EVREST Project Report:

Report on the resilience of barrier systems

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TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1. Introduction

This report covers the activities performed in the framework of 'Task 5: Integration of results and quantification of resilience'. The objectives of this task were to integrate results obtained in previous tasks, and to propose innovative resilient parameters.

The task was implemented mainly by the members of the CIMA research group, with presentation and discussion of the proposed methodology and framework for the resilience assessment with the other team members during the third EVREST Meeting/Workshop, that took place in the University of Algarve between the 27th and 28th of September, 2018 (see related report). Extensive bibliographic research on resilience theories and their applicability to natural systems was performed under this task, with the innovative view of ecological resilience selected as the most appropriate one. The team discussed and analysed extensively the principles of the ecological resilience theory and how these can be transferred to barrier geomorphic evolution. These issues and the main results on the resilience assessment of Ria Formosa are presented in this report.

To date, the work has been published in one scientific journal and presented in one international conference (*Earth-Science Reviews* and *X Jornadas de Geomorfología Litoral*, respectively; see report on Task 6). One more journal article, directly deriving from the work implemented under task 5, is under preparation and will soon be submitted for review.

2. Resilience Theories

2.1 Emerging Issues

Resilience, highly important in the context of achieving sustainability (Brand and Jax, 2007), is a multi-faceted concept that has been adapted differently to various uses and contexts (Alexander, 2013). The term was historically grounded in law and politics (Flood and Schechtman, 2014), passed from mechanics to ecology and psychology, and then was adopted by social science and sustainability science (Alexander, 2013). The multiple levels of meaning of resilience include a sustainability-related metaphor, a property of dynamic models and a measurable attribute of socioecological systems (Carpenter et al., 2001). These multiple uses of the term, with different objectives, over a broad contextual frame and with a mixture of descriptive and normative aspects has led to divergent conceptions of resilience, ambiguous uses of terminology and to an increasingly diluted and unclear specific meaning of resilience (Brand and Jax, 2007). Distinct views, perceptions and definitions seem to coexist even within disciplines (e.g., physics, ecology, geography, psychology, economy), while, between disciplines, the differences are even more significant (Piégay et al., 2018). For example, Brand & Jax (2007) pinpoint 10 different approaches to resilience, four of which fall in ecological sciences, each one emphasizing on different aspects of resilience, with respect to the specific interest of the analysis.

It becomes clear that the term has been used ambiguously and for fundamentally different intentions, giving rise to trade-offs between social and environmental objectives, while resilience is increasingly conceived as a perspective, rather than a clear and well-defined concept (Brand and Jax, 2007). Both scientific interest and confusion regarding the application of resilience theories to natural systems is high, whereas little focus has been given to complex coastal systems like barrier islands. Thoms et al. (2018) specify three main emerging issues in a resilience-based approach to geomorphology: (1) confusion over resilience terminology across social and physical sciences; (2) the role of humans as external drivers or internal components of geomorphic systems and what this means for system resilience; and (3) questions of scale in general, involving how to address cross-scale interactions in social-ecological systems.

Furthermore, humans and geomorphic systems are inextricably linked, given that human activity influences bio-geophysical processes and events, which, in turn influence human reactions and decision making (Berkes and Ross, 2016; Chaffin and Scown, 2018). According to Walker and Salt (2006), 'even though the link between social and ecological systems should be a self-evident truth, this is not reflected in the manner in which we traditionally analyse and practice natural resource management', meaning that critical feedbacks to understanding and managing systems for sustainability are often ignored (Berkes et al., 2003). This is mainly due to the complexities and uncertainties involved in how humans and natural systems anticipate and respond to disasters (Gunderson, 2010). Socio-ecosystem interactions can also include individual attitudes (cognition, emotion and behaviour), raising questions on what is valued and not valued in landform changes (Piégay et al., 2018). All these complexities give rise to numerous research challenges, such as clarifying feedbacks, their interplay across scales and the role of adaptive capacity in this context (Folke, 2006). Meeting these challenges would require both inter-disciplinary (i.e. geomorphologists and social scientists) research and meaningful cooperation with governance actors (Chaffin and Scown, 2018).

