Supporting information 1. Physiologically–structured population model

The physiologically–structured population model follows the cohort-based approach for populations with seasonal reproduction introduced by (Persson et al., 1998). Since reproduction occurs as a discrete event at a specific time in the year, all individuals that are born in the same reproductive event are equal. They are collected into a single cohort and assumed to grow at the same rate. Thus, we can describe the dynamics of each cohort $i \in \mathbb{N}$ with a system of ordinary differential equations, which keeps track of the density of individuals N_i, their age A_i, their structural mass W_i and their energy reserves storage S_i. Juveniles are defined as individuals with structural mass smaller than the structural mass at maturity W_p and adults as individuals with structural mass equal or larger than W_p. For each cohort i, age is a monotonically increasing function of time,

$$\frac{d}{dt}A_i = 1 \tag{1}$$

The age of the individuals determines the stage, which in turn, determines the differential equations that describe the variation in density of individuals, their structural mass and stored energy reserves. Equations (2), (3) and (4) define the dynamics of eggs, presmolts and postsmolts, respectively. The density of individuals decreases due to a mortality rate specific to each stage. In addition, the presmolts and postsmolts may die due to starvation. During the egg stage the structural mass and storage do not change. The dynamics of the structural mass and energy reserves storage in presmolts and postsmolts depend on the amount of food they encounter as well as the breeding travel period if they are adults.

for $0 \leq A_i < a_h$

$$\begin{cases} \frac{d}{dt}N_i = -\mu_e N_i \\ \frac{d}{dt}W_i = 0 \\ \frac{d}{dt}S_i = 0 \end{cases}$$

(2)

for $a_h \leq A_i < a_s$

$$\begin{cases} \frac{d}{dt} N_i = \begin{cases} -\mu_r N_i & \text{if } \frac{S_i}{W_i} \geq q_S \\ -\left(\mu_r N_i + \varphi\left(q_S \frac{W_i}{S_i} - 1\right)\right) & \text{if } S_i > 0 \text{ and } \frac{S_i}{W_i} < q_S \\ -\infty & \text{otherwise} \end{cases} \\ \frac{d}{dt} W_i = \begin{cases} \zeta_W \left(\kappa \frac{R_r}{K + R_r} j_a W_i^{2/3} - j_m W_i\right) & \text{if } \kappa \frac{R_r}{K + R_r} j_a W_i^{2/3} > j_m W_i \\ 0 & \text{otherwise} \end{cases} \\ \frac{d}{dt} S_i = \begin{cases} (1 - \kappa) \frac{R_r}{K + R_r} j_a W_i^{2/3} & \text{if } \kappa \frac{R_r}{K + R_r} j_a W_i^{2/3} > j_m W_i \\ \frac{R_r}{K + R_r} j_a W_i^{2/3} - j_m W_i & \text{otherwise} \end{cases} \end{cases}$$

(3)

for $a_s \leq A_i$

$$\begin{cases} \frac{d}{dt} N_i = \begin{cases} -\mu_s N_i & \text{if } \frac{S_i}{W_i} \geq q_S \\ -\left(\mu_s N_i + \varphi\left(q_S \frac{W_i}{S_i} - 1\right)\right) & \text{if } S_i > 0 \text{ and } \frac{S_i}{W_i} < q_S \\ -\infty & \text{otherwise} \end{cases} \\ \frac{d}{dt} W_i = \begin{cases} \zeta_W \left(\kappa f_s\, j_a W_i^{2/3} - j_m W_i\right) & \text{if } c1 \text{ and } (\sim c2 \text{ } or \sim c3) \\ 0 & \text{otherwise} \end{cases} \\ \frac{d}{dt} S_i = \begin{cases} (1 - \kappa) f_s\, j_a W_i^{2/3} & \text{if } c1 \text{ and } (\sim c2 \text{ } or \sim c3) \\ f_s\, j_a W_i^{2/3} - j_m W_i & \text{if } \sim c1 \text{ and } (\sim c2 \text{ } or \sim c3) \\ -(j_m W_i + C\, j_m W_i) & \text{otherwise} \end{cases} \end{cases}$$

(4)

In this last equation $c1$, $c2$ and $c3$ are the conditions $\kappa f_s\, j_a W_i^{2/3} > j_m W_i$, $t_{um} \leq t \leq t_{dm}$, and $W_p \leq W_i$, respectively, while $\sim c1$, $\sim c2$ and $\sim c3$ refer to the situation that these conditions do not hold. When the conditions are true, the amount of assimilates necessary to meet metabolic maintenance from the κ fraction are enough ($c1$), the current time corresponds to the breeding travel period ($c2$) and the cohort is adult ($c3$).

