

Aggregation, Allee effects and critical thresholds for the management of the crown of thorns starfish *Acanthaster planci*

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Marine Ecology Progress Series 578: 99–114 (2017)

Table S1: Nearest neighbour analysis (index R) – variance to mean (VMR) approximations and corresponding nearest neighbour distance for 5, 15, 25, and 40 *A. planci* ha^{-1} . Entries are given by R ($VMR^{\pm SEM}$) where means are computed over 5000 simulations and approximate an analytically computed R value (by Equation 1) with a VMR over a region of 4 ha in 10 m by 10 m quadrats. Only $R > 0$ (0 – 1: random to highly aggregated) is considered as $R < 0$ (regular spatial distributions) would cause the aggregation model to simulate individuals outside the model region.

Nearest Neighbour Distance (m)	<i>A. planci</i> Density (ha^{-1})			
	5	15	25	40
0.5	0.98 (6.78 $^{\pm 0.03}$)	0.96 (7.47 $^{\pm 0.05}$)	0.95 (7.34 $^{\pm 0.04}$)	0.94 (10.34 $^{\pm 0.06}$)
1	0.96 (5.09 $^{\pm 0.03}$)	0.92 (6.62 $^{\pm 0.04}$)	0.90 (6.58 $^{\pm 0.04}$)	0.87 (6.67 $^{\pm 0.04}$)
2	0.91 (3.24 $^{\pm 0.03}$)	0.85 (5.19 $^{\pm 0.03}$)	0.80 (5.21 $^{\pm 0.03}$)	0.75 (5.34 $^{\pm 0.03}$)
3	0.87 (2.38 $^{\pm 0.02}$)	0.77 (3.70 $^{\pm 0.02}$)	0.70 (3.86 $^{\pm 0.03}$)	0.62 (3.96 $^{\pm 0.02}$)
4	0.83 (1.97 $^{\pm 0.01}$)	0.69 (2.89 $^{\pm 0.02}$)	0.60 (3.08 $^{\pm 0.02}$)	0.50 (3.22 $^{\pm 0.02}$)
5	0.78 (1.61 $^{\pm 0.01}$)	0.62 (2.42 $^{\pm 0.01}$)	0.51 (2.54 $^{\pm 0.02}$)	0.37 (2.62 $^{\pm 0.02}$)
6	0.74 (1.44 $^{\pm 0.01}$)	0.54 (2.03 $^{\pm 0.01}$)	0.41 (2.17 $^{\pm 0.01}$)	0.25 (2.29 $^{\pm 0.02}$)
7	0.69 (1.32 $^{\pm 0.01}$)	0.47 (1.78 $^{\pm 0.01}$)	0.31 (1.89 $^{\pm 0.01}$)	0.12 (1.68 $^{\pm 0.01}$)
8	0.65 (1.20 $^{\pm 0.01}$)	0.39 (1.55 $^{\pm 0.01}$)	0.21 (1.86 $^{\pm 0.01}$)	0.00 (1.00 $^{\pm 0.01}$)
9	0.61 (1.16 $^{\pm 0.01}$)	0.31 (1.43 $^{\pm 0.01}$)	0.11 (1.20 $^{\pm 0.01}$)	–
10	0.56 (1.10 $^{\pm 0.01}$)	0.24 (1.41 $^{\pm 0.01}$)	0.01 (1.00 $^{\pm 0.01}$)	–
11	0.52 (1.06 $^{\pm 0.01}$)	0.16 (1.14 $^{\pm 0.01}$)	–	–
12	0.48 (1.04 $^{\pm 0.01}$)	0.08 (0.98 $^{\pm 0.01}$)	–	–
13	0.43 (1.02 $^{\pm 0.01}$)	0.01 (0.99 $^{\pm 0.01}$)	–	–
14	0.39 (1.00 $^{\pm 0.01}$)	–	–	–
15	0.34 (1.00 $^{\pm 0.01}$)	–	–	–
16	0.30 (0.99 $^{\pm 0.01}$)	–	–	–
17	0.26 (0.98 $^{\pm 0.01}$)	–	–	–
18	0.21 (0.97 $^{\pm 0.01}$)	–	–	–
19	0.17 (0.97 $^{\pm 0.01}$)	–	–	–
20	0.13 (0.98 $^{\pm 0.01}$)	–	–	–
21	0.08 (0.99 $^{\pm 0.01}$)	–	–	–
22	0.04 (0.99 $^{\pm 0.01}$)	–	–	–

