Supplementary information

Contrasting effects of ocean warming on different components of plant-animal interactions

Jordi F. Pagès[1]*

Timothy M. Smith[2,3]

Fiona Tomas[4,5]

Neus Sanmartí[6]

Jordi Boada[3]

Harriet de Bari[3]

Marta Pérez[6]

Javier Romero[6]

Rohan Arthur[3,7]

Teresa Alcoverro[3,7]

[1]School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, United Kingdom

[2]Deakin University, Centre of Integrative Ecology, School of Life and Environmental Sciences, Geelong, Australia

[3]Centre d'Estudis Avançats de Blanes (CEAB-CSIC), Accés a la cala Sant Francesc, 14, Blanes, Catalunya, Spain

[4]Institut Mediterrani d'Estudis Avançats, IMEDEA (CSIC-UIB), Miquel Marquès 21, Esporles, Illes Balears, Spain

[5]Department of Fisheries and Wildlife, Oregon State University, OR, United States

[6]Departament d'Ecologia, Facultat de Biologia, Universitat de Barcelona, Diagonal 643, Barcelona, Catalonia, Spain

[7]Oceans and Coasts Program, Nature Conservation Foundation, 3076/5, 4th Cross, Gokulam Park, Mysore, India

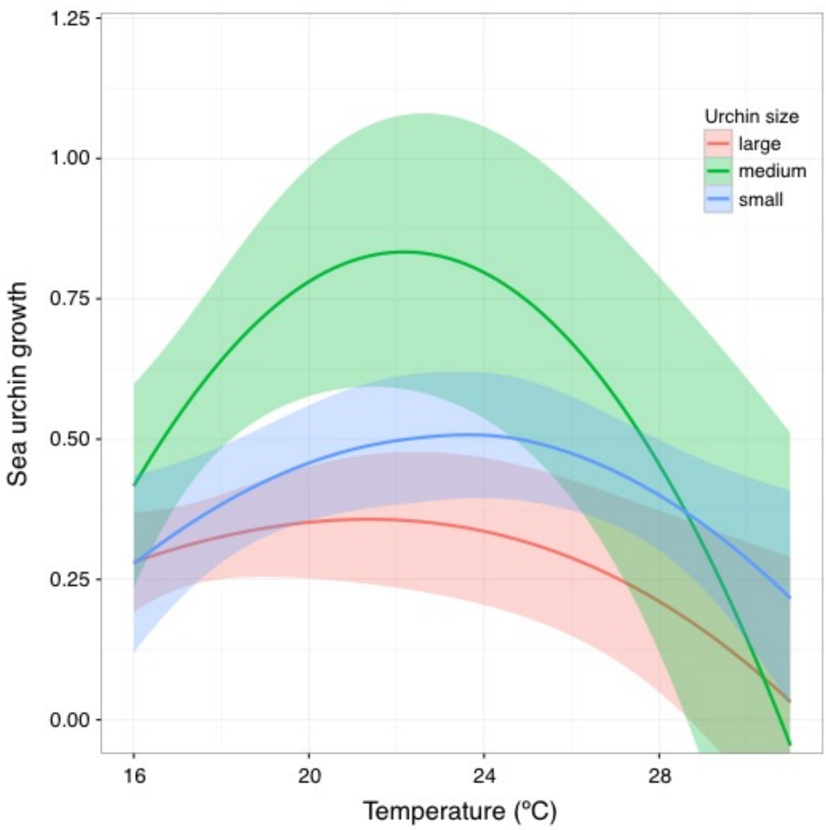
*Corresponding author: j.pages@bangor.ac.uk

Long-range correlation analysis

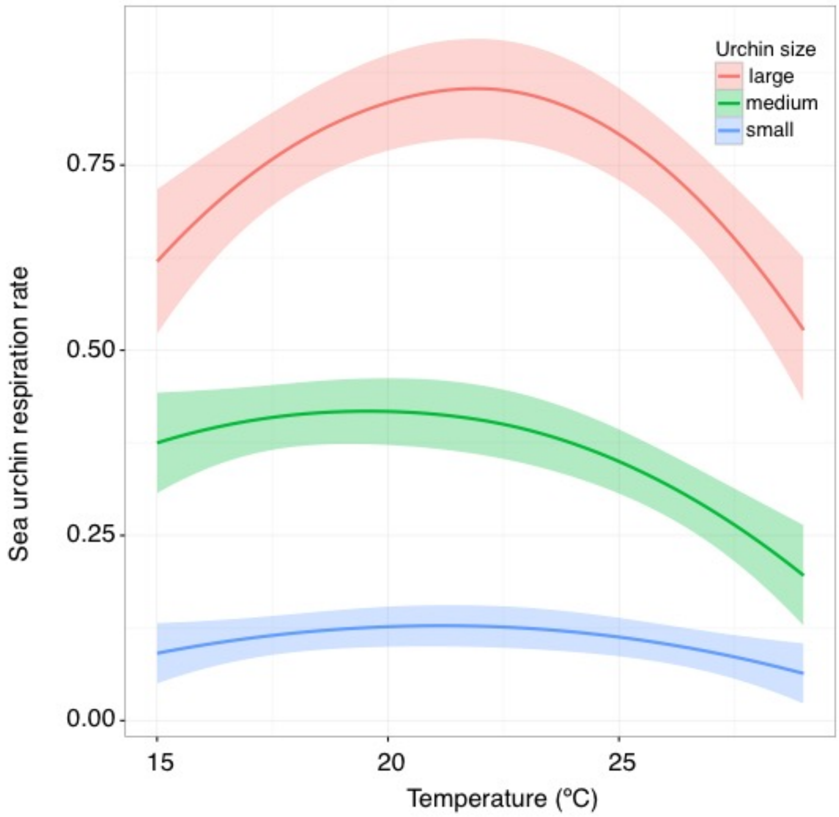
The exponents $\zeta(q)$ were estimated as the slope of the linear trend of $\| \Delta X\tau \| q$ vs. τ in log-log plots (see appendix in Seuront and Stanley, 2014). The moment function $\zeta(q)$ characterises the statistics of the random walk $\| \Delta X\tau \|$ of *P. lividus* regardless of the scale and intensity (Seuront, 2009), and the related diffusive properties. Low orders of q characterise smaller and more frequent displacements, while high orders of q characterise larger and less frequent displacements. The mean (q = 1) and the variance (q = 2) are not sufficient to quantify the behaviour of probability density functions. A complete description requires an infinite number of moments (of q's), hence the use of the whole function $\zeta(q)$ instead of a single exponent to completely describe urchin movement behaviour (Seuront and Stanley, 2014). Each individual-level function $\zeta(q)$ was plotted along with the results for the Brownian motion (dashed line in plots) and ballistic motion (dotted line in plots). With this analysis, we could assess the nature of the diffusive properties of sea urchin trajectories, and discern whether these were ballistic, superdiffusive, Brownian or subdiffusive.