Whenever a juvenile cohort reaches the maturation size $W_i = W_p$, at a particular time $t = t_p$, a maturation event occurs. At a maturation event, the juvenile cohort becomes an adult cohort. This does not affect any cohort statistics:

$$\begin{cases} A_i(t_p) = A_i(t_p{}^{-}) \\ N_i(t_p) = N_i(t_p{}^{-}) \\ W_i(t_p) = W_i(t_p{}^{-}) \\ S_i(t_p) \ = S_i(t_p{}^{-}) \end{cases} \tag{5}$$

Reproduction occurs instantaneously at $t_{rn} = n\,t_y + t_r$, where $n \in \mathbb{N}$. At a reproductive event, a new cohort is formed from the storage biomass of adults, but only if their storage is such that their current storage:structural mass ratio exceeds the storage:structural mass ratio with which the adult individual matured:

$$\begin{cases} A_0(t_{rn}) = 0 \\ N_0(t_{rn}) = \left(\sum_{i \in \{j \le n | W_j \ge W_p\}} N_i \cdot \max\left(S_i - \frac{S_p}{W_p} W_i, 0 \right) \right) \frac{\zeta_e}{W_b} \\ W_o(t_{rn}) = \kappa\, W_b \\ S_0(t_{rn}) \ = (1 - \kappa)\, W_b \end{cases} \tag{6}$$

At the same time, all other cohorts are renumbered and the energy reserves storage of the adults that do reproduce is set to the amount that makes their storage:structural mass ratio equal to their storage:structural mass ratio at maturation.

$$\begin{cases} A_{i+1}(t_{rn}) = A_i({t_{rn}}^{-}) \\ N_{i+1}(t_{rn}) = N_i({t_{rn}}^{-}) \\ W_{i+1}(t_{rn}) = W_i({t_{rn}}^{-}) \\ S_{i+1}(t_{rn}) \ = \begin{cases} \min\left(S_i({t_{rn}}^{-}), \dfrac{S_p}{W_p} W_i({t_{rn}}^{-}) \right) & \text{if } W_i \geq W_p \\ S_i({t_{rn}}^{-}) & \text{otherwise} \end{cases} \end{cases} \tag{7}$$

The resource density in the breeding habitat grows following a semi–chemostat growth and declines by foraging of presmolts (8).

$$\frac{d}{dt} R_r = \rho(R_{max} - R_r) - \frac{R_r}{K + R_r} j_a \sum_{i \in \{ j \leq n | a_h < a_j < a_s \}} N_i \, {W_i}^{2/3} \tag{8}$$

Supporting information 2. Intracohort variation in growth rate

Figure SI2.1. Effects of variation in feeding level in the non-breeding habitat (top row), annual survival of postmolts (middle row) and cost of the breeding travel (bottom row) on life history traits of postsmolts (solid lines in left column plots), population reproductive output (dashed lines in left column plots), food availability in the breeding habitat (solid lines in right column plots) and growth rate of presmolts (dashed lines in right column plots). Colored lines correspond to a population formulation without intracohort variation (lines redrawn from figure 2 in the main text) while black lines correspond to a model formulation in which within a year class the parameter j_a follows a truncated normal distribution ranging from 80% to 120% of its mean. Default values representing favorable conditions (feeding level in the non-breeding habitat = 1, annual survival of postsmolts = 0.1 and cost of the breeding travel = 0) are used for parameters that are not varied. R_{max}= 5 g m^{-3}, other parameter values as in table 2. The values correspond to the average population statistics after the transient dynamics have disappeared.