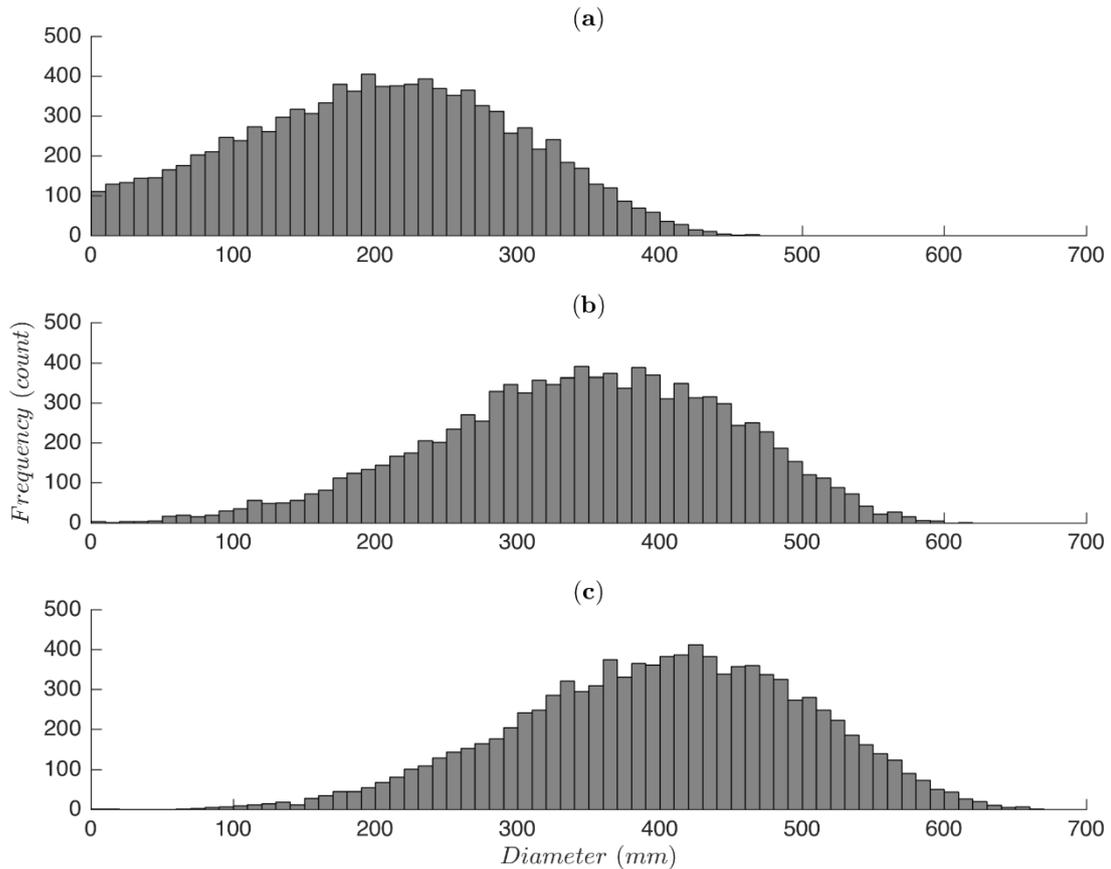


Figure S1. Diameters of male and female *A. planci* (ξ mm) were drawn from a Pearson distribution with mean (a) 200 mm, (b) 345 mm, and (c) 400 mm. Distributions had a standard deviation of 100 mm, skewness of -0.25 (negatively skewed), and a kurtosis of 2.7 (where a normal distribution has kurtosis of 3). Parameters were chosen such that the distribution was similar to those of Pratchett (2005). The absolute value of negative diameters was taken which slightly increased the frequency of very small starfish (<75 mm) for populations of mean diameter 200 mm. There was no influence in 345 mm or 400 mm diameter populations. Gamete contributions of very small starfish are exponentially small due to size-fecundity relationships (female gonad <10.5 g and male <4.8 g for 75 mm diameter; Babcock *et al.* 2016) Figure uses bins of width 10 mm and samples 10 000 points for each distribution.