2.2 The ecological and the engineering view on resilience

There are two main schools of thought regarding resilience, representing distinct views and focal points, one concentrating on recovery and return time following a disturbance, and the other on how much a system can be disturbed and still persist without changing function (Miller et al., 2010). The former corresponds to the engineering principle, which is the resilience to non-permanent disturbances (after some time the system relaxes to its previous state), whereas the latter refers to the ecological resilience and is associated with a changing set of internal or external drivers (Piégay et al., 2018). These different views on resilience are fundamental, with the engineering view concerned with maintaining efficiency of function and the ecosystem one on maintaining existence of function (Gunderson and Holling, 2002). They are often depicted using the ball-and-cup analogy (Figure 1), where the cup represents the 'basin of attraction', defined by all possible values of system variables of interest, and the ball represents the state of the system at a given temporal point (Flood and Schechtman, 2014). Engineering resilience considers a single basin of attraction and is interested in whether the system can remain at its bottom, whereas ecological resilience accepts multiple basins of attraction and focuses on whether the system can remain within the current basin (Holling, 1996).

It follows that the engineering interpretation does not consider thresholds and is used in a narrow sense of elasticity, with resilience representing the ability to resist departure from equilibrium (bottom of the basin) and maximize the speed of return to it after disturbance (Flood and Schechtman, 2014). Conversely, ecological resilience thinking is all about identifying and understanding thresholds and, even though the speed with which a system recovers after disturbance can also be important, the ability of the system to recover at all is much more relevant (Walker and Salt, 2006). These different approaches also have to do with how they treat opposing feedbacks, that is self-reinforcing or positive ones (secondary effects that enhance the impacts of the original stimulus) that can create instabilities in geomorphic systems and negative ones (secondary effects that dampen the impacts) that are essential for maintaining dynamic equilibrium (Chaffin and Scown, 2018). The engineering view deals with negative feedback, with constancy of the system and with a predictable world near a single steady state (Folke, 2006) and, under this narrow sense, can be considered to express (and be synonymous to) the stability of the system. Contrastingly, ecological resilience focuses on the role of positive feedbacks, of behaviour far from steady states and deterministic outcomes and with internally generated variability (Gunderson et al., 2009).

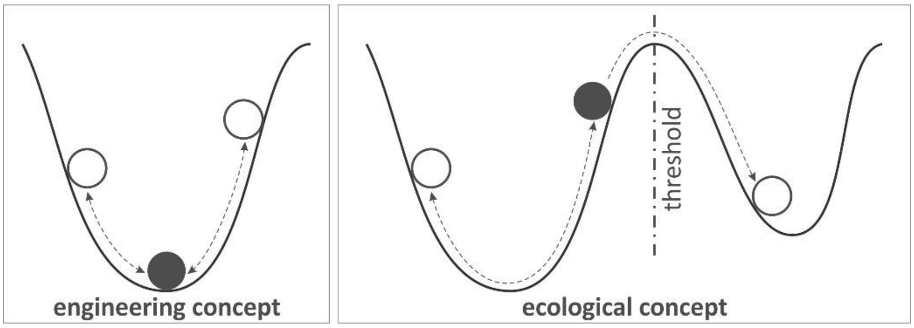


Figure 1: Graphical representation of the different views on resilience under the engineering and ecological concepts, using the ball-and-cup analogy; after Holling (1996).

Ecological resilience is currently defined as 'the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same functions, structure, identity and feedbacks' (Flood and Schechtman, 2014; Folke, 2006; Scheffer and Carpenter, 2003; Walker et al., 2004). The ecological concept focuses on remaining within the same regime (Walker et al., 2004), avoiding to cross a threshold into an alternate and possibly irreversible new state, and on regenerating

after disturbance (Miller et al., 2010). On the other hand, the opportunities in terms of recombination of evolved structures and processes, renewal of the system and emergence of new trajectories after disturbance, are also inherent to resilience thinking (Folke, 2006).

