

Effects of marine warming on the spatial distribution of *Posidonia oceanica* in the marine ecosystems

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Environmental data

Posidonia oceanica is the dominant seagrass in shallow waters of the Mediterranean Sea. Here, *P. oceanica* meadows cover between $2.5 \times 10^{10} m^2$ and $5.0 \times 10^{10} m^2$ of continental platform surface, where survive up to 45 m depth. *P. oceanica* forms underwater meadows supporting significantly the biodiversity in shoreline ecosystems. *Posidonia oceanica*, is also considered an important carbon sink due to its capability to remove carbon dioxide from the biosphere.

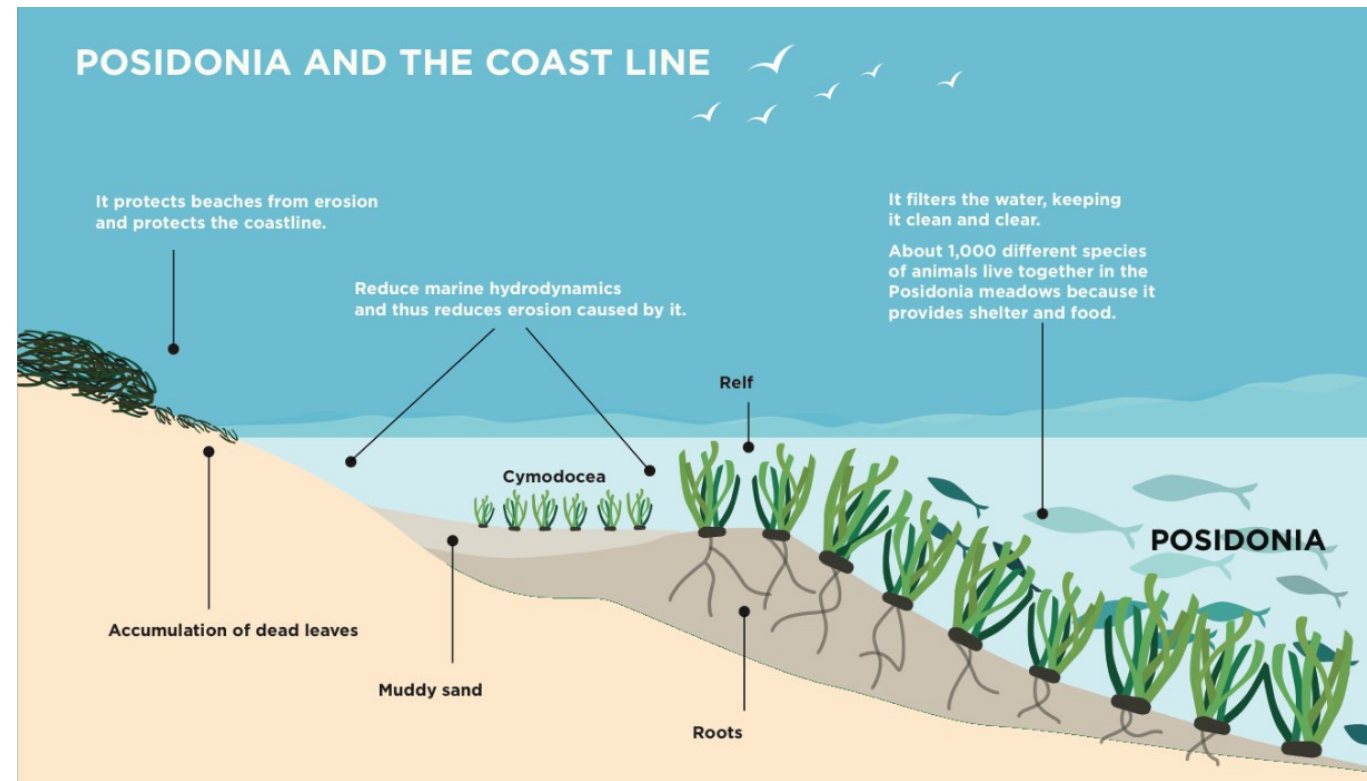


Fig. 1 – Scheme of the marine ecosystem of *P. oceanica* close to the shoreline (Courtesy of Santjosep.net).

The seawater temperature close to seabed plays a key role in the performance and survival of *P. oceanica*. In fact, the recent temperature enhancement due to global warming caused a significant increase of shoot mortality rates for this species. The recruitment rate of *P. oceanica* is strictly connected with the light intensity close to seabed, which depends on the incident solar radiation, the seawater turbidity and seabed depth. The health and conservation status of *P. oceanica* meadow is also affected by direct anthropogenic impacts, such as the high levels of eutrophication and turbidity recorded close to coasts. For these reasons, in last years the behavior of *P. oceanica* density has been investigated also by using predictive models.