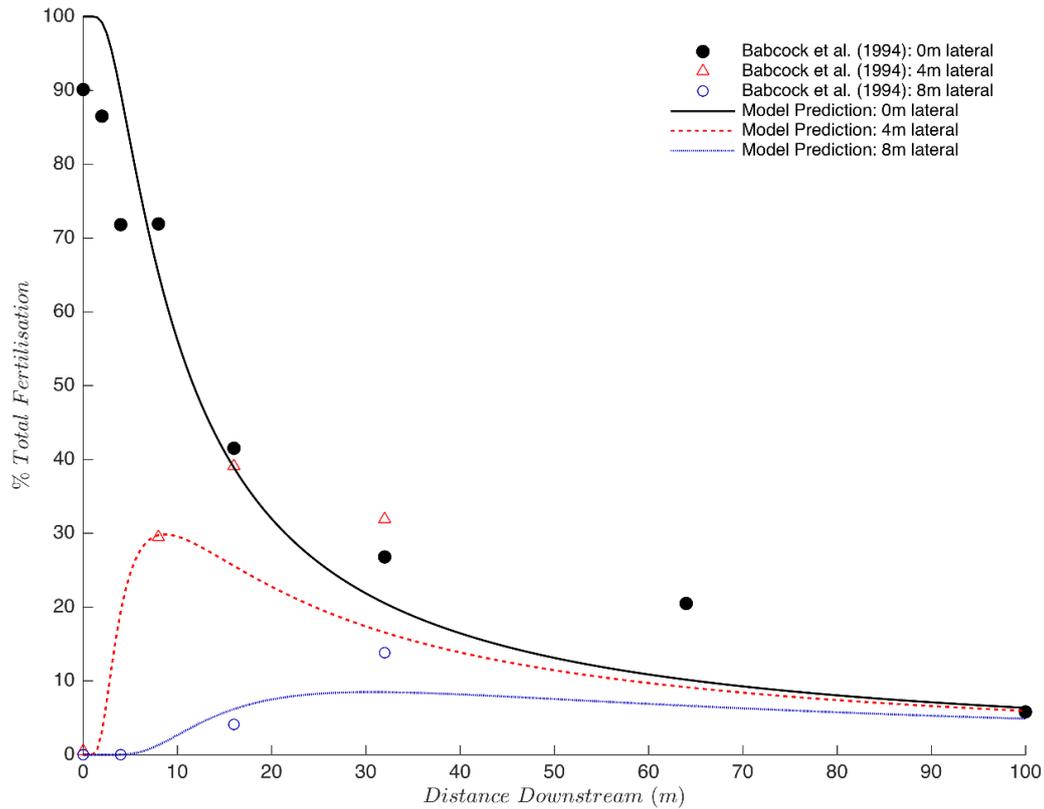


Figure S2. Fit of tuned model parameters to *A. planci* fertilisation data of Babcock et al. (1994). Data was measured with the male located at different downstream distances and different lateral offset distances (from directly downstream) of female. The study was conducted within a sandy bottomed channel of Davies reef lagoon. Focus was on tuning to lateral measures rather than directly downstream to characterise the plume shape. Tuned plume parameters were $\kappa = 0.55$, $\alpha_z = 0.51$, and $\alpha_y = 8.61$ and closely resembled those directly measured within a sandy, marine influenced estuary – $\kappa = 0.5$, $\alpha_z = 0.77$, and $\alpha_y = 7.79$ (Babcock *et al.* 2000). Re-tuning of the model was required due to variations in key parameters (usage of sperm swimming speed – closed vessel fertilisation, and *A. planci* volumetric sperm density).