It is also important to distinguish between “specified” and “general” resilience. Specified resilience refers to answering the question “of what to what?”—that is, over what time period and at what scale (Carpenter et al., 2001). The concept of general resilience, on the other hand, concerns the resilience of all aspects of a system to unspecified, including novel and unforeseen, disturbances (Miller et al., 2010). When managing for resilience, both types need to be considered (Walker and Salt, 2006). A further distinction can be made between resilience, measured by the size of basins of attraction, and resistance, which is measured by the magnitude of an external force, or pressure, needed to disturb (displace) a system by a given amount.

3. Ecological Resilience: Fundamentals and Principles

3.1 The myths of nature

Gunderson and Holling (2002) identify five worldviews or myths that people hold regarding how nature works (Figure 2). This section is based on the pioneering work of Gunderson and Holling (2002), explaining how each of these caricatures, or myths, leads to different assumptions about stability, different perceptions of the processes that affect that stability, and different policies that are deemed appropriate (Table 1).

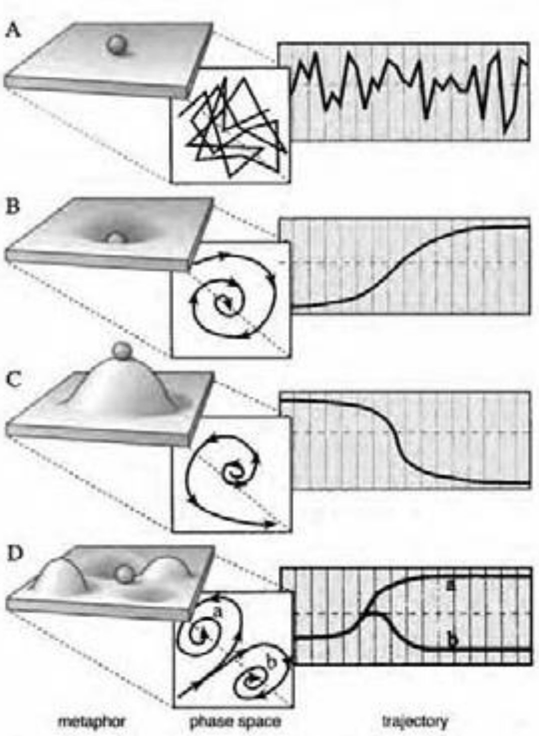


Figure 2: Depictions of four myths of nature: (A) Nature Flat, (B) Nature Balanced, (C) Nature Anarchic, and (D) Nature Resilient. Each myth has three representations or metaphors: as stability landscape (left), phase diagram (centre), and time-course chart or trajectory of key system variables over time (right). Image from *Gunderson and Holling (2002)*.

Nature Flat. In this view, "flat" is used to describe a system in which there are few or no forces affecting stability. There are therefore few limitations on the ability of humans to change nature. There are no feedbacks or consequences from nature of human actions. It is much like rolling a ball around on a cookie sheet (Figure 2A). The processes that affect the position of the ball (i.e., state of nature) are random or stochastic. It is a nature that is infinitely malleable and amenable to human control and domination if only the "right" values and the "right" timing are chosen. The issues of resource use, development, and control are identified as issues that are exclusively of human action, issues that can be resolved by community activism or stakeholder control. Alternatively, it can be a view of comucopian nature where human ingenuity and knowledge surmount all obstacles to produce exponential growth. Such a "flat worlder" view is not wrong, just incomplete. There are indeed strong stochastic elements; the timing of decisions is important. Human ingenuity is a powerful force for change.

Nature Balanced. The second myth is a view of nature existing at or near an equilibrium condition (Figure 2B). That equilibrium can be a static one or a dynamic one. Hence if nature is disturbed, it will return to an equilibrium through (in systems terms) negative feedback. Nature appears to be infinitely forgiving. It is the myth of maximum sustainable yield and of achieving fixed carrying capacities for animals and humanity. It imposes a static goal on a dynamic system. This view of nature underpins prescriptions for logistic growth, where the issue is how to navigate a looming and turbulent transition-demographic, economic, social, and environmental - to a sustained plateau. The "balanced worlder" view is also not wrong - just incomplete. There are indeed, forces of balance in the world, forces that can become overwhelmed.

