Oikos

OIK-07267

Belgrad, B. A. and Griffen, B. D. 2020. Which mechanisms are responsible for population patterns across different quality habitats? A new approach. – Oikos doi: 10.1111/oik.07267

Appendix 1

To determine if field patterns were produced by differences in individual movement and not by differences in individual dominance, simulations were run with either larger crabs performing actions first, bolder crabs performing actions first, or no order in which individuals perform actions. Four additional models were also created where individuals would experience interspecific competition for space as well as food. Here, crabs would immediately move to a random adjacent space when finding oneself in a location containing a dominant individual. Thus, subordinate crabs could be forced from a space by a dominant crab entering the location while moving subordinate individuals would avoid locations with dominant crabs. Simulations were run where dominance depended either on size or personality and where movement propensity was also dependent on size and personality or where all individuals had equal probabilities of moving (N = 12 000 simulations; 1000 simulations x 4 models x 3 orders actions performed). In these simulations all other mechanisms governing crab movement and survival were turned on in the model.

Importantly, the model failed to reproduce field patterns when just individual dominance governed space and food competition with no direct differences in individual movement propensity, (Supplementary Fig. A1 – A3, variable sets 1 and 3). Only when models including individual dominance also incorporated size and personality dependent movement would crab distributions begin to match field observations (Supplementary Fig. A2 and AS, variable sets 2 and 4).

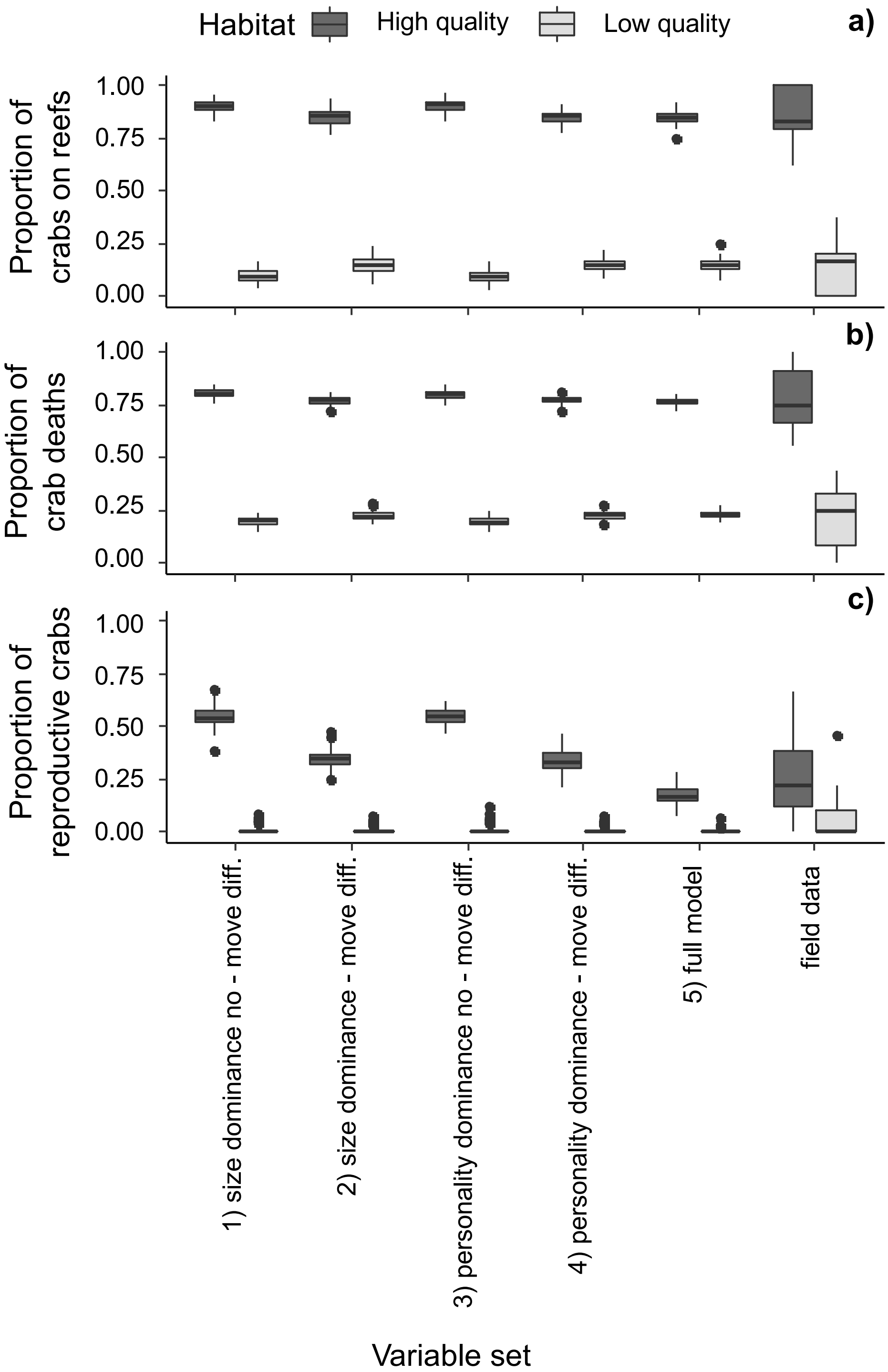

Fig. A1. Mean ± SD proportion of individuals **a)** inhabiting, **b)** dying, and **c)** reproducing on high- and low-quality habitat at the end of 1000 simulations for five variable sets and field data taken from Belgrad et al. (2017) and Belgrad and Griffen (2018). Simulations contain individuals where 1) individual size governs dominance and ability to compete for resources with no direct differences in individual movement, 2) individual size governs dominance and ability to compete for resources with size and personality also governing movement propensity, 3) individual personality governs dominance and ability to compete for resources with no direct differences in individual movement, 4) individual personality governs dominance and ability to compete for resources with size and personality also governing movement propensity, and 5) the fully parameterized model with no dominance differences.