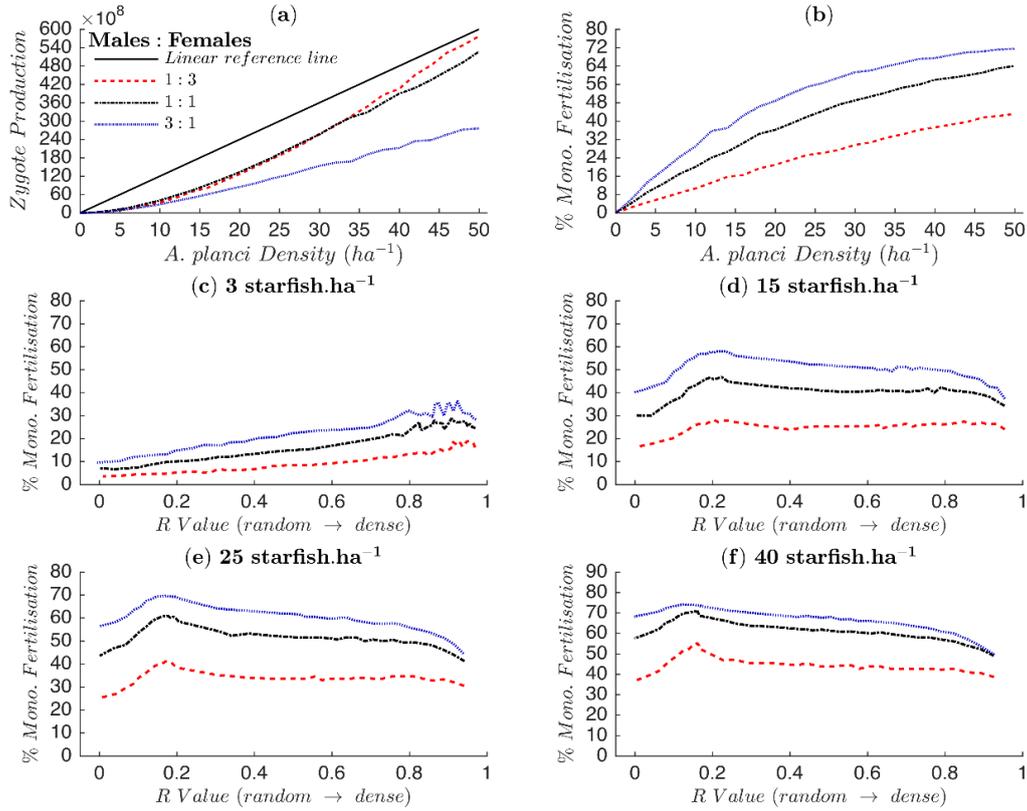


Figure S3. Sex ratio sensitivity (males to females 0.25, 0.5, 0.75) – (a) zygote production versus density with a linear reference line (Ref. line), (b) % monospermic fertilisation versus density, and % monospermic fertilisation versus aggregation for fixed densities (c) 3 *A. planci* ha^{-1} , (d) 15 *A. planci* ha^{-1} , (e) 25 *A. planci* ha^{-1} , (f) 40 *A. planci* ha^{-1} . In each subplot and parameter case, results were averaged over 350 simulations in water of depth 7 m. Reducing the number of female compared to male *A. planci* resulted in decreased rates of zygote production. More female compared to male *A. planci* increased zygote production at densities >40 starfish. ha^{-1} . Fertilisation efficiency however increased with the relative number of males to females. Increased fertilisation associated with higher male to female ratios is independent of the level of population aggregation. Model parameters were $D = 7$ m, $T_s = 2700$ s, $U = 0.12$ $\text{m}\cdot\text{s}^{-1}$ ($\Delta t = 4.17$ s), $h = 0.5$ m, $\kappa = 0.55$, $\alpha_y = 8.61$, $\alpha_z = 0.51$, $P_s = 0.68$, $\xi = 345$ mm, and results averaged over 350 simulations.