Nature Anarchic. If the previous myth is one where the system stability could be defined as a ball at the bottom of a cup, this myth is one of a ball at the top of a hill (Figure 2C). It is globally unstable. It is a view dominated by hyperbolic processes of growth and collapse, where increase is inevitably followed by decrease. It is a view of fundamental instability, where persistence is possible only in a decentralized system where there are minimal demands on nature. If the Nature Flat view assumes that infinitely ingenious humans do not need to learn anything different, this view assumes that humans are incapable of learning. This view presumes that small is beautiful, because the inevitable catastrophe of any policy must be kept localized. It is a view where the precautionary principle of policy dominates, and social activity is focused on maintenance of the status quo. The "anarchist worlder" view is also not wrong - just incomplete. There are indeed destabilizing forces, and there is a value in diversity of the small and local.

Nature Resilient. The fourth is a view of multi-stable states, some of which become irreversible traps; while others become natural, alternating states that are experienced as part of the internal dynamics (Figure 2D). Those dynamics result from cycles organized by fundamentally discontinuous events and nonlinear processes. There are periods of exponential change, periods of growing stasis and brittleness, periods of readjustment or collapse, and periods of reorganization for renewal. Instabilities organize the behaviours as much as stabilities do. That was the view of Schumpeter's (1950) economics, and it has more recently been the focus of fruitful scholarship in a wide range of fields-ecological, social, economic, and technical. These dynamics are the ones argued for ecosystems (Holling, 1992). It is a view of multiple stable states in ecosystems, economies, and societies and of policies and management approaches that are adaptive. However, this view presumes a stationary stability landscape-stationary underlying forces that shape events. In this case, our cookie sheet has been moulded and curved in three dimensions, but its basic contours are fixed over time (Figure 2D). This "resilient worlder" view is also not wrong - just incomplete. There are, indeed, cycles of change, that can move variables among stability domains, but those very movements contribute to the apparent fixed nature of the contours. Constrain those movements through policy actions, and the contours shift, as slow variables change. That can precipitate a more structural kind of surprise that is a consequence of successful but myopic policy. Many of the examples of the pathology of resource management and regional development are just those kinds of structural surprises.

Nature Evolving. The emerging fifth view is evolutionary and adaptive. It has been given recent impetus by the paradoxes that have emerged in successfully applying the previous more limited views. Complex systems behaviour, discontinuous change, chaos and order, self-organization, nonlinear system behaviour, and adaptive evolving systems are all code words characterizing the more recent activities. They are leading to integrative studies that combine insights and people from developmental biology and genetics, evolutionary biology, physics, economics, ecology, and computer science. Profound innovations have been created and led by John Holland in his applications of genetic algorithms and development of complex adaptive system theory. It is a view of an actively shifting

stability landscape with self-organization (the stability landscape affects behaviour of the variables, and the variables, plus exogenous events, affect the stability landscape). Nature Evolving is a view of abrupt and transforming change. It is a view that exposes a need for understanding unpredictable dynamics in ecosystems and a corollary focus on institutional and political flexibility.

Table 1: Characteristics of Alternative Views or Myths of Nature (from Gunderson and Holling (2002))

	Stability	Processes	Policies	Consequence
Nature Flat	none	stochastic	random	trial & error
Nature Balanced	globally stable	negative feedback	optimize or return to equilibrium	pathology of surprise
Nature Anarchic	globally unstable	positive feedback	precautionary principle	status quo
Nature Resilient	multiple stable states	exogenous input and internal feedback	maintain variability	recovery at local scales or adaptation; structural surprise
Nature Evolving	shifting stability landscape	multiple scales and discontinuous structures	flexible and actively adapting probing	active learning and new institutions