The model

The model used to describe the dynamics of the density of *P. oceanica* in marine ecosystems, consists a simplified version of the advection-branching-death (ABD) model. The model considers the main three physical processes involved in the clonal growth of seagrass meadow: the horizontal growth of apex, the lifetime of shoots and apices, the new branches growth in other directions separated by a characteristic angle from the initial one.

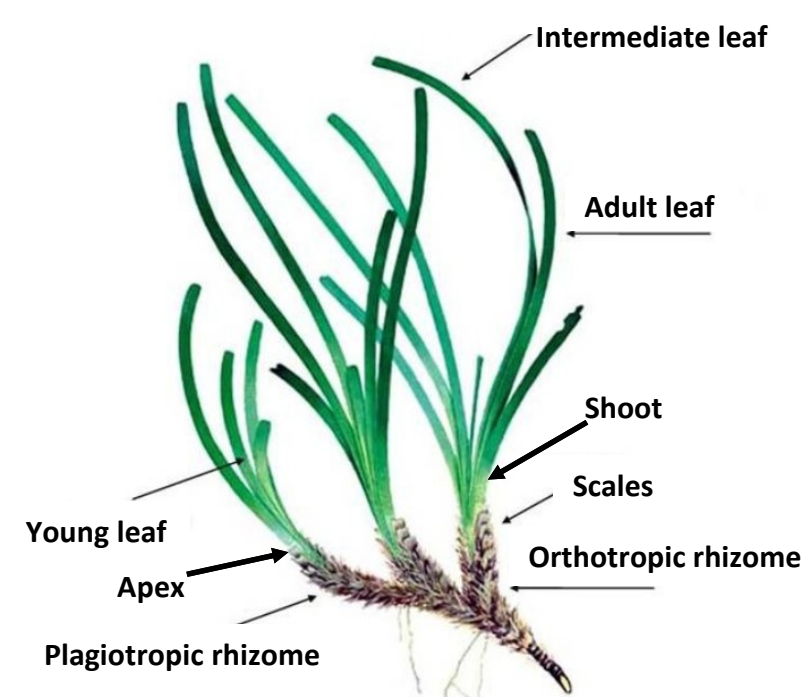


Fig. 2 – Description of the clonal growth mechanism for *P. oceanica* (Courtesy of Flagella, 2010).

The partial differential equation (PDE) which describes the spatiotemporal dynamics of *P. oceanica* density (n) is given by:

$$\frac{\partial n}{\partial t} = (\omega_b - \omega_{d0}[D, z])n - a(k - \omega_b)n^2 - bn^3 - \alpha n \nabla^2 n - \beta n \nabla^4 n + d_0 \nabla^2 n + d_1 \|\nabla n\|^2 \quad (1)$$

where the mortality rate (ω_{d0}) as a function of the annual cumulative temperature increase or degree-days (D) and depth (z), is obtained as follows:

$$\omega_{d0}[D, z] = 0.118 + 0.001 \cdot D(t) - 0.003 \cdot z. \quad (2)$$

Here, the degree-days ($D(t)$) are considered as a function of time (t), since the model aims to reproduce the effects of a progressive temperature on the spatiotemporal dynamics of *P. oceanica* density.

Symbol	Interpretation	Unit	Value
ω_b	Branching rate	y^{-1}	0.00 – 0.12
ω_{d0}	Mortality rate (as a function of degree-days and depth)	y^{-1}	0.04 – 0.18
a	Magnitude of local facilitative interactions	$cm^2 \cdot y^{-1}$	10 – 150
b	Magnitude of local competitive interactions	$cm^4 \cdot y^{-1}$	10 – 100
k	Strength of the non-local competitive interactions	y^{-1}	0.03 – 0.06
α	Magnitude of second order non-local facilitative/competitive interactions	$cm^4 \cdot y^{-1}$	$10^4 - 10^7$
β	Magnitude of fourth order non-local facilitative/competitive interactions	$cm^6 \cdot y^{-1}$	$10^6 - 10^{12}$
d_0	Diffusion coefficient for rhizome elongation	$cm^2 \cdot y^{-1}$	$10^2 - 10^3$
d_1	Spreading coefficient for rhizome branching	$cm^4 \cdot y^{-1}$	$10^3 - 10^4$
z	Depth of the water column	m	0 – 38
D	Annual seawater temperature enhancement or degree-days (as a function of time)	$^\circ C$	0.0 – 76.5

Table 1 – Biological and environmental parameters used in the simplified ABD model.