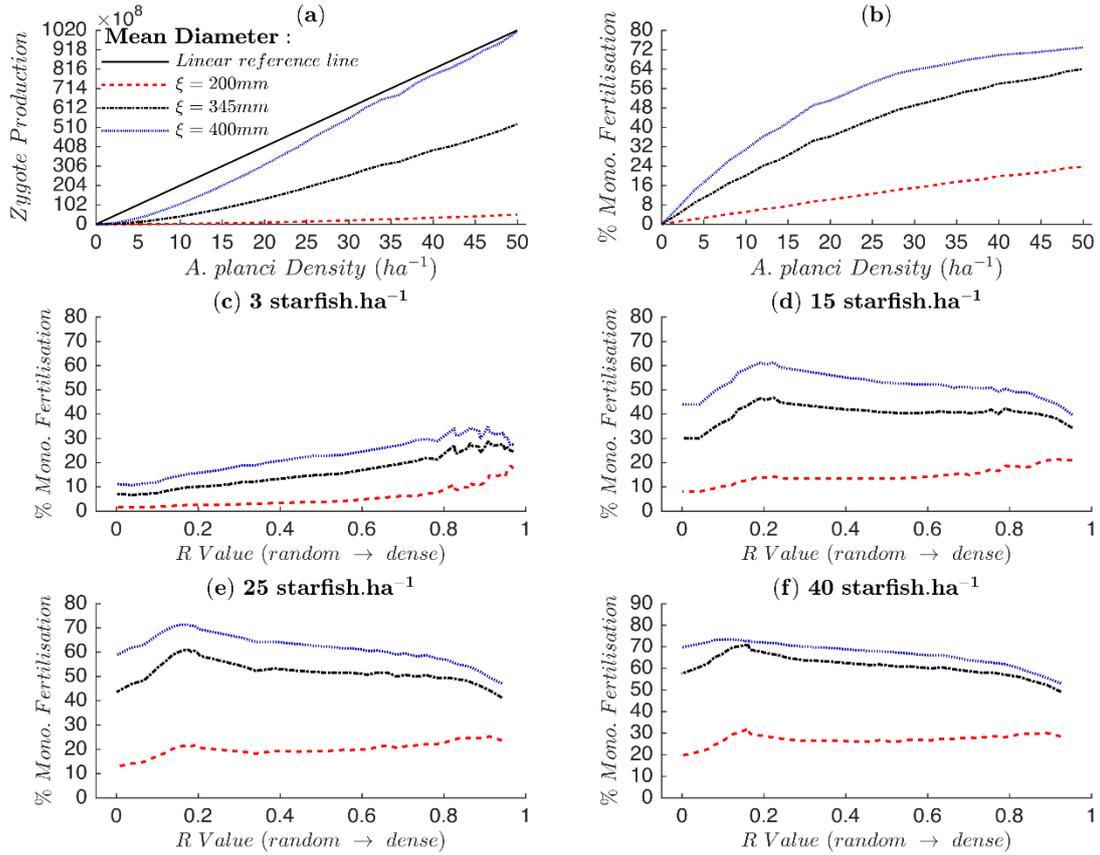


Figure S4. Mean population diameter sensitivity ($\xi = 200$ mm, 345 mm, 400 mm) – (a) zygote production versus density with a linear reference line (Ref. line), (b) % monospermic fertilisation versus density, and % monospermic fertilisation versus aggregation for fixed densities (c) 3 *A. planci* ha^{-1} , (d) 15 *A. planci* ha^{-1} , (e) 25 *A. planci* ha^{-1} , (f) 40 *A. planci* ha^{-1} . Model parameters were $D = 7$ m, $T_s = 2700$ s, $U = 0.12$ m. s^{-1} ($\Delta t = 4.17$ s), $h = 0.5$ m, $\kappa = 0.55$, $\alpha_y = 8.61$, $\alpha_z = 0.51$, $P_s = 0.68$, an even sex ratio and results averaged over 350 simulations. Increased Mean population diameter greatly increased both zygote production and fertilisation rates.