Fig. S1. Size-specific sea urchin thermal performance curves (a) for growth and (b) respiration rates. Solid lines correspond to loess smoother applied to the data set. Shaded areas define the 95% confidence intervals around fitted values of the loess curve.

(a)



(b)



Urchin size
large
medium
small
0.75
0.50
0.25
0.00
Sea urchin respiration rate
15
20
25
Temperature (ºC)

Theoretical and empirical thermal performance curves

Below are the thermal performance functions we used to draw the conceptual models in Fig. 1 of the main text. For both plants and urchins we used modified Gaussian curves obtained from Angilletta (2006). The parameters in each function do not bear biological meaning, they were used only to observe the shape of the resulting graphs using the web app Geogebra (www.geogebra.org).

$$\mathrm{plant}_{mid}(x) = 2\,e^{-0.5\left(\frac{|1-x|}{3}\right)^2}$$

$$\mathrm{urchin}(x) = 2\,e^{-0.5\left(\frac{|1-x|}{3}\right)^2}$$

$$\mathrm{plant}_{warm}(x) = 2\,e^{-0.5\left(\frac{|4-x|}{3}\right)^2}$$

$$\mathrm{plant}_{cool}(x) = 2\,e^{-0.5\left(\frac{|-3-x|}{3}\right)^2}$$

$$\mathrm{urchin2}(x) = \begin{cases} 2\,e^{-0.5\left(\frac{|1-x|}{3}\right)^2} & : x < 2 \\ -x^2 + 5.9 & : \text{otherwise} \end{cases}$$

$$\mathrm{herbivore}_{pressure}(x) = \frac{\mathrm{urchin}(x)}{\mathrm{plant}_{mid}(x)}$$

$$\rightarrow \quad \mathrm{herbivore}_{pressure}(x) = \frac{2\,e^{-0.5\left(\frac{|1-x|}{3}\right)^2}}{2\,e^{-0.5\left(\frac{|1-x|}{3}\right)^2}}$$

We modelled two types of curves for the sea urchins:

- urchin(x) is a continuous modified Gaussian function
- urchin2(x) is a stepwise function, where for $x<2$, urchin2(x) behaves as a modified Gaussian, but otherwise quickly drops to 0 (and then negative values, with no biological meaning in this case). We used a stepwise function to represent the truncation of the thermal performance curves of sea urchins when offered plants incubated at warm temperatures (potentially more chemically defended, and hence less preferred, see Fig. 6).

Finally, to obtain the herbivore pressure curve, we divided the thermal performance function of sea urchins by the thermal performance function of each plant.

Fig. S2. Graphical representation of the functions $plant_{mid}$ (green line), urchin (purple line) and herbivore pressure (i.e. urchin/$plant_{mid}$, black line). Note that when plant and urchin curves are of the same shape and completely overlapping, the resulting herbivore pressure function is a straight line with no slope.

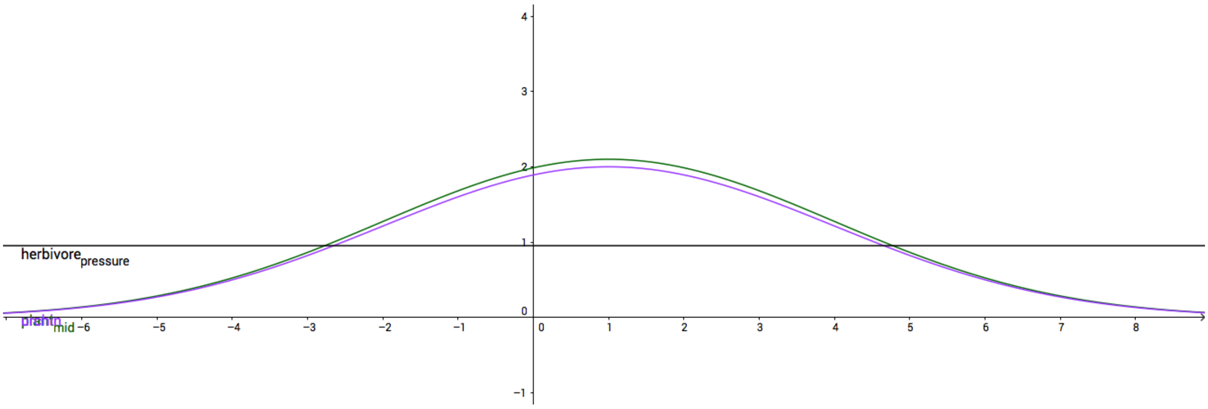


Fig. S3. Graphical representation of the functions $plant_{warm}$ (pink line), urchin (purple line) and herbivore pressure (i.e. urchin/$plant_{warm}$, black line). Note that when plant and urchin curves are of the same shape and the plant curve is shifted to the right, the resulting herbivore pressure function is a negative exponential curve.