Stability of homogeneous meadows

The solutions of the PDE for the dynamics of *P. oceanica* density depend on the ABD model parameters. The parameter a controls the degree of bistability of the two homogeneous solutions of the PDE, while the parameter b fixes the magnitude of the shoot density determining the saturation level for *P. oceanica* meadow. The parameters α and β fix the magnitude of the long-range non-linear competitive processes.

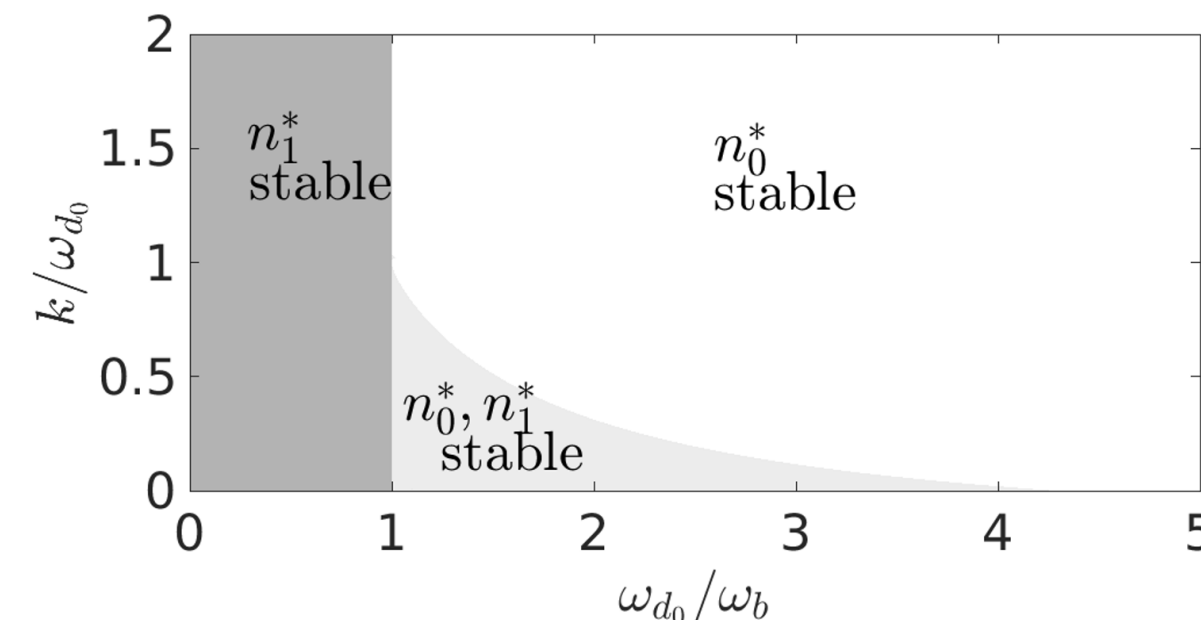


Fig. 3 – Phase diagram of the ABD model considering only the kinetics. The region of stable populated solution is in dark grey; the region of stable unpopulated solution is in white; the region of coexistence between the populated and unpopulated solutions is in grey.

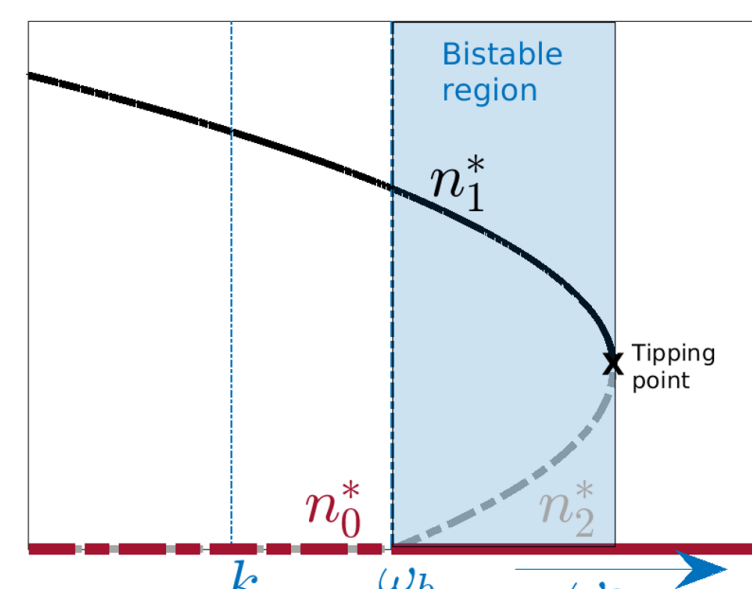


Fig. 4 – Bifurcation diagram of the ABD model considering only the kinetics.

Patterned solutions driven by spatial heterogeneity

The mortality rate variations due to prolonged marine warming are modelled by simulating the seawater temperature growth according to equation (2).