Figure SI2.2. Effects of variation in feeding level in the non-breeding habitat (top row), annual survival of postmolts (middle row) and cost of the breeding travel (bottom row) on sea-age (left) and body length at first spawning (right). Same parameters as in figure SI2.1. Colored lines correspond to a population formulation without intracohort variation (lines redrawn from figure 3 in the main text) while black lines correspond to a model formulation in which within a year class the parameter j_a follows a truncated normal distribution ranging from 80% to 120% of its mean. The black dashed lines show the average body length at first spawning and the shaded areas show the frequency distribution of body lengths at first spawning within the population. The transition from 2 to 1 year of age at first spawning when the food abundance and the survival in the non-breeding habitat decrease coincides with a bimodal distribution of body length at first spawning in the population. The values correspond to the average population statistics after the transient dynamics have disappeared.

Figure SI2.3. a) Effect of feeding level in the non-breeding habitat, b) annual survival of postmolts and c) cost of the breeding travel on population biomass dynamics. Colored lines correspond to a population formulation without intracohort variation (lines redrawn from figure

4 in the main text) while black lines correspond to a model formulation in which within a year class the parameter j_a follows a truncated normal distribution ranging from 80% to 120% of its mean. Default values representing favorable conditions (feeding level in the non-breeding habitat = 1, annual survival of postsmolts = 0.1 and cost of the breeding travel = 0) are used for parameters that are not varied. R_{max}= 8 g m^{-3}, other parameter values as in table 2. The values correspond to the population biomass census occurring every year at the time of hatching after the transient dynamics have disappeared.

Supporting information 3.

Figure SI3.1. Types of dynamics (left column) and total biomass (right column) of a population exposed to different feeding levels in the non-breeding habitat (top row), cost of the breeding travel (middle row) and survival of postsmolts (bottom row) and variation in maximum food density in the breeding habitat (horizontal axes). Default values representing favorable conditions (annual survival of postsmolts = 0.1 and cost of the breeding travel = 0) are used for parameters that are not varied. Feeding level equals 0.6 and 0.8 in middle and bottom plot respectively. The values correspond to the average population statistics after the transient dynamics have disappeared.