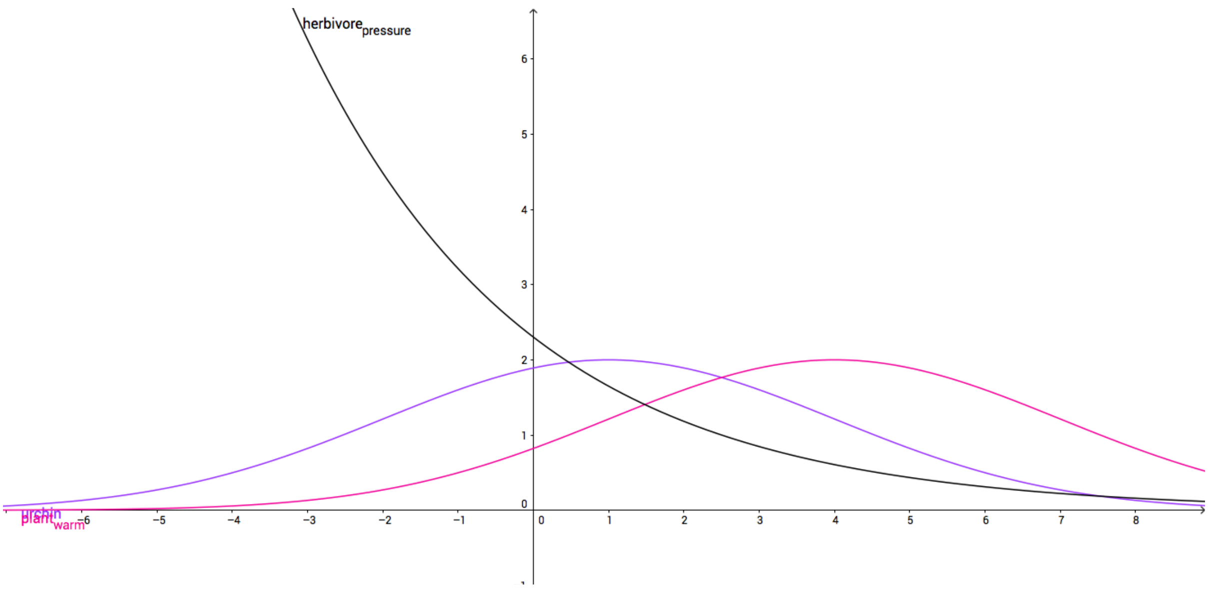


Fig. S4. Graphical representation of the functions $plant_{cool}$ (orange line), urchin (purple line) and herbivore pressure (i.e. urchin/$plant_{cool}$, black line). Note that when plant and urchin curves are of the same shape and the plant curve is shifted to the left, the resulting herbivore pressure function is a positive exponential curve.

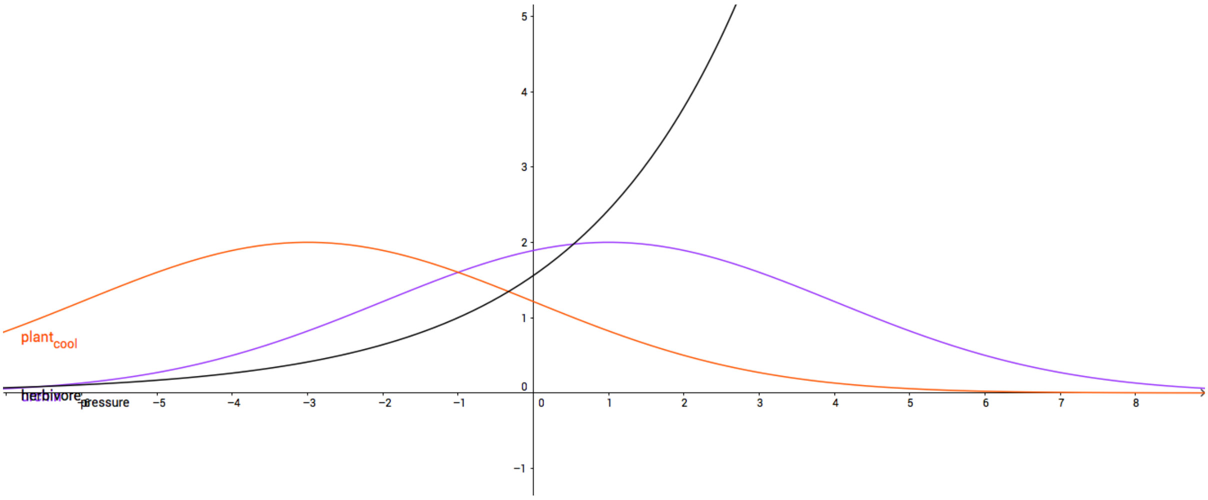


Fig. S5. Graphical representation of the continuous function $plant_{mid}$ (green line), the stepwise function urchin2 (blue line) and the continuous function herbivore pressure (i.e. urchin/$plant_{mid}$, black line). Note that when plant and urchin curves are of the same shape and completely overlapping, the resulting herbivore pressure function is a straight line with no slope, until the urchin performance curve drops (for x>2).