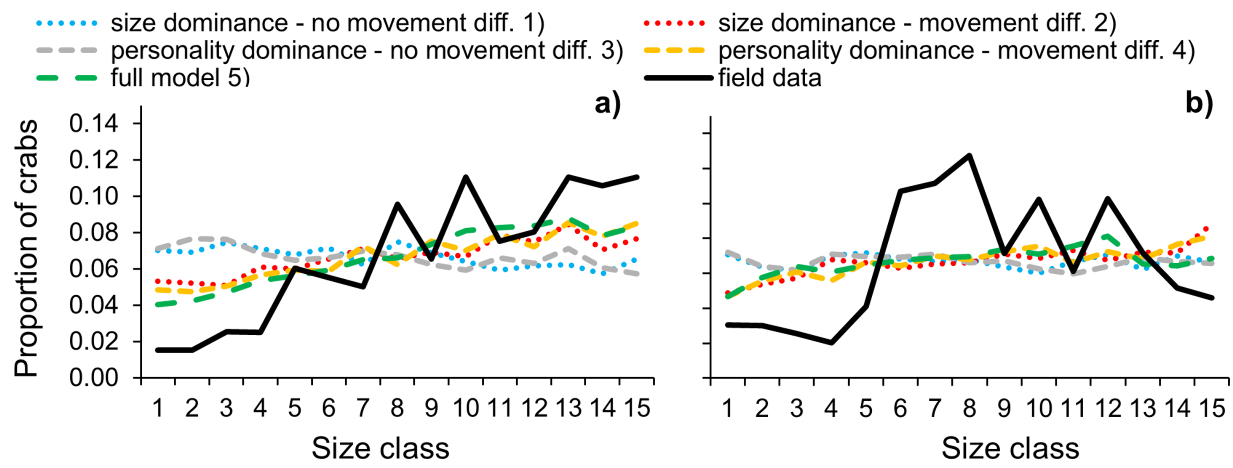

Fig. A2. Mean size distribution of individuals on a) high quality and b) low quality habitat at the end of 1000 simulations for five variable sets and field data taken from Belgrad et al. (2017) and Belgrad and Griffen (2018). Details on the variable sets are provided in Figure 6S.

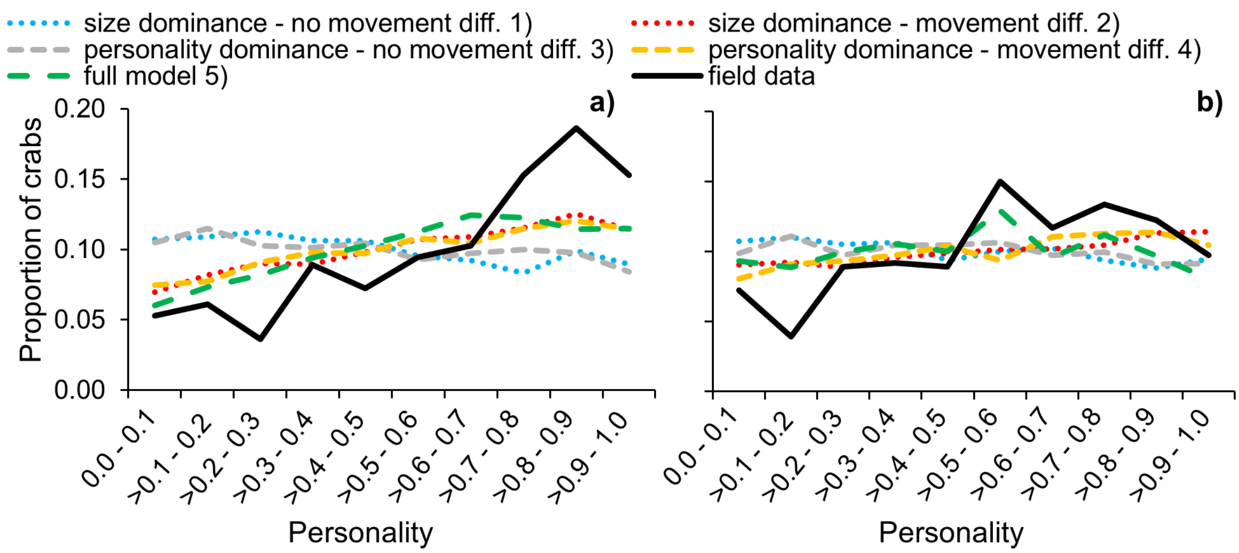

Fig. A3. Mean personality distribution of individuals on **a)** high quality and **b)** low quality habitat at the end of 1000 simulations for five variable sets and field data taken from Belgrad et al. (2017) and Belgrad and Griffen (2018). Personality levels indicate proportion of time crabs are active (in field) or choose to move (in model). Details on the variable sets are provided in Figure 6S.