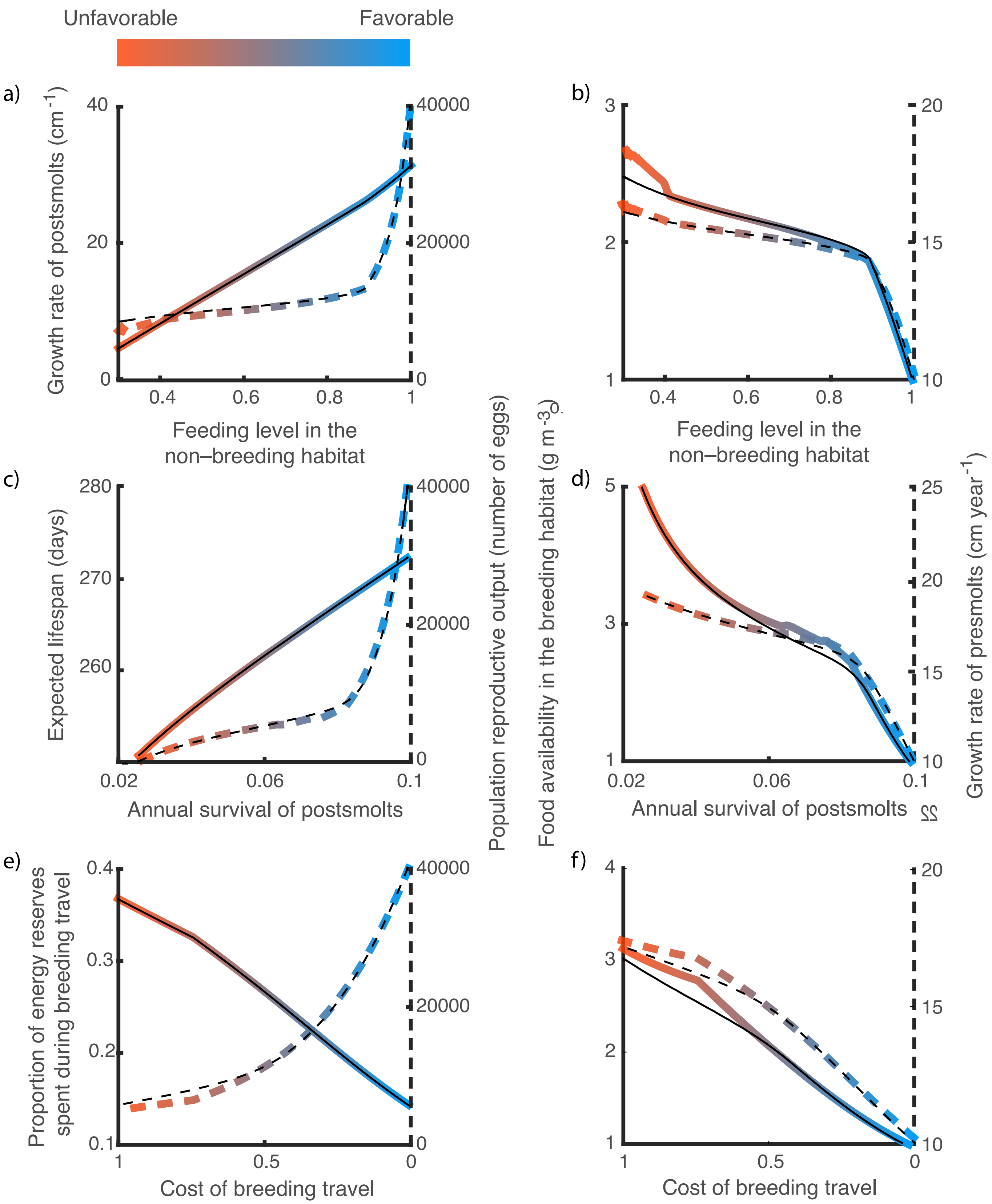
Unfavorable
Favorable
a)
Growth rate of postsmolts (cm⁻¹)
40
20
0
40000
20000
0
0.4
0.6
0.8
1
Feeding level in the non–breeding habitat
b)
3
2
1
20
15
10
0.4
0.6
0.8
1
Feeding level in the non–breeding habitat
Population reproductive output (number of eggs)
Food availability in the breeding habitat (g m-3)
c)
Expected lifespan (days)
280
270
260
40000
20000
0
0.02
0.06
0.1
Annual survival of postsmolts
d)
5
3
1
25
20
15
10
0.02
0.06
0.1
Annual survival of postsmolts
Growth rate of presmolts (cm year⁻¹)
e)
Proportion of energy reserves spent during breeding travel
0.4
0.3
0.2
0.1
40000
20000
0
1
0.5
0
Cost of breeding travel
f)
4
3
2
1
20
15
10
1
0.5
0
Cost of breeding travel

Figure SI2.1.