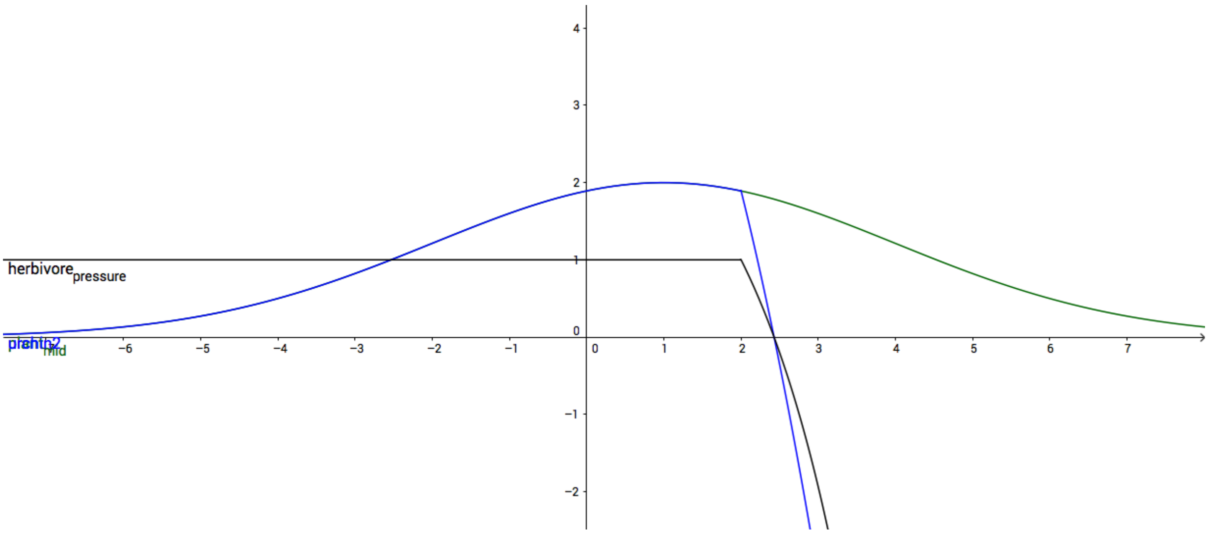


Fig. S6. Graphical representation of the continuous function $plant_{warm}$ (pink line), the stepwise function urchin2 (blue line) and the continuous function herbivore pressure (i.e. urchin/$plant_{warm}$, black line). Note that when plant and urchin curves are of the same shape but plant performance is shifted to the right, the resulting herbivore pressure function is a negative exponential, until the urchin performance curve drops (for x>2).

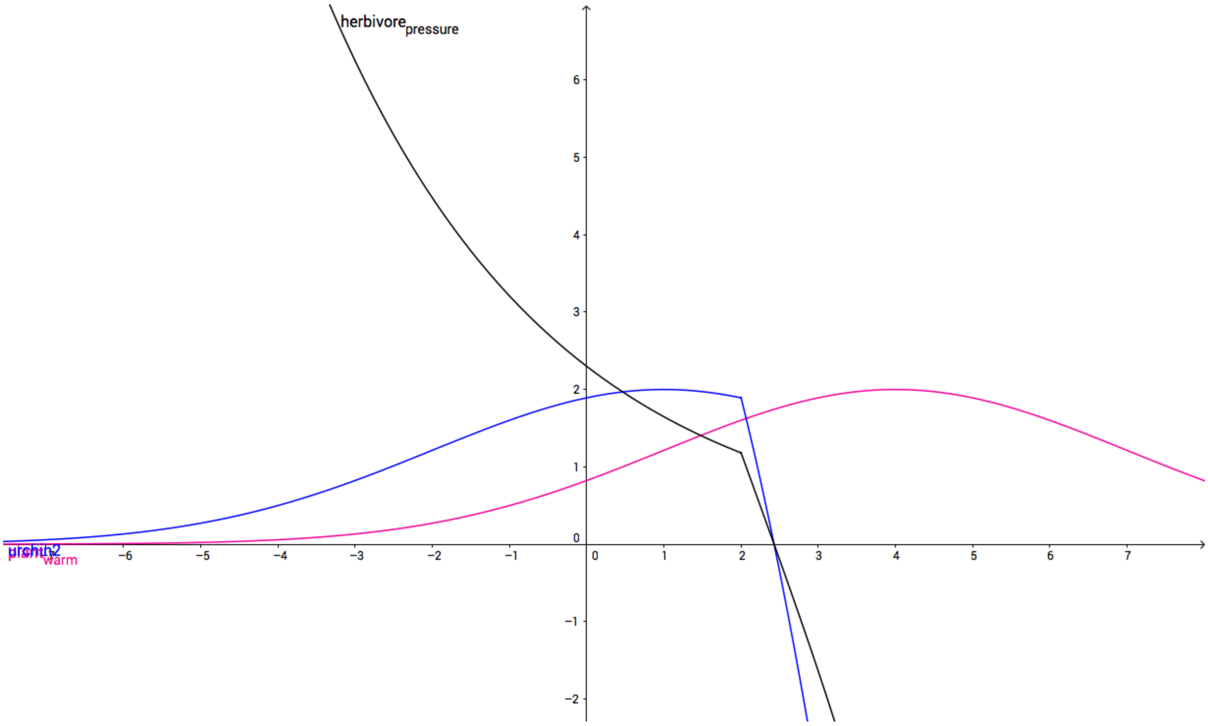


Fig. S7. Graphical representation of the continuous function $plant_{cool}$ (orange line), the stepwise function urchin2 (blue line) and the continuous function herbivore pressure (i.e. urchin/$plant_{cool}$, black line). Note that when plant and urchin curves are of the same shape and plant performance is shifted to the left, the resulting herbivore pressure function is a positive exponential, until the urchin performance curve drops (for x>2).