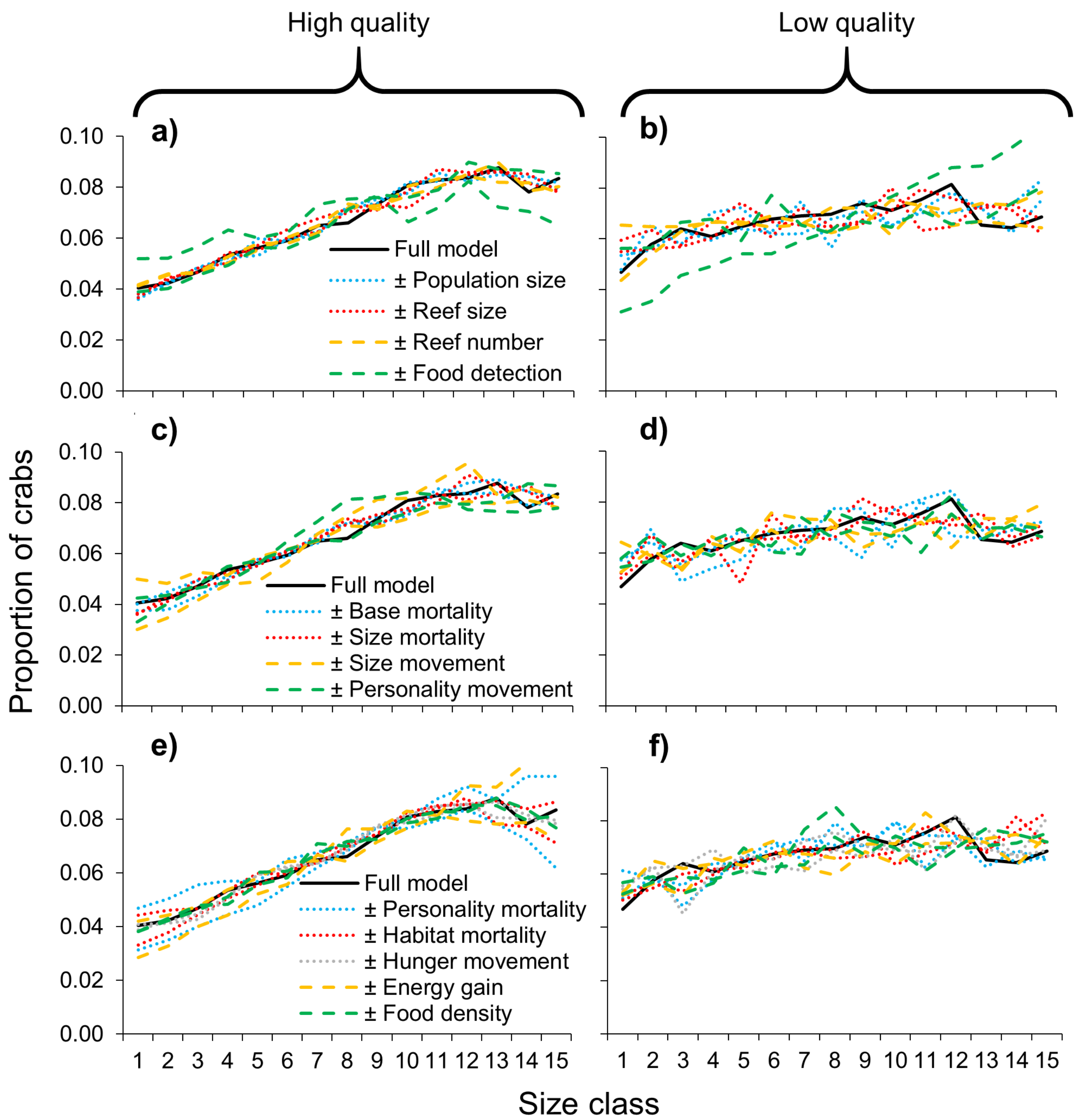

Fig. A4. Sensitivity analyses of the size distribution of individuals on a), c), e) high quality and b), d), f) low quality habitat where values are the mean from 1000 simulations. Comparison of the fully parameterized model results to a ± 25% change in underlying model parameters. Reef number and energy gain were altered by ± 66% and ± 50% respectively as one reef and one unit were the smallest measured values.