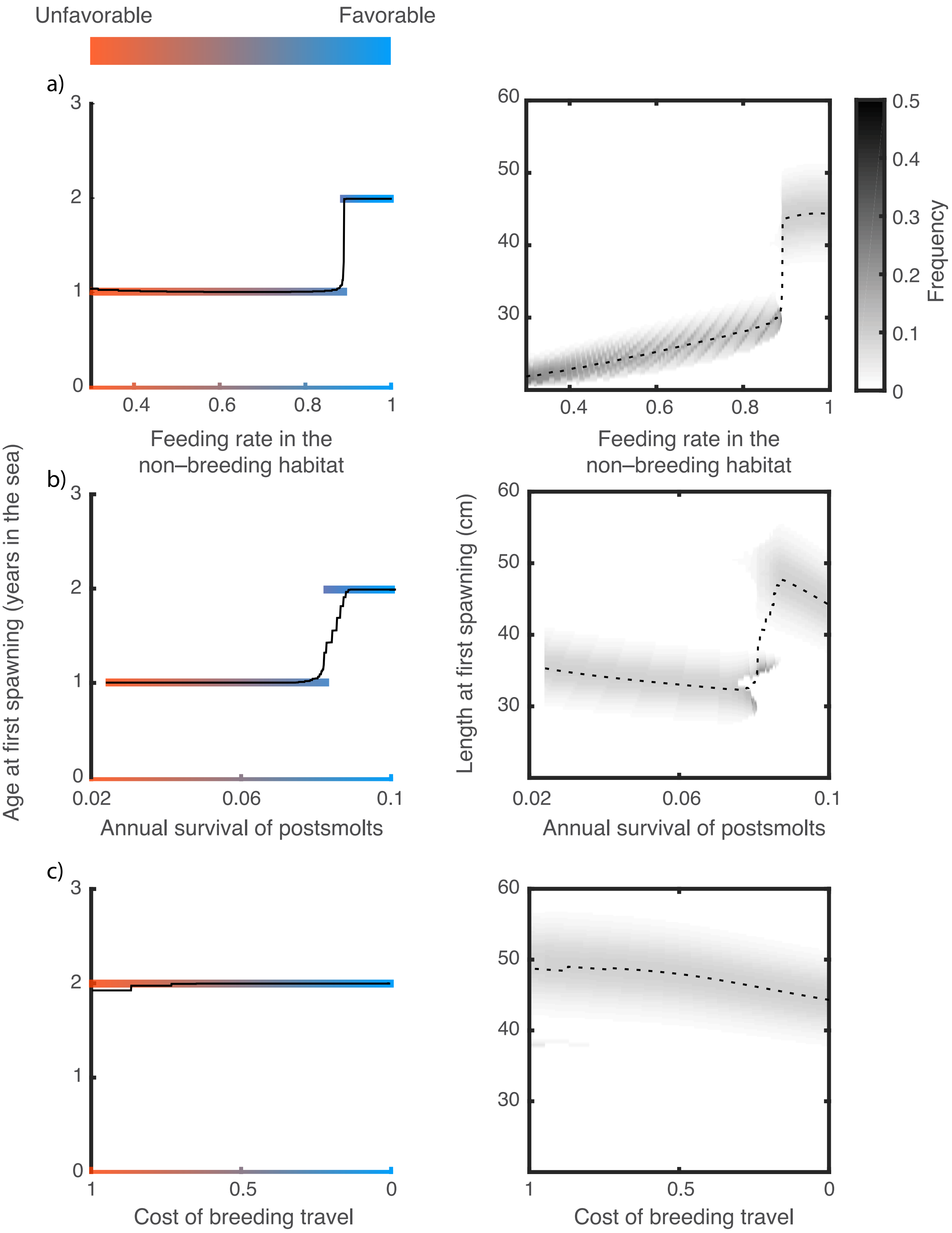
Unfavorable
Favorable
a)
b)
c)
Age at first spawning (years in the sea)
0
1
2
3
0.4
0.6
0.8
1
Feeding rate in the non–breeding habitat
Annual survival of postsmolts
0.02
0.06
0.1
Cost of breeding travel
0.5
Length at first spawning (cm)
30
40
50
60
Frequency
0
0.1
0.2
0.3
0.4
0.5