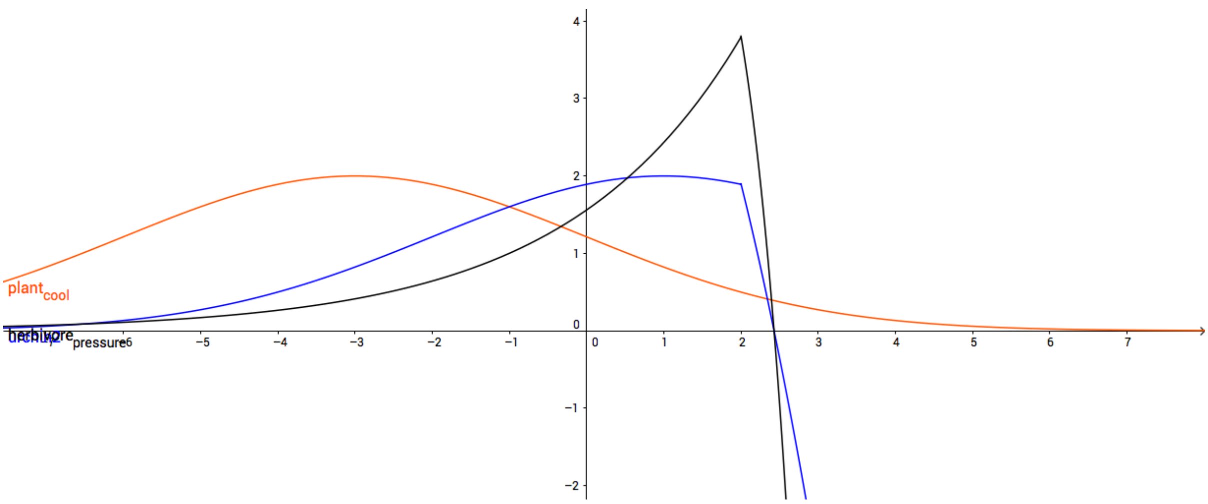
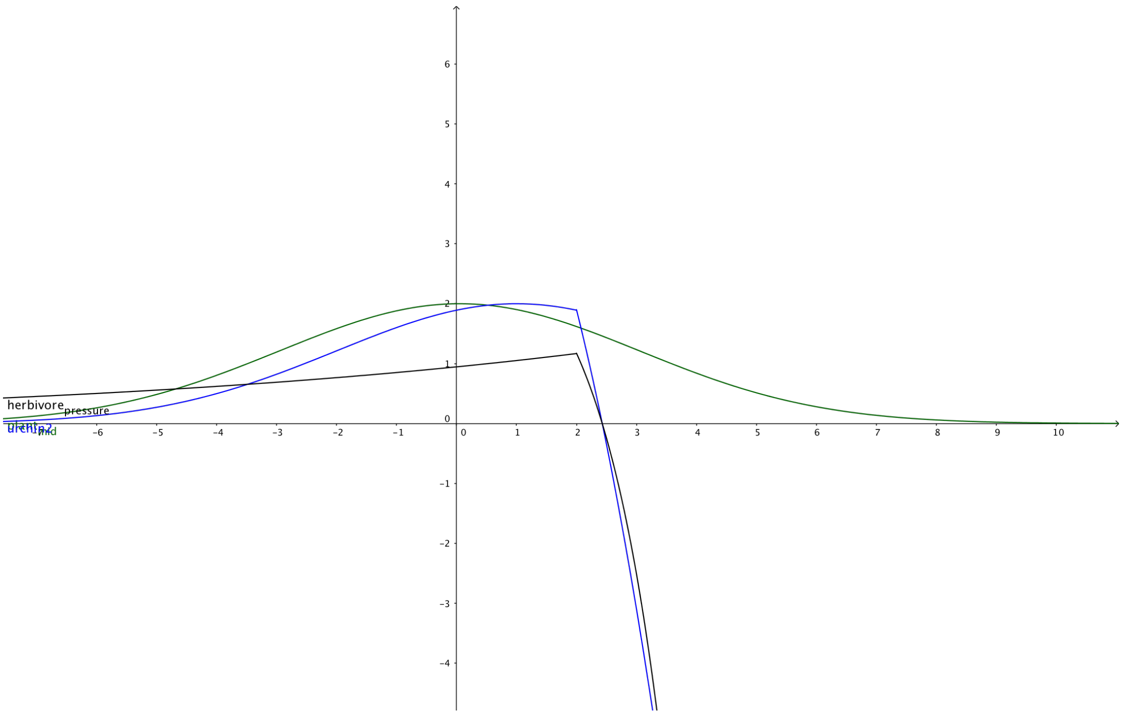


Fig. S8. Sensitivity analysis. (a) Graphical representation of the continuous function plant$_{mid}$ (green line) with the optimum temperature of this plant shifted to the left. (b) Graphical representation of the continuous function plant$_{mid}$ (green line) with the optimum temperature of this plant shifted to the right. In both cases (a,b), the urchin performance curve remains unchanged. Note the change to the herbivore performance curve (black line) is minimal.