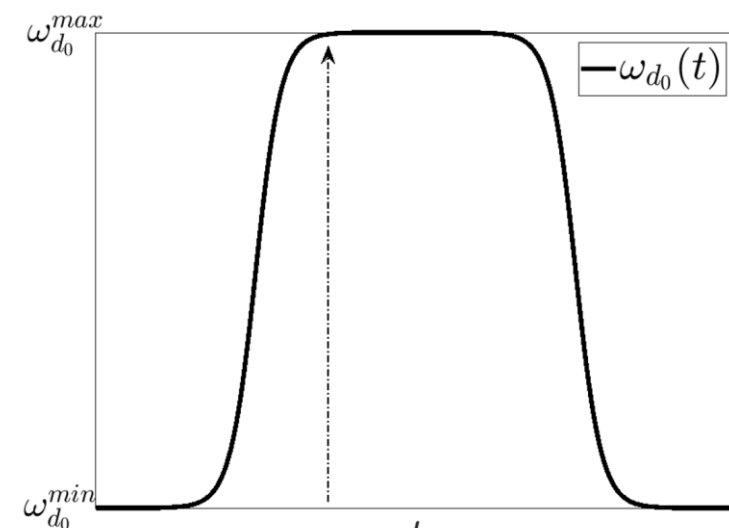


Fig. 5 – Mortality rate profile over time.

The effects of random perturbations of environmental variables on the dynamics of *P. oceanica* density in each point of 2D spatial domain are reproduced by inserting a term of multiplicative Gaussian noise in equation (1):

$$\frac{\partial n}{\partial t} = (\omega_b - \omega_{d0}[D, z]) \cdot (1 + \xi(t))n - a(k - \omega_b)n^2 - bn^3 - \alpha n \nabla^2 n - \beta n \nabla^4 n + d_0 \nabla^2 n + d_1 \|\nabla n\|^2$$

where the noise ($\xi(t)$) is modelled as a spatio-temporal Wiener process.

Spatial noise triggers the spatial instability (Turing instability) for the distribution of *P. oceanica* density favouring the transition to patterned heterogeneous states [1].