3.2 The adaptive cycle

The notion of the adaptive cycle has a key role in the resilience interpretation of natural systems (Gunderson and Holling, 2002). According to the theory of the adaptive cycle (Figure 3), dynamical systems, such as ecosystems, societies, corporations, economies, nations, and socioecological systems, do not tend toward some stable or equilibrium condition (Carpenter et al., 2001). Instead, they pass through four characteristic phases: rapid growth and exploitation (r), conservation (K), collapse or release (or "creative destruction", Ω), and renewal or reorganization (α). Two opposing loops form the adaptive cycle: (a) the development (or 'fore') loop, characterized by the accumulation of capital and by stability and conservation and b) the release and reorganization (or "back") loop, characterized by uncertainty, novelty, and experimentation (Walker and Salt, 2006). The former is essential for system's well-being to increase and the latter is the time of greatest potential for the initiation of either destructive or creative change in the system and the time when human actions can have the strongest impact (Gunderson and Holling, 2002).

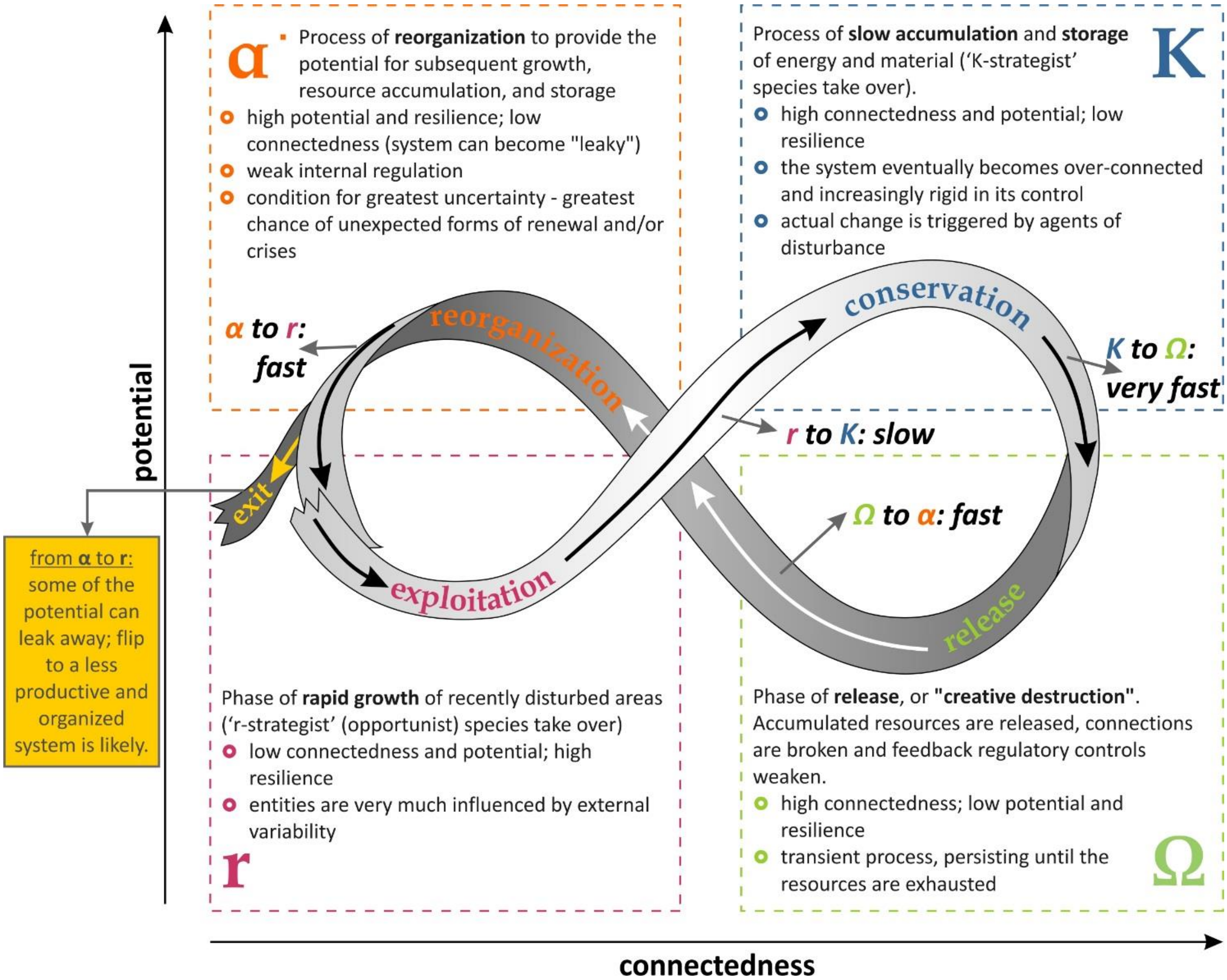


Figure 3: Graphic representation of the adaptive cycle (modified after: Gunderson et al., 2009; Gunderson and Holling, 2002). The four phases of the cycle, their characteristics and the transition from phase to phase are presented, along with the dimensions of potential and connectedness. Resilience, the third dimension of the cycle, is vertical to the plot, expanding near α and r and contracting towards K and Ω.

Let us assume a complex and maturing system that is in the conservation phase (K), characterised by high accumulated potential and internal organisation (Figure 3). With maturation and higher internal organisation, the components of the system become increasingly interdependent (connectedness grows). This can gradually lead to an overly tightly bound system that reaches saturation, becomes more vulnerable to surprise and can reach collapse under relatively small external disturbance. The passage from K to Ω is very rapid and the system releases all accumulated resources and loses internal organisation and controls. The phase of 'creative destruction' is a transient process, during which the potential is low, that lasts until the exhaustion of resources and total loss of organisation. Afterwards, the system quickly passes to the reorganisation phase (α), where the accumulated resources, released from the previous stage, start to loosely reorganize (low connectedness) and the potential for other uses re-emerges. This is the stage of highest uncertainty for the system and highest possibility for unexpected forms of renewal. It is a period of innovation and initial restructuring that provides the stepping-stone for the next phase of the cycle, exploitation (r). The system passes fast from α to r, losing of some of the potential, as accumulated resources may leak away, which can lead to a less productive and organized system. At the exploitation phase, the 'surviving' resources, loosely