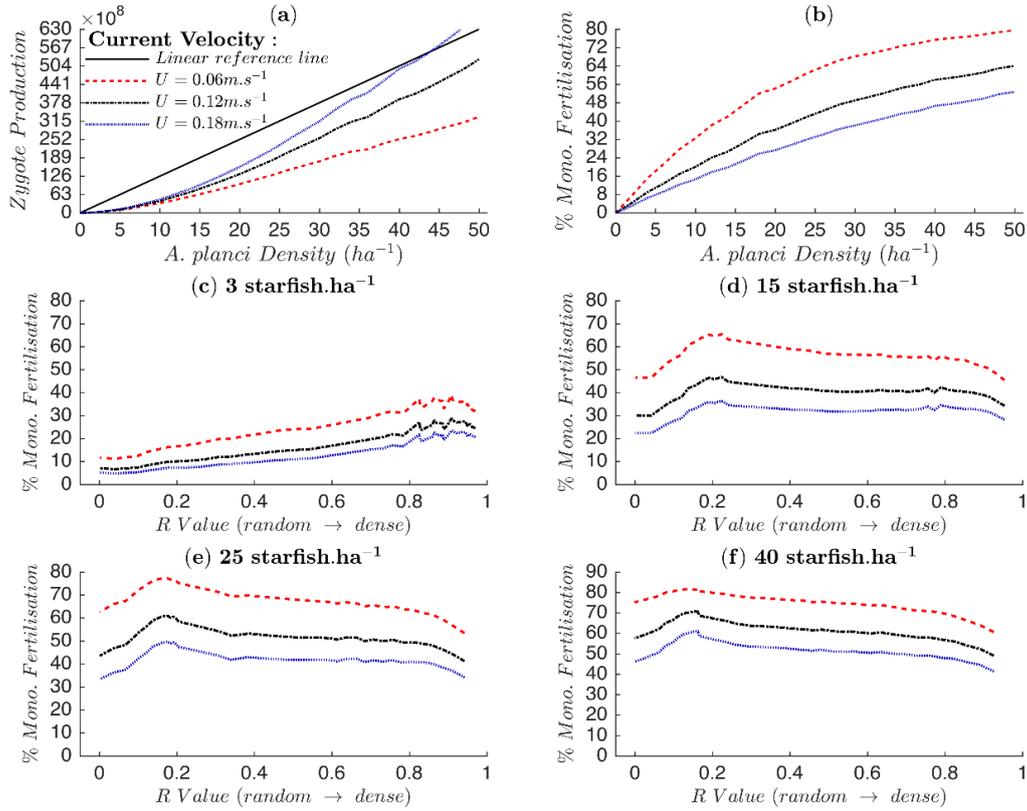


Figure S5. Model sensitivity to mean current velocity ($U=0.06, 0.12, 0.18 \text{ m}\cdot\text{sec}^{-1}$) – (a) zygote production versus density with a linear reference line (Ref. line), (b) % monospermic fertilisation versus density, and % monospermic fertilisation versus aggregation for fixed densities (c) 3 *A. planci* ha⁻¹, (d) 15 *A. planci* ha⁻¹, (e) 25 *A. planci* ha⁻¹, (f) 40 *A. planci* ha⁻¹. For each current velocity gamete interaction times changed to reflect transit time through each 0.5 m cell and were $\Delta t = 8.33 \text{ s}$ ($U = 0.06 \text{ m}\cdot\text{s}^{-1}$), $\Delta t = 4.17 \text{ s}$ ($U = 0.12 \text{ m}\cdot\text{s}^{-1}$), and $\Delta t = 2.78 \text{ s}$ ($U = 0.18 \text{ m}\cdot\text{s}^{-1}$). Model parameters were $D = 7 \text{ m}$, $T_s = 2700 \text{ s}$, $h = 0.5 \text{ m}$, $\kappa = 0.55$, $\alpha_y = 8.61$, $\alpha_z = 0.51$, $P_s = 0.68$, $\xi = 345 \text{ mm}$, an even sex ratio and results averaged over 350 simulations. The model was sensitive to mean current velocity through greater zygote production at faster mean currents for densities $>20 \text{ starfish}\cdot\text{ha}^{-1}$. It was also found that slower currents greatly increased fertilisation.