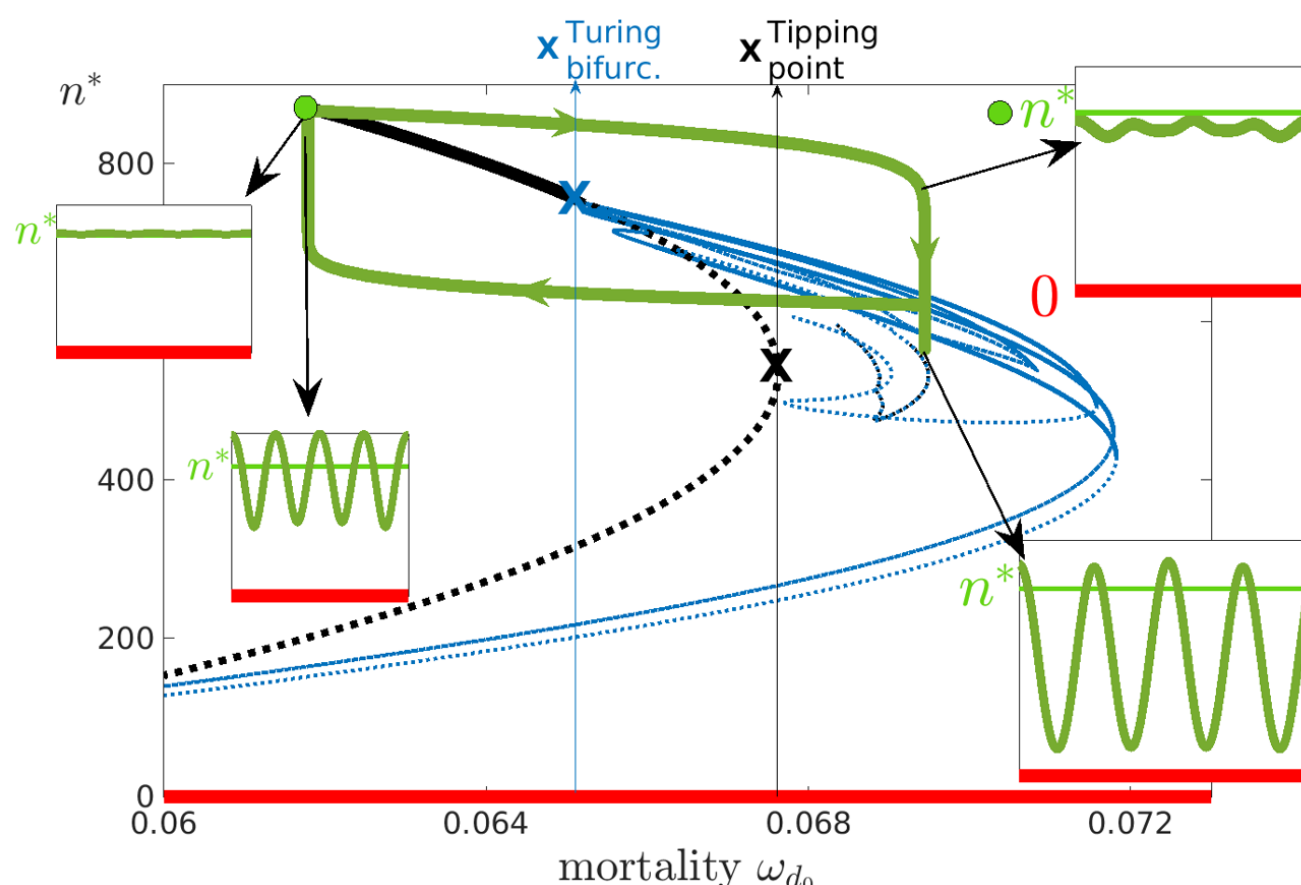


Fig. 6 – Bifurcation diagram of the ABD model. The ω_{d0} varies according to the law shown in Fig. 5. The maximum mortality rate allows a restoring process for *P. oceanica*.