Figure SI2.2

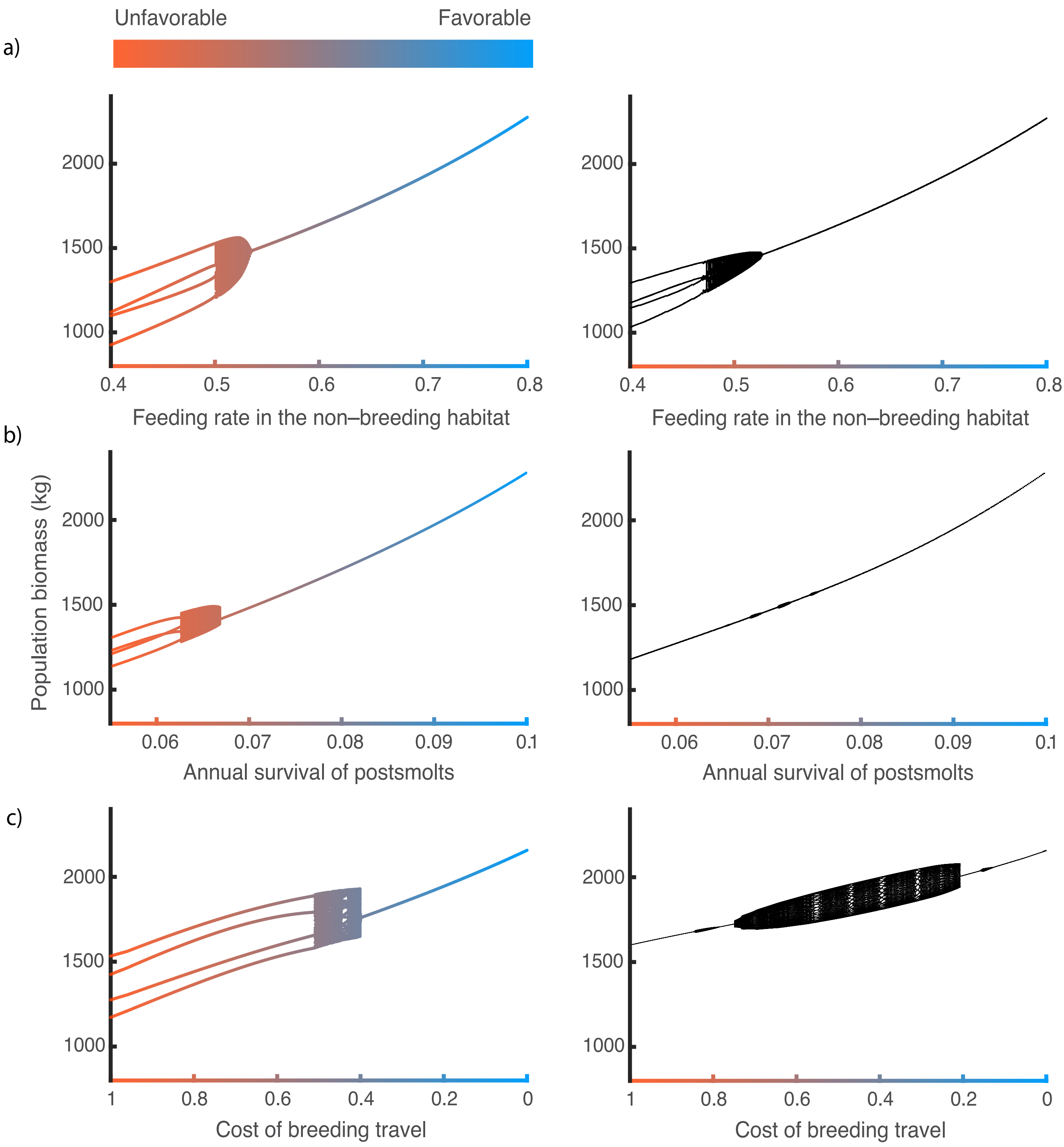
Unfavorable
Favorable
a)
2000
1500
1000
0.4
0.5
0.6
0.7
0.8
Feeding rate in the non–breeding habitat
2000
1500
1000
0.4
0.5
0.6
0.7
0.8
Feeding rate in the non–breeding habitat
b)
Population biomass (kg)
2000
1500
1000
0.06
0.07
0.08
0.09
0.1
Annual survival of postsmolts
2000
1500
1000
0.06
0.07
0.08
0.09
0.1
Annual survival of postsmolts
c)
2000
1500
1000
1
0.8
0.6
0.4
0.2
0
Cost of breeding travel
2000
1500
1000
1
0.8
0.6
0.4
0.2
0
Cost of breeding travel