(a)



(b)

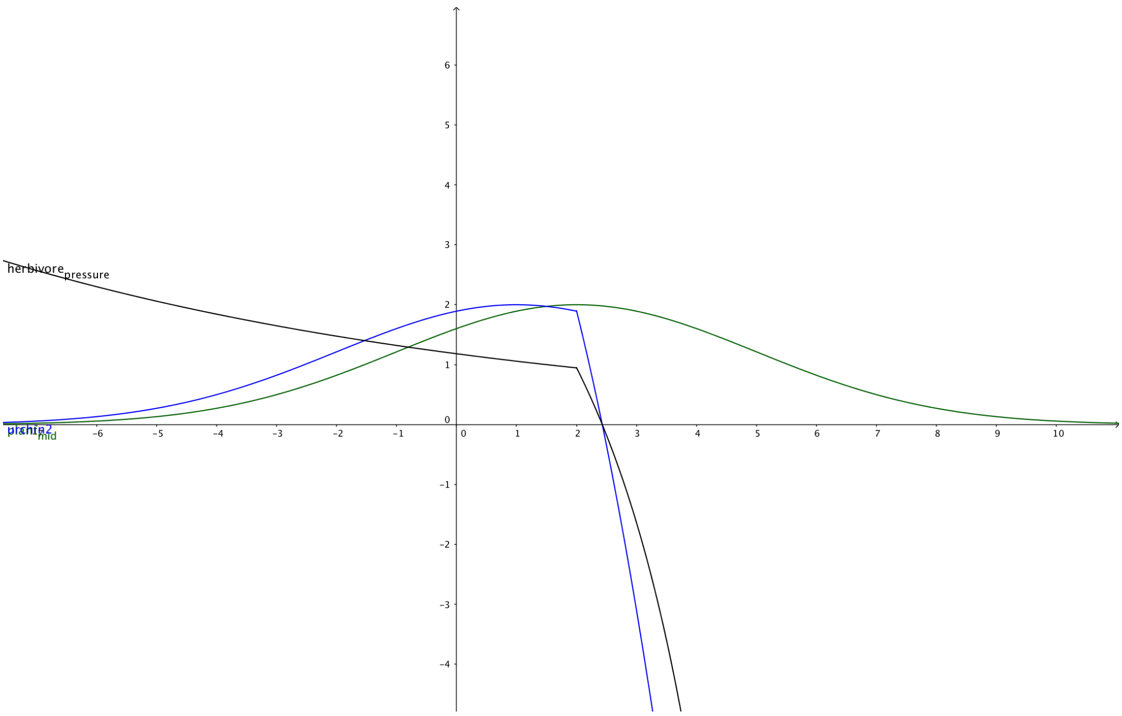
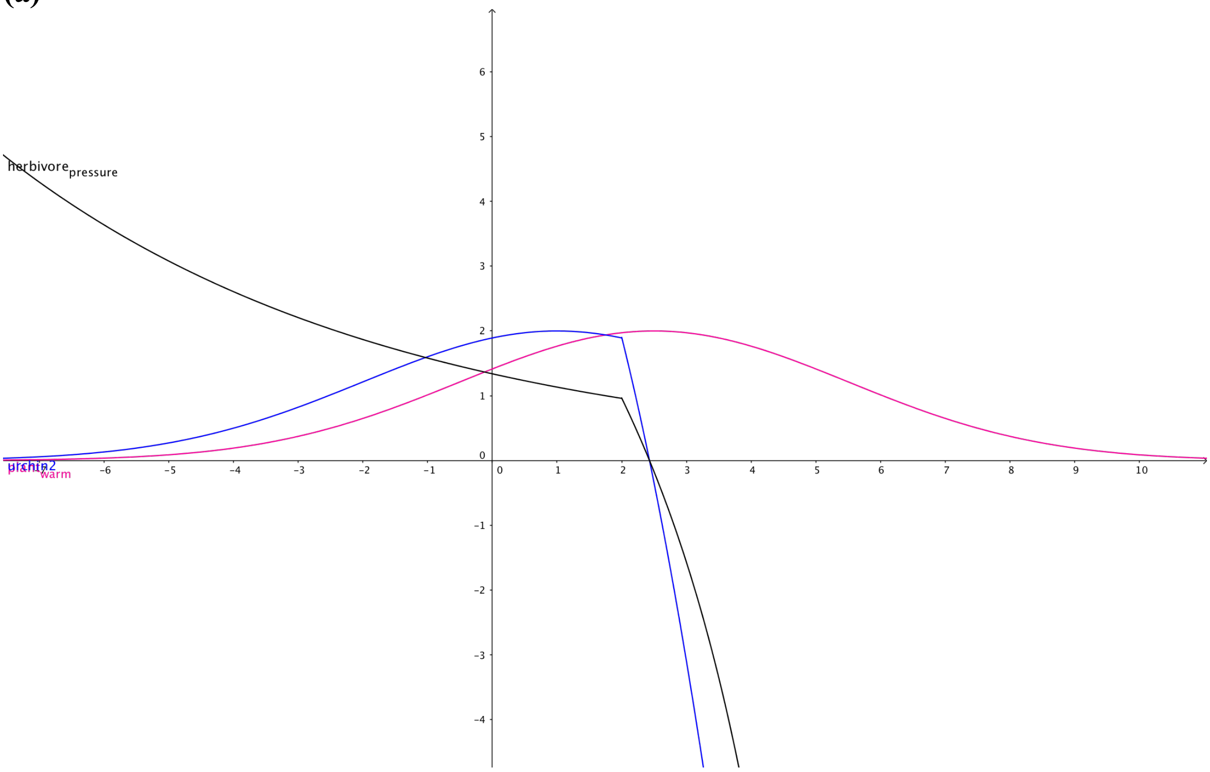


Fig. S9. Sensitivity analysis. (a) Graphical representation of the continuous function $plant_{warm}$ (pink line) with the optimum temperature of this plant shifted to the left. (b) Graphical representation of the continuous function $plant_{warm}$ (pink line) with the optimum temperature of this plant shifted to the right. In both cases (a,b), the urchin performance curve remains unchanged. Note the change to the herbivore performance curve (black line) is minimal.