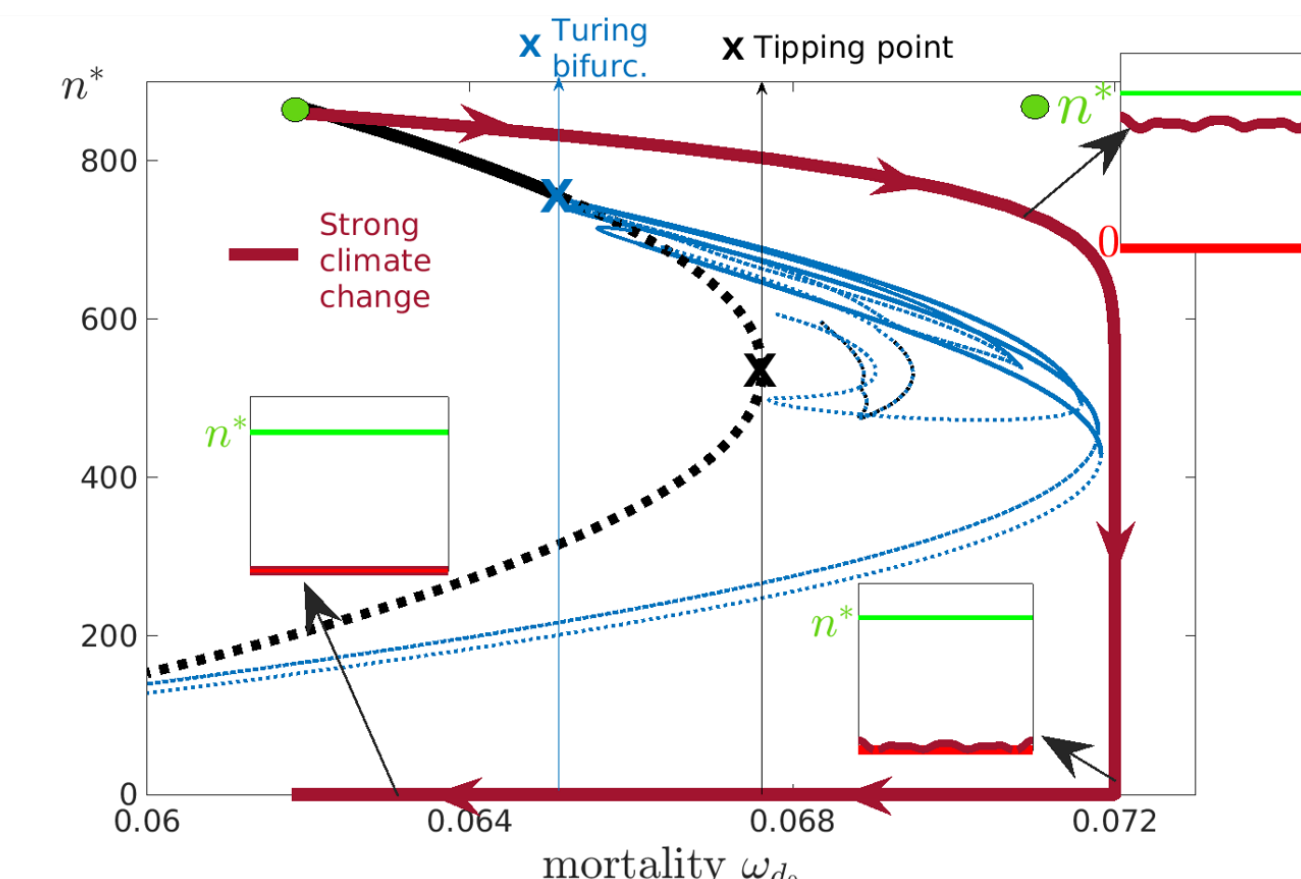


Fig. 7 – Bifurcation diagram of the ABD model. The ω_{d0} varies according to the law shown in Fig. 5. The maximum mortality rate causes the desertification of *P. oceanica*.

Numerical results

Numerical investigations have been performed with the mortality rate varying in the range 0.060-0.072 y^{-1} [2]. We define the mortality rate function which linearly grows for the first 50 years up its maximum and then remains constant for the next 50 years. Initial condition is a uniform homogeneous meadow. The model parameters are chosen to drive the spatial heterogeneity (Turing instability) of *P. oceanica* density both in the super-critical and sub-critical region, leading to the formation of a patterned solutions.

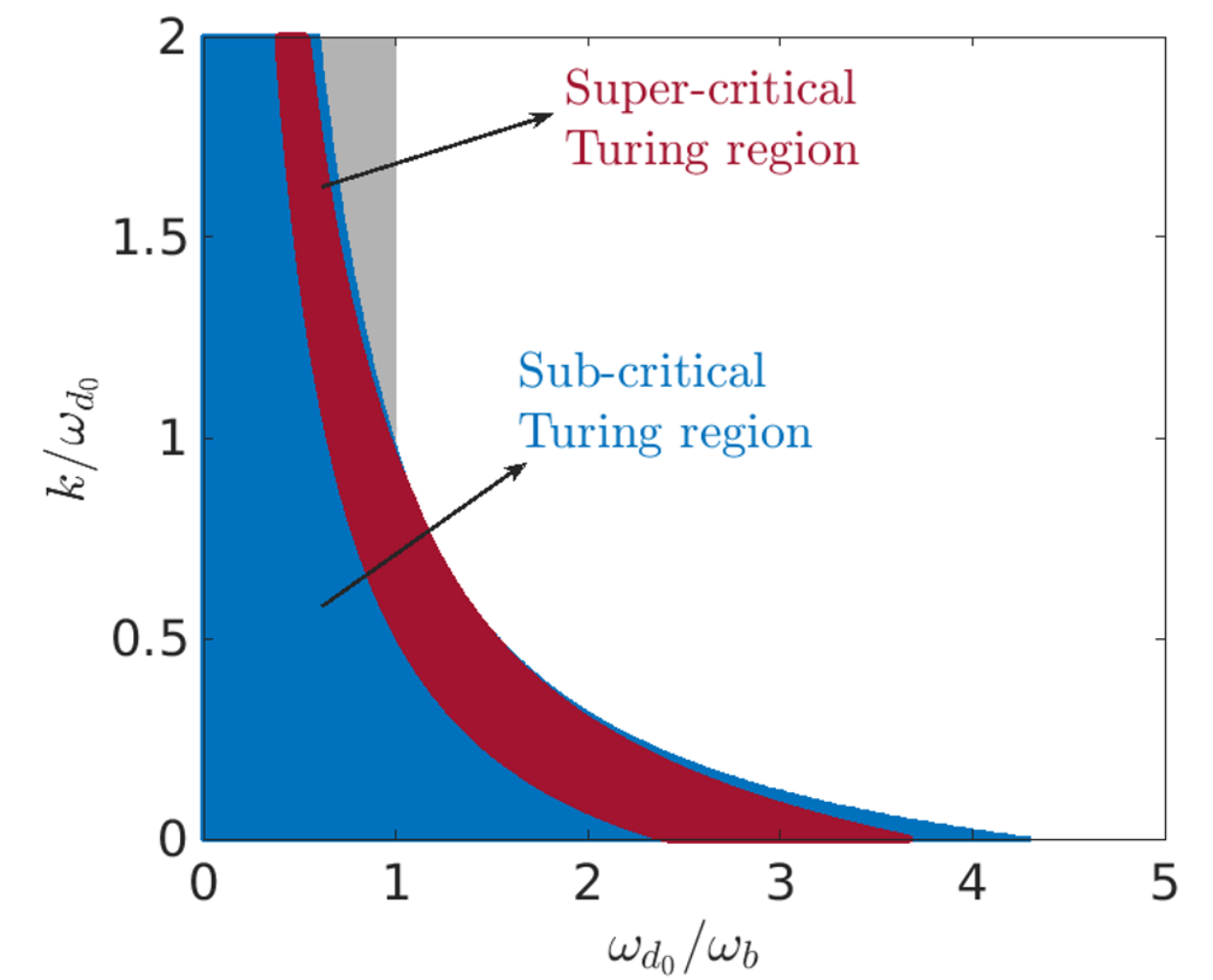


Fig. 7 – Phase diagram of the ABD model considering the Turing instability. The super-critical Turing region of patterned solutions is in dark red; the sub-critical Turing region of patterned solutions is in blue; the super-critical region of stable populated solutions is in grey; the region of stable unpopulated solution is in white.