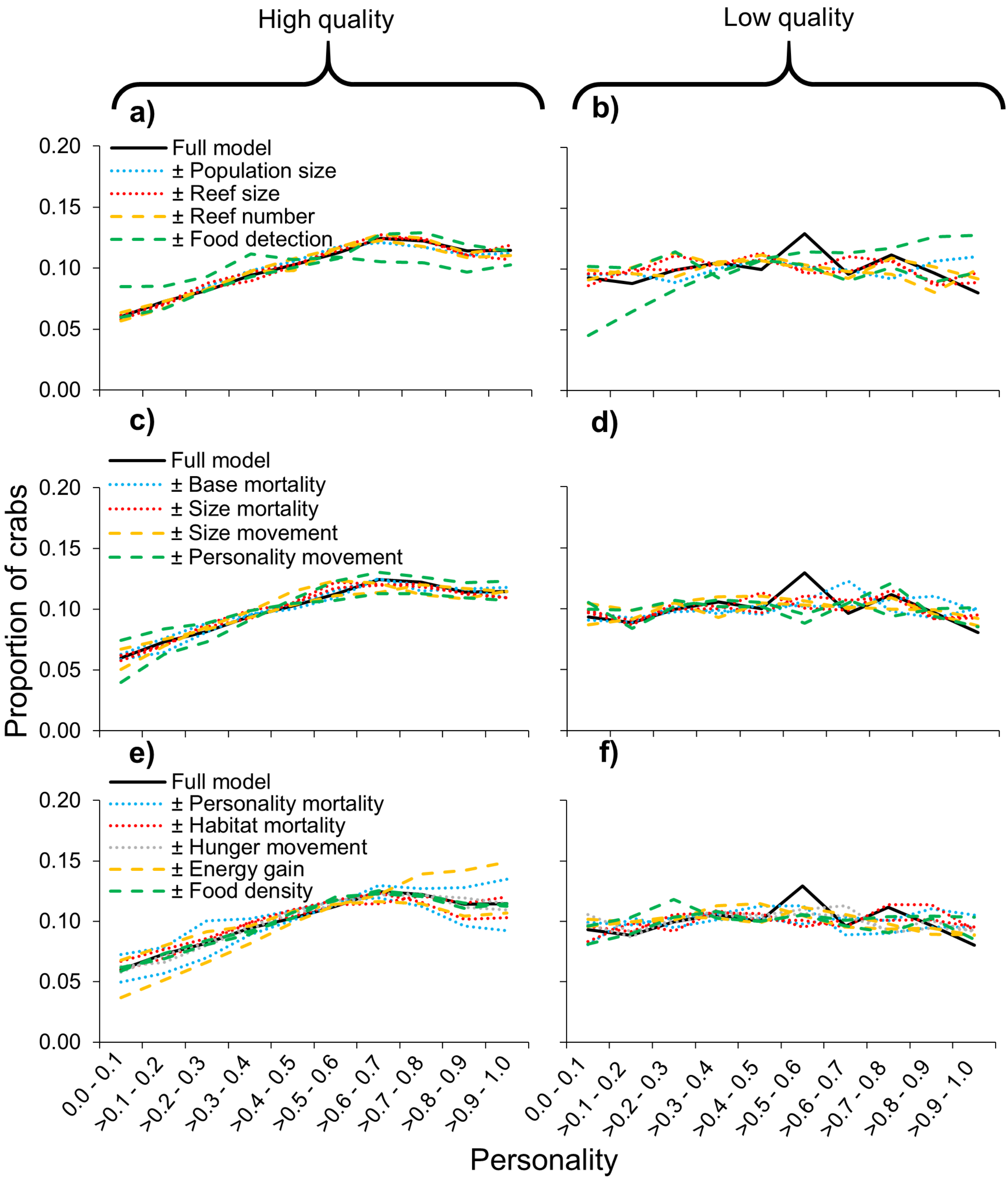

Fig. A5. Sensitivity analyses of the personality distribution of individuals on a), c), e) high quality and b), d), f) low quality habitat where values are the mean from 1000 simulations. Comparison of the fully parameterized model results to a ± 25% change in underlying model parameters. Reef number and energy gain were altered by ± 66% and ± 50% respectively as one reef and one unit were the smallest measured values.

Table A1. Sensitivity analyses of the full model where values are the average of 1000 simulations. Percent change in the proportion of individuals, deaths, and reproducing crabs on high (H) and low (L) quality reefs when model parameters were altered by ± 5%. Reef number and energy gain were altered by ± 33% and ± 25% respectively as one reef and one unit were the smallest measured values. Positive changes in either mortality or movement meant the effect of the model parameter was programmed to increase while a negative change meant the parameter effect decreased (i.e. for difference between individuals, a positive change meant differences in mortality or movement increased while a negative change meant individuals experienced more similar effects). Bold values indicate model response was greater than the percent change in parameter value.

