will consist of only about 5 % of the total wet weight. Therefore, fresh mussels sold for the mussel meal production could only achieve a market price of 0.06 € kg^{-1} (Haas et al., 2015).

The potential to compensate mussel farmers for the nutrient removal was based on Petersen et al. (2014). The removal of nitrogen (N) and phosphorous (P) from the harvest of one kilogram fresh mussels (1.2 % N and 0.05 % P after Petersen et al. (2014)) was merged with the productions costs to obtain the costs for nutrient removal at each site. These costs were then compared with cost estimates for nutrient removal using other measures, such as sewage treatment plants, wetlands, and reduced fertilizer use (Gren et al., 2008). While Gren et al. (2008) analyzed the entire Baltic Sea watershed, this study only used their estimates for the German-Baltic coast (“Gerso”). While Gren et al. (2008) recorded cost ranges for certain measures (e.g., sewage divided into rural and urban), the present study used the averages instead.

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[1] https://www.schleswig-holstein.de/DE/Landesregierung/LLUR/Organisation/abteilungen/pdf/Jahresbericht_2018.pdf

[2] Kieler Meeresfarm GmbH: https://www.kieler-meeresfarm.de/aktuelles/