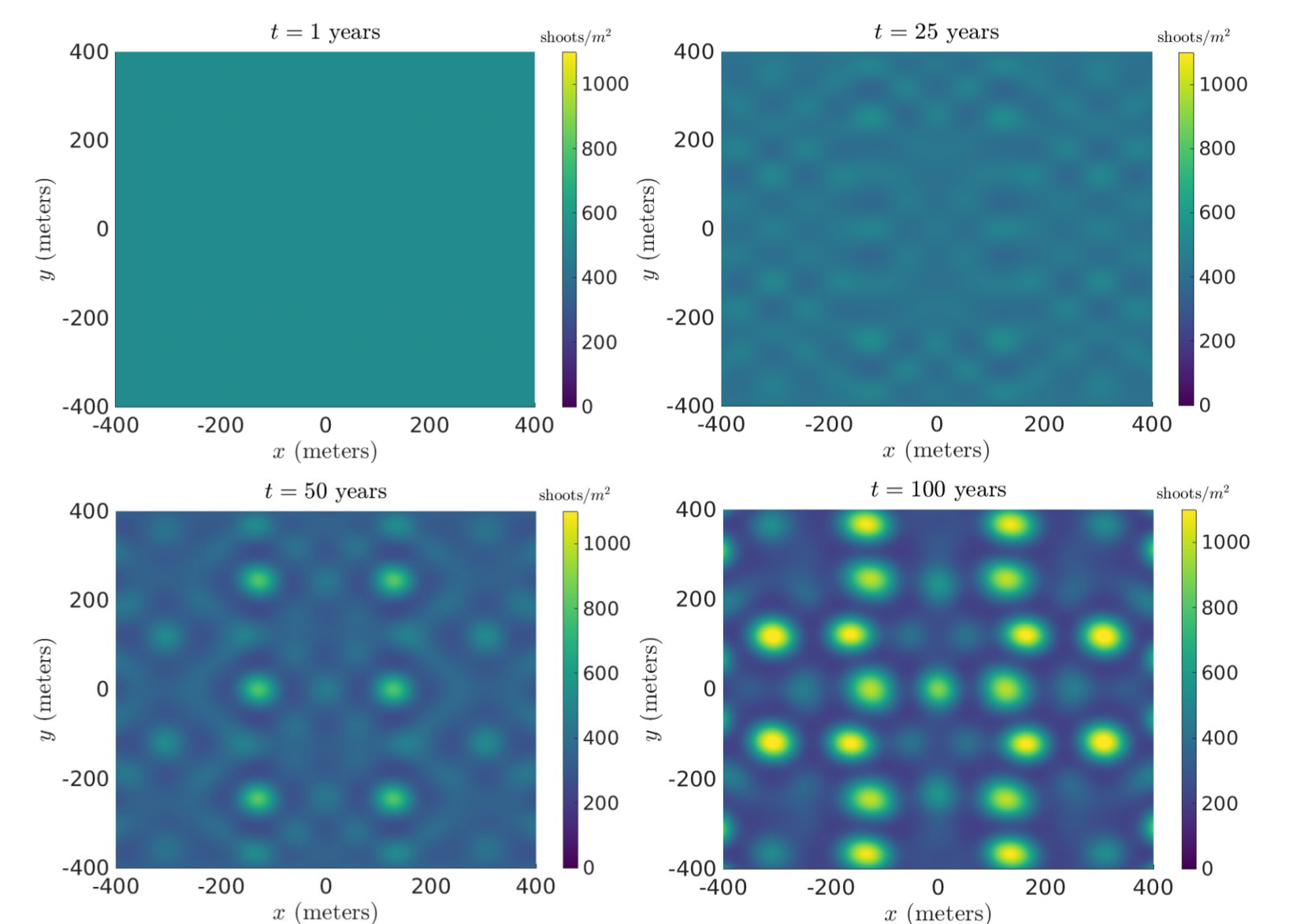


Fig. 8 – Time evolution of the spatial density of an initially homogeneous *P. oceanica* meadow in the super-critical case. The initial uniform density is 500 shoots/ m^2 .