Variables		**Percent change (%Δ) individuals on reefs**		**Percent change (%Δ) deaths on reefs**		**Percent change (%Δ) reproduction on reefs**	
		H-Quality	L-Quality	H-Quality	L-Quality	H-Quality	L-Quality
Population size	+ 5%	-0.09	0.76	0.39	-1.37	0.72	**-16.56**
	- 5%	-0.01	2.35	0.58	-2.06	-2.65	**48.87**
Reef Size	+ 5%	-0.57	2.91	0.07	-0.23	0.93	**60.15**
	- 5%	1.29	**-6.54**	1.19	-4.19	0.27	**5.35**
Reef Number	+ 33%	-1.13	5.76	0.06	-0.22	0.10	**47.65**
	- 33%	0.14	-0.71	0.38	-1.32	-0.83	-16.67
Food Detection	+ 33%	-2.97	12.33	4.31	-11.09	**77.62**	**36.61**
	- 33%	-4.54	18.86	-2.51	6.47	-5.76	**103.58**
Base Mortality	+ 5%	-0.12	0.59	0.50	-1.76	**-7.04**	**13.56**
	- 5%	0.80	-4.06	0.22	-0.76	2.92	**34.86**
Size Mortality	+ 5%	-0.02	0.11	0.54	-1.91	0.32	**-6.23**
	- 5%	-0.09	0.46	0.44	-1.56	-1.38	**24.40**
Size Movement	+ 5%	-0.27	1.38	0.42	-1.47	-0.03	**68.39**
	- 5%	-0.10	0.49	-0.05	0.16	-1.37	**20.82**
Personality Movement	+ 5%	0.45	-2.28	0.08	-0.27	0.77	**-7.20**
	- 5%	1.03	-4.91	0.92	-3.25	-1.12	-3.78
Personality Mortality	+ 5%	-0.52	3.02	0.37	-1.23	2.82	**11.15**
	- 5%	0.25	-1.41	1.05	-3.45	1.65	**28.50**

Habitat	+ 5%	-0.38	1.94	0.40	-1.40	**-7.96**	**24.77**
Mortality	- 5%	1.78	**-9.01**	0.49	-1.74	**5.68**	**53.57**
Hunger	+ 5%	0.16	-0.79	0.45	-1.57	1.89	**8.02**
Movement	- 5%	0.40	-2.03	0.48	-1.70	-1.36	**16.22**
Energy gain	+ 25%	0.25	-1.29	2.30	-8.11	14.13	**42.78**
	- 25%	-1.41	7.14	-2.11	7.45	**-28.23**	-5.44
Relative	+ 5%	1.10	**-6.33**	0.36	-1.26	-0.37	**58.84**
Food Density	- 5%	-0.14	0.79	0.21	-0.74	1.12	-1.12