(a)



(b)

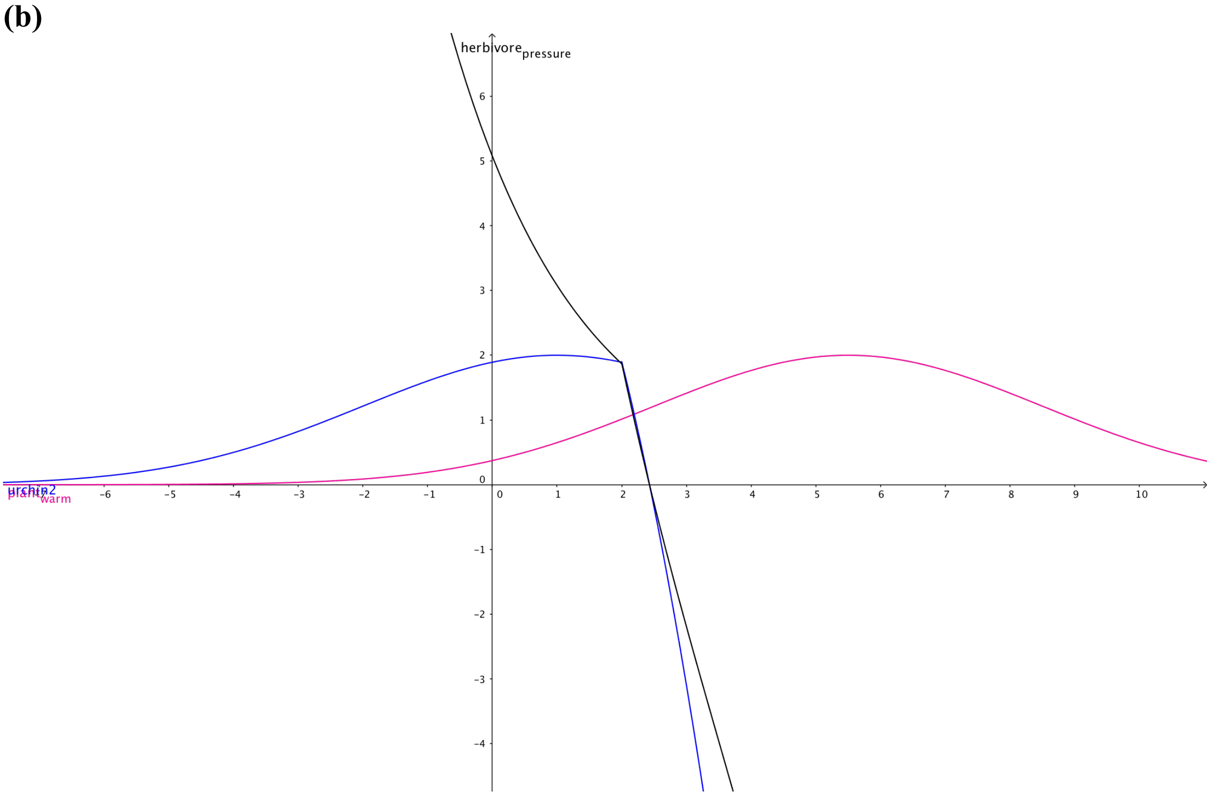
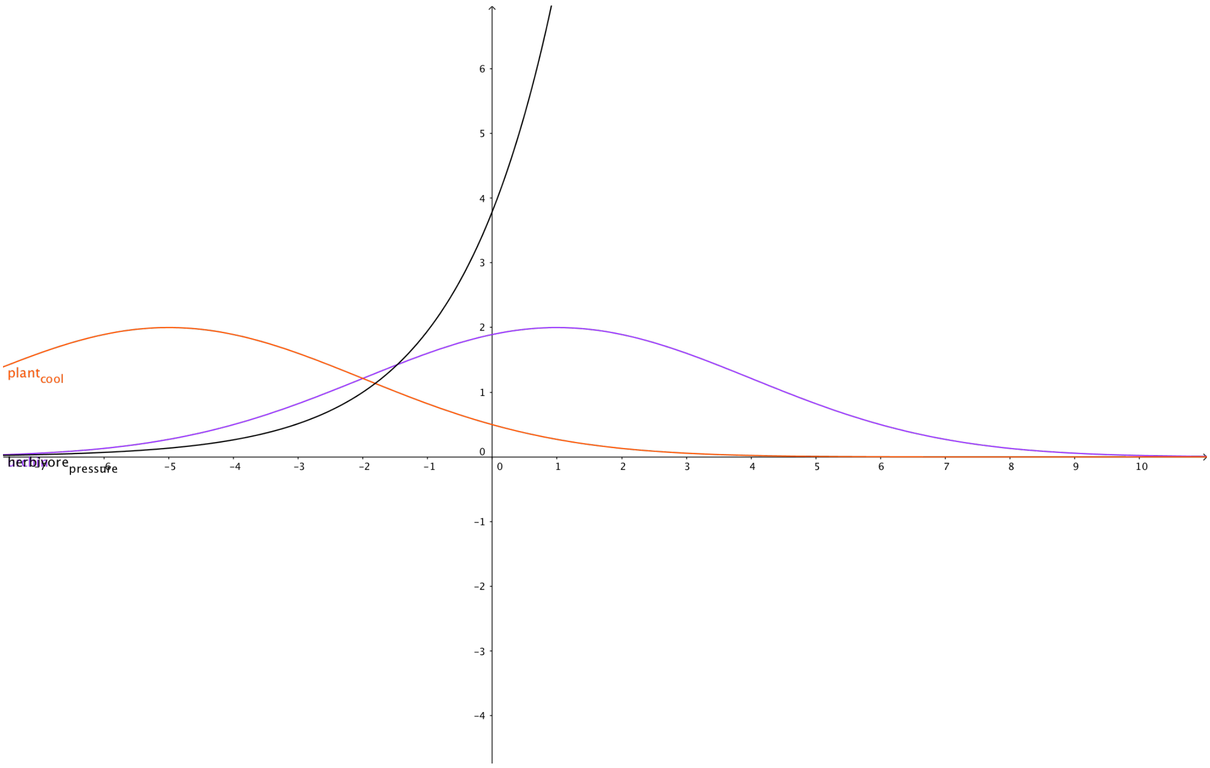
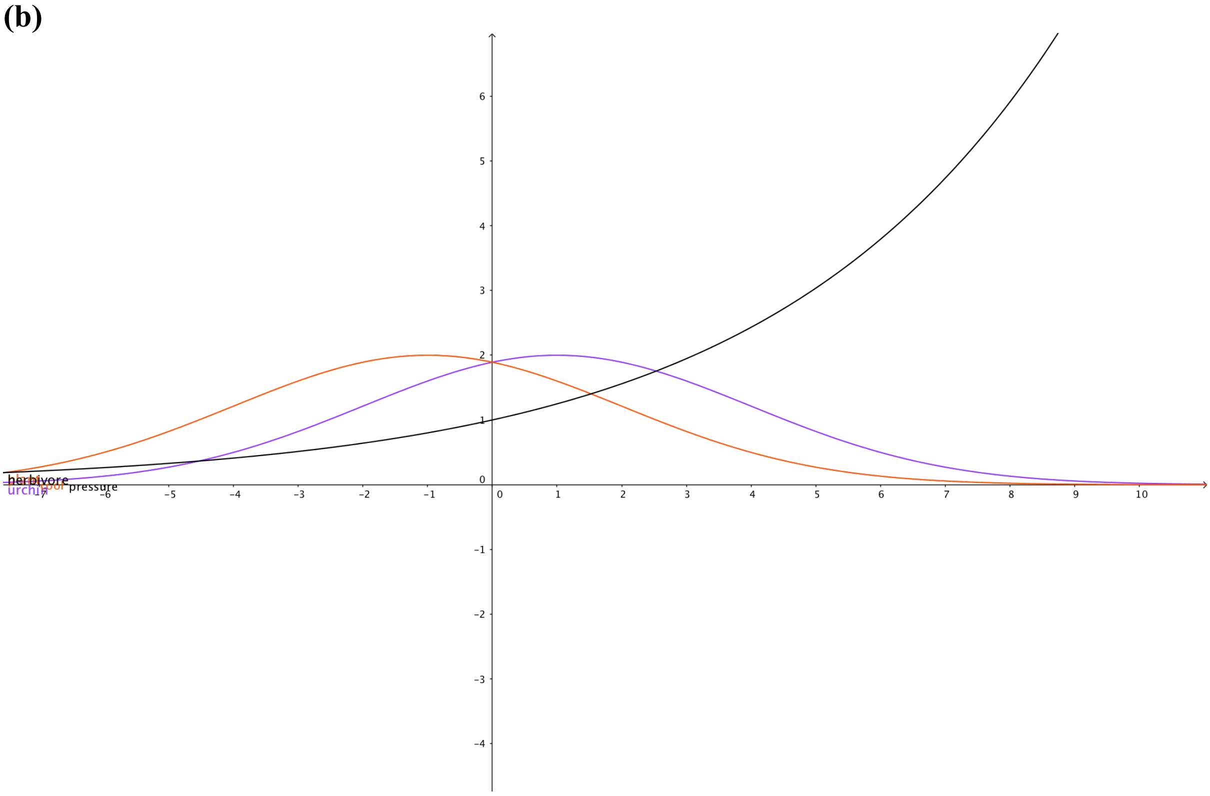


Fig. S10. Sensitivity analysis. (a) Graphical representation of the continuous function $plant_{warm}$ (orange line) with the optimum temperature of this plant shifted to the left. (b) Graphical representation of the continuous function $plant_{mid}$ (orange line) with the optimum temperature of this plant shifted to the right. In both cases (a,b), the urchin performance curve remains unchanged. Note the change to the herbivore performance curve (black) is minimal.

(a)



(b)



References

Angilletta, M.J., 2006. Estimating and comparing thermal performance curves. J. Therm. Biol. 31, 541–545. doi:10.1016/j.jtherbio.2006.06.002

Seuront, L., 2009. Fractals and Multifractals in Ecology and Aquatic Science. CRC Press, Boca Raton.

Seuront, L., Stanley, H.E., 2014. Anomalous diffusion and multifractality enhance mating encounters in the ocean. Proc. Natl. Acad. Sci. U. S. A. 111, 2206–11. doi:10.1073/pnas.1322363111