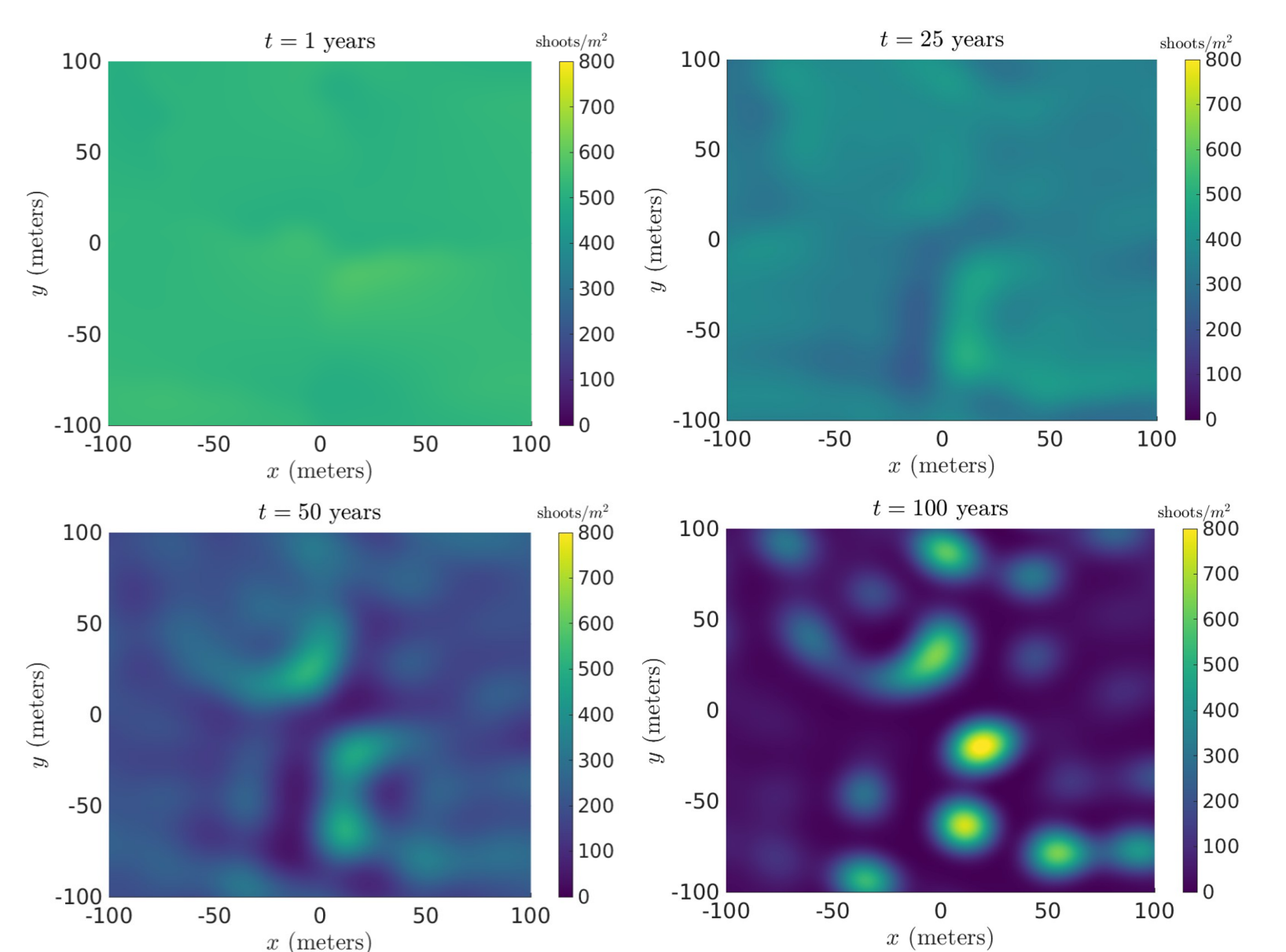


Fig. 9 – Time evolution of the spatial density of an initially homogeneous *P. oceanica* meadow in the sub-critical case. The initial uniform density is 500 shoots/ m^2 .

In the super-critical case, the patterned solution describes the self-organization of the meadow away from the desertification. The sub-critical patterned solution describes a wide spread presence of desertified areas.

References

- [1] D. Ruiz-Reynés, F. Schonsberg, E. Hernández-García and D. Gomila (2020), *General model for vegetation patterns including rhizome growth*, Physical Review Research 2, 023402.
- [2] N. Marbà and C.M. Duarte (2010), *Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality*, Global Change Biology 16, 2366–2375.
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