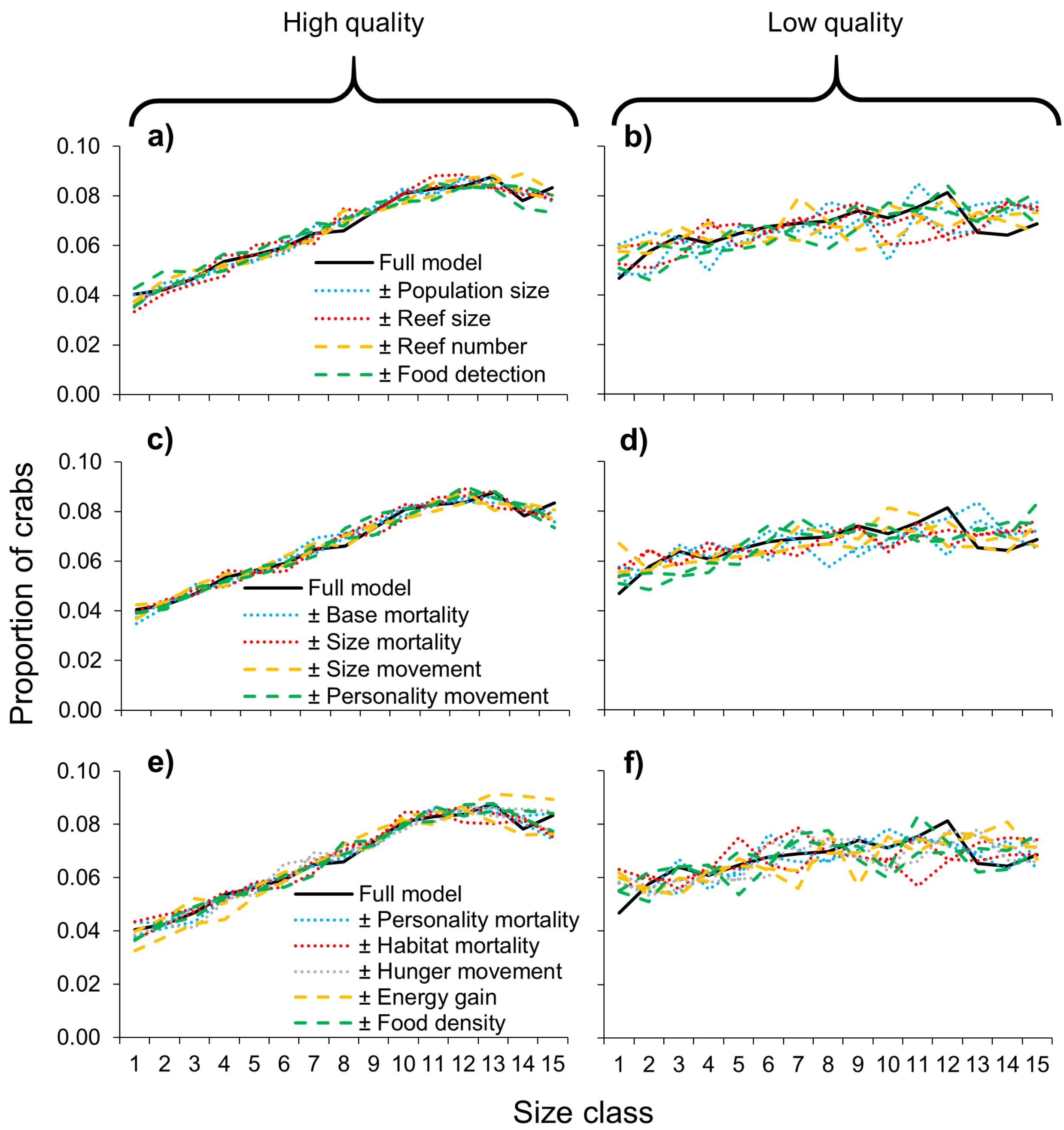

Fig. A6. Sensitivity analyses of the size distribution of individuals on a), c), e) high quality and b), d), f) low quality habitat where values are the mean from 1000 simulations. Comparison of the fully parameterized model results to a ± 5% change in underlying model parameters. Reef number and energy gain were altered by ± 33% and ± 25% respectively as one reef and one unit were the smallest measured values.

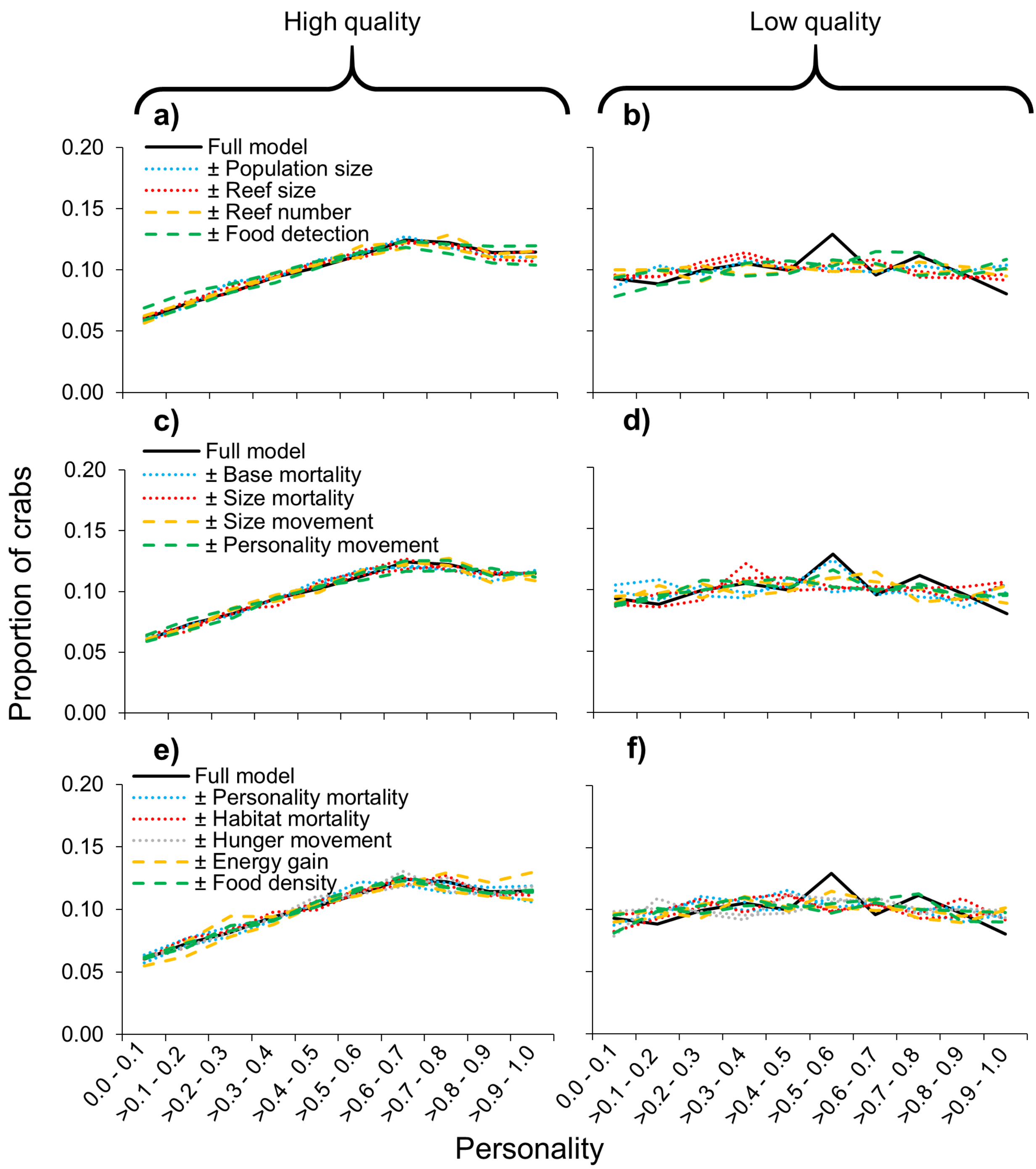

Fig. A7. Sensitivity analyses of the personality distribution of individuals on a), c), e) high quality and b), d), f) low quality habitat where values are the mean from 1000 simulations. Comparison of the fully parameterized model results to a ± 5% change in underlying model parameters. Reef number and energy gain were altered by ± 33% and ± 25% respectively as one reef and one unit were the smallest measured values.