Figure SI2.3

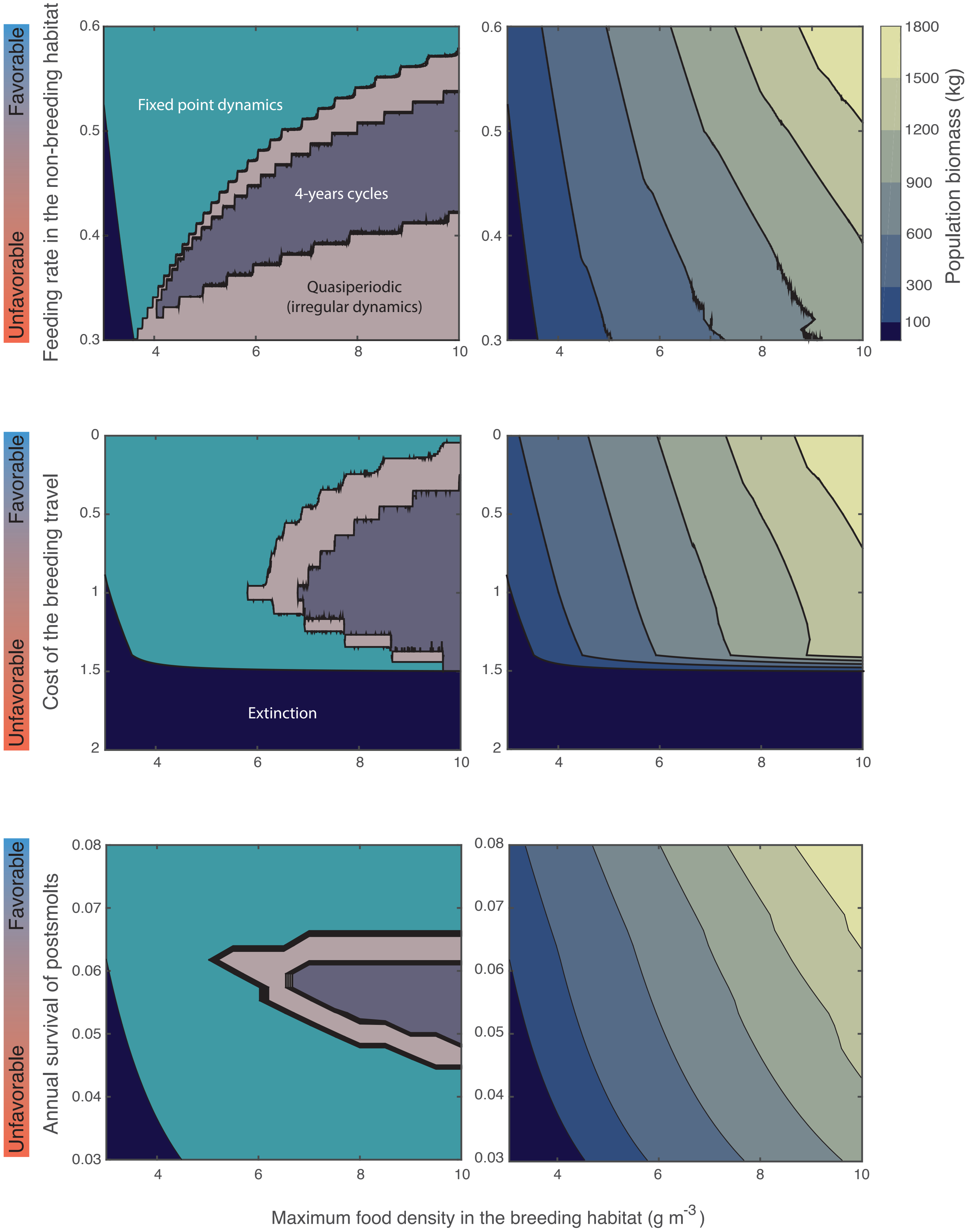
Favorable
Unfavorable
Feeding rate in the non-breeding habitat
0.6
0.5
0.4
0.3
Fixed point dynamics
4-years cycles
Quasiperiodic
(irregular dynamics)
4
6
8
10
1800
1500
1200
900
600
300
100
Population biomass (kg)
Favorable
Unfavorable
Cost of the breeding travel
0
0.5
1
1.5
2
Extinction
Favorable
Unfavorable
Annual survival of postsmolts
0.08
0.07
0.06
0.05
0.04
0.03
Maximum food density in the breeding habitat (g m-3)

Figure SI3.1.