organised from the previous phase, give ground for pioneer growth, with incremental exploitation of capital. External variability remains high and, therefore, flexible and rapidly growing development schemes, most likely to withstand the shifting conditions, prevail (e.g. rapid colonisation by '*r-strategist*' species, from where the stage was named). Due to the high adaptability of the system at the time, resilience is also high. During the slow progression from exploitation to conservation (K), the system becomes more stable and mature, accumulates potential and resources, increasing its' connectedness, as mutually supportive interrelations develop within the system that reinforce expansion and control external variability (e.g. '*K-strategist*' species, from where the stage was named, take over and flourish under conditions of high competitiveness). The future starts to be more predictable and less driven by uncertain forces, outside the control of the system. In this process the resilience decreases, as stability domains contract and the system becomes more susceptible to surprise (Gunderson et al., 2009).

3.3 Panarchy: cross-scale interactions in adaptive systems

To express cross-scale influences and interactions in complex adaptive systems, Gunderson and Holling (2002) proposed the notion of panarchy (instead of hierarchy), as a way to view and understand the manner in which elements of complex adaptive systems nest in one another. Since the word hierarchy is so burdened by the rigid, top-down nature of its common meaning, Gunderson and Holling (2002) invented the term 'panarchy' that captures the adaptive and evolutionary nature of adaptive cycles that are nested one within the other across space and time scales. The name was inspired by the Greek god Pan-the universal god of nature-, who could have a destabilizing, creatively destructive role (reflected in the word panic, derived from one facet of his paradoxical personality).

The levels of a panarchy can be drawn as a nested set of adaptive cycles (Figure 4), potentially with multiple connections between phases at one level and phases at another level. Two are most significant in assessing sustainability, the connections labelled "**Revolt**" and "**Remember**" in Figure 4, where three levels of a panarchy are represented. The Revolt and Remember connections become important at times of change in the adaptive cycles. When a level in the panarchy enters its Ω phase of creative destruction and experiences a collapse, that collapse can cascade up to the next larger and slower level by triggering a crisis, particularly if that level is at