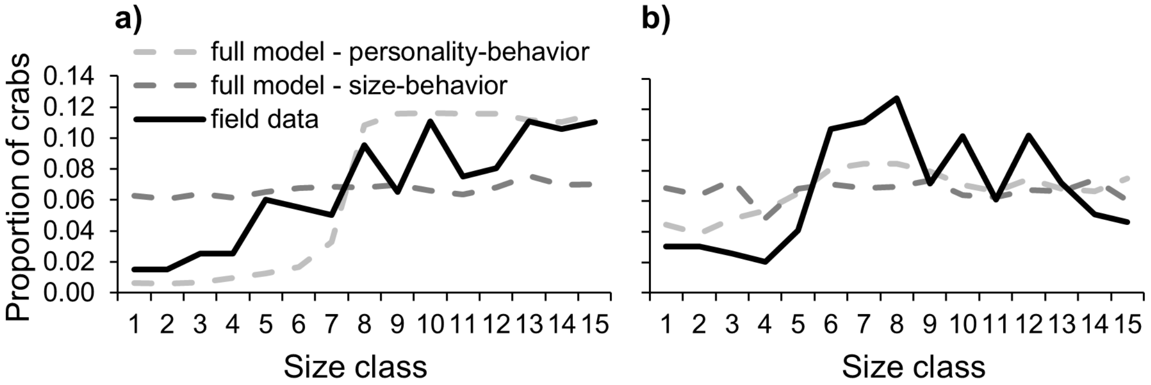

Fig. A8. Mean size distribution of individuals on a) high quality and b) low quality habitat at the end of 1000 simulations for two variable sets and field data taken from Belgrad et al. (2017) and Belgrad and Griffen (2018). Simulations contain the fully parameterized model (described in the legend for Fig. A1) minus personality-dependent movement and the fully parameterized model minus size-dependent movement.

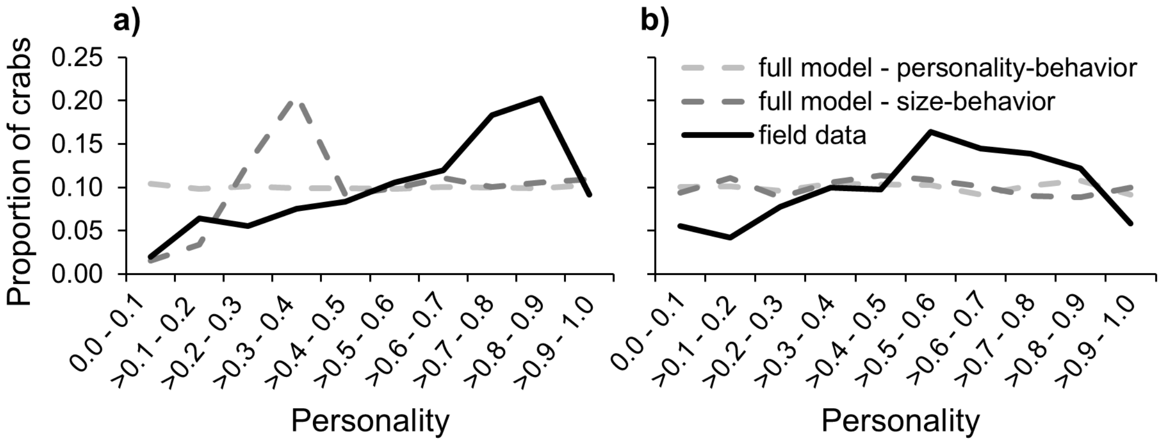

Fig. A9. Mean personality distribution of individuals on a) high quality and b) low quality habitat at the end of 1000 simulations for two variable sets and field data taken from Belgrad et al. (2017) and Belgrad and Griffen (2018). Simulations contain the fully parameterized model (described in the legend for Fig. A1) minus personality-dependent movement and the fully parameterized model minus size-dependent movement.

Appendix 2

Table A2. List of model variable sets. Variables are the biological and environmental mechanisms that have an influence on individual movement, survival, and reproduction.

Variable set	**Variables included in model**
1	"*Null model*" no variables included. Individuals are immortal and have 50% chance of moving each time step with no ability to detect the presence of food
2	Energy stores
3	Hunger-behavior
4	Personality-behavior
5	Size-behavior
6	Random-mortality
7	Personality-mortality
8	Size-mortality
9	Habitat-mortality
10	Energy stores, behavior-energy consumption
11	Energy stores, size-energy consumption
12	Food detection *(model patterns match first field pattern)*
13	Food detection, energy stores
14	Food detection, hunger-behavior
15	Food detection, personality-behavior
16	Food detection, size-behavior
17	Food detection, random mortality *(model patterns match first three field patterns)*
18	Food detection, personality-mortality
19	Food detection, size-mortality *(model patterns roughly match 4 field patterns)*
20	Food detection, habitat mortality
21	Food detection, random mortality, size-behavior
22	Food detection, random mortality, personality-behavior