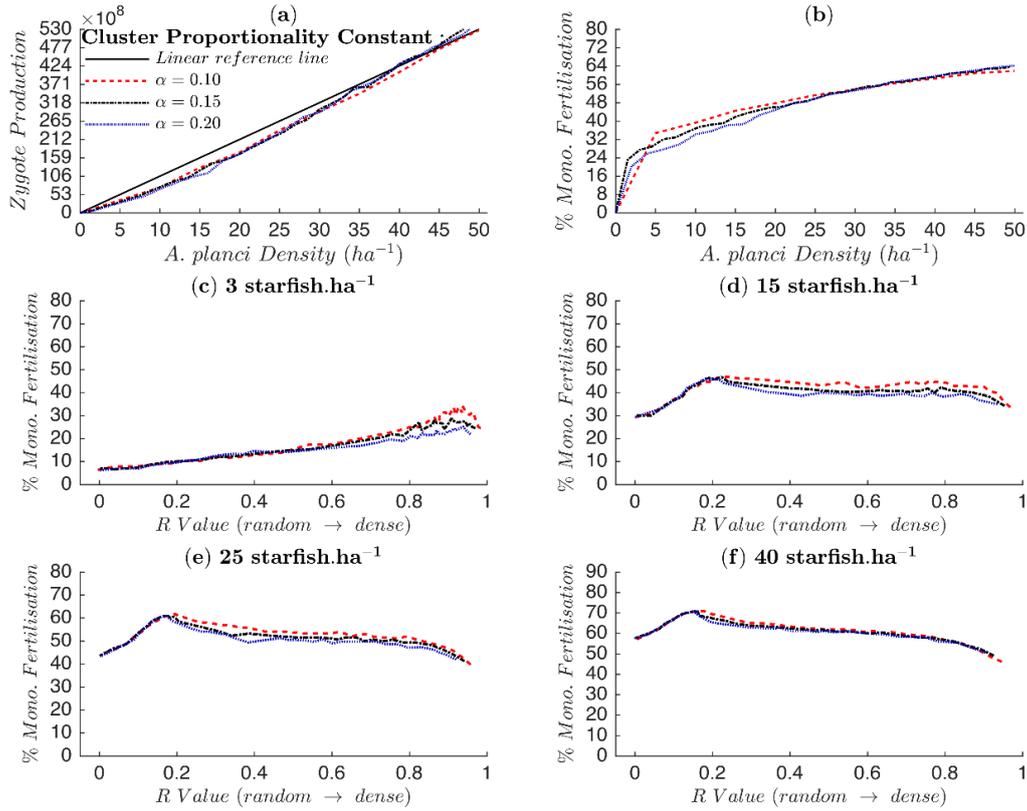


Figure S6. Model sensitivity to cluster-proportionality constant ($\alpha = 0.10, 0.15, 0.20$) – (a) zygote production versus density ($\beta^* = 0.05$) with a linear reference line (Ref. line), (b) % monospermic fertilisation versus density ($\beta^* = 0.05$), and % monospermic fertilisation versus aggregation for fixed densities (c) 3 *A. planci* ha $^{-1}$, (d) 15 *A. planci* ha $^{-1}$, (e) 25 *A. planci* ha $^{-1}$, (f) 40 *A. planci* ha $^{-1}$. Model parameters were $D = 7$ m, $T_s = 2700$ s, $U = 0.12$ m.s $^{-1}$ ($\Delta t = 4.17$ s), $h = 0.5$ m, $\kappa = 0.55$, $\alpha_y = 8.61$, $\alpha_z = 0.51$, $P_s = 0.68$, $\xi = 345$ mm, an even sex ratio and results averaged over 350 simulations. Small difference in the cluster proportionality constant (α) did not adversely affect outcomes with small variations attributable to slightly increased ($\alpha = 0.10$) or decreased ($\alpha = 0.20$) aggregation densities and patchiness.

Box S1: Tuning of the model

The steady state diffusion model used here was originally selected and fitted by Babcock *et al.* (1994) to estimate observations of *in situ* fertilisation rates of induced *A. planci* spawnings. Retuning of the model – specifically plume diffusion parameters (κ , α_y and α_z) – was necessary due to (1) the polyspermic model requirement of additional parameters, (2) a different assumption under which fertilisation is calculated, and (3) updated volumetric sperm density (V_m) from that of urchins to *A. planci*. The fertilisation model of Babcock *et al.* (1994) did not distinguish between mono- and polyspermic fertilisation and scored rates of fertilisation directly above a spawning female at different distances downstream of a male. Hence, tuning of the model encompassed applying the VCCW equation (equation 12) – as opposed to the EVCCW equation (equation 13) – to the model-predicted sperm plume distribution of a male (345 mm in diameter equal to mean population size). Empirically measured egg concentrations 0.05-0.10 m above spawning females (350-400 mm diameter) are quantified at $\sim 10^3$ eggs.L⁻¹ (Benzie *et al.* 1994). Assuming minimal dispersion over such small distances we extrapolate the egg concentration above the female to be $E_0=10^3$ eggs.m⁻³. This approximates predicted emission rates for a female of 345 mm in diameter (3.0629×10^3 eggs.s⁻¹; equation 3). Moreover, the original model was formulated under the assumption that fertilisation takes place in open water, using friction velocity (u) to account for sperm motility (Babcock *et al.* 1994; Babcock *et al.* 2014). This study implements a closed vessel formulation that uses sperm swimming speed (u_s), rather than friction velocity (1/32 motility reduction). This variation better reflects the submersible planktonic pump conditions through which data – to which the original model were fitted – were collected (Babcock *et al.* 1994; Babcock *et al.* 2000). Furthermore, volumetric sperm density is increased from that of urchins to that of *A. planci*. Cumulatively, these factors facilitated very narrow and highly concentrated gamete plumes (Babcock *et al.* 1994). Re-tuning of the model's plume parameters reflected field measures of similar conditions (Babcock *et al.* 2000) and rectified such discrepancies.

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