	(model patterns roughly match 4 field patterns)
23	Food detection, random mortality, hunger-behavior
24	Food detection, random mortality, energy stores
25	Food detection, random mortality, personality-behavior, hunger-behavior
26	Food detection, random mortality, personality-behavior, energy stores
27	Food detection, random mortality, personality-behavior, size-behavior (*model patterns roughly match 5 field patterns*)
28	Food detection, size-mortality, hunger-behavior
29	Food detection, size-mortality, energy stores
30	Food detection, size-mortality, personality-behavior
31	Food detection, size-mortality, size-behavior
32	Food detection, size-mortality, personality-mortality
33	Food detection, size-mortality, habitat-mortality
34	Food detection, size-mortality, personality-behavior, hunger behavior
35	Food detection, size-mortality, personality-behavior, energy stores
36	Food detection, size-mortality, personality-behavior, size-behavior *("Minimum model; model patterns match all 5 field patterns)*
37	Food detection, size-mortality, personality-behavior, personality-mortality
38	Food detection, size-mortality, personality-behavior, habitat mortality
39	Food detection, size-mortality, personality-behavior, size-behavior, hunger-behavior
40	Food detection, size-mortality, personality-behavior, size-behavior, energy stores
41	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, behavior-energy consumption
42	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, size-energy consumtpion
43	Food detection, size-mortality, personality-behavior, size-behavior, personality-mortality
44	Food detection, size-mortality, personality-behavior, size-behavior, habitat mortality
45	Food detection, size-mortality, personality-behavior, energy stores, hunger-

	behavior
46	Food detection, size-mortality, personality-behavior, energy stores, personality-mortality
47	Food detection, size-mortality, personality-behavior, energy stores, habitat-mortality
48	Food detection, size-mortality, personality-behavior, size-behavior, hunger-behavior, energy stores
49	Food detection, size-mortality, personality-behavior, size-behavior, hunger-behavior, personality-mortality
50	Food detection, size-mortality, personality-behavior, size-behavior, hunger-behavior, habitat-mortality
51	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, hunger-behavior
52	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality-mortality
53	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, habitat mortality
54	Food detection, size-mortality, personality-behavior, size-behavior, personality-mortality, habitat mortality
55	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality mortality, hunger-behavior
56	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality-mortality, habitat-mortality
57	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality-mortality, habitat-mortality, hunger-behavior
58	Food detection, personality-mortality, hunger-behavior
59	Food detection, personality-mortality, energy stores
60	Food detection, personality-mortality, size-behavior
61	Food detection, personality-mortality, personality-behavior
62	Food detection, personality-mortality, habitat-mortality
63	Food detection, personality-mortality, size-behavior, hunger-behavior
64	Food detection, personality-mortality, size-behavior, energy stores

65	Food detection, personality-mortality, size-behavior, personality-behavior
66	Food detection, personality-mortality, size-behavior, habitat-mortality
67	Food detection, personality-mortality, size-behavior, personality-behavior
68	Food detection, personality-mortality, size-behavior, personality-behavior, hunger-behavior
69	Food detection, personality-mortality, size-behavior, personality-behavior, energy stores
70	Food detection, personality-mortality, size-behavior, personality-behavior, energy stores, behavior-energy consumption
71	Food detection, personality-mortality, size-behavior, personality-behavior, energy stores, size-energy consumption
72	Food detection, personality-mortality, size-behavior, personality-behavior, habitat-mortality
73	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality-mortality, habitat-mortality, hunger-behavior, size-energy consumption
74	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality-mortality, habitat-mortality, hunger-behavior, behavior-energy consumption
75	Food detection, size-mortality, personality-behavior, size-behavior, energy stores, personality-mortality, habitat-mortality, hunger-behavior, size-energy consumption, behavior-energy consumption *(Full model)*

Model verification

In order to ensure that the computer code running the model works according to its specification in the ODD model description, a series of tests were performed each time new code was added. These tests included syntax checking of the code and visual testing through the NetLogo interface, the use of print statements and spot tests with agent and patch monitors to check against calculations of expected values, and independent code reviews.

Submodel routines would be tested in isolation before again testing in the full model to ensure code follows the expected commands. Submodel routines (e.g. individual survival differences, movement differences, feeding) would first be tested in smaller modeled worlds with 1-10 individuals that could be monitored simultaneously before again testing in the full world size and integrated with the rest of the code for retesting.

All parameter values except initial energy stores and absolute values of energy gained/lost were calculated from the literature or experiments conducted on the species. However, to assess the robustness of the model, we implemented stress tests using extreme parameter values in addition to the sensitivity analyses described in the manuscript. Here, conditions were repeated with values 2x, 4x, and 8x difference in magnitude. Some values like "energy gained from feeding" could only be increased by these magnitudes as their input values were initially too small to be decreased by the same magnitude. Size of habitats and individuals in the model were calculated to roughly approximate the relative scale of mud flats with oyster reefs. However, world sizes ½, 2x, and 4x this size were also examined. We chose the current world size because smaller sizes did not have enough space to substantially vary the density and abundance of different quality habitat spheres while larger sizes did not differ in their ultimate outputs but substantially increased computer processing time.

Changes to individual survival and movement based off size were added or subtracted depending on If the individual was larger or smaller than the median crab size. In order to ensure that this code did not artificially produce step functions in model output around the median size, we also wrote code where effects of size caused a linear change in survival and movement. These two formats produced exactly the same results when the initial effect of size was adjusted to match the smallest individual rather than the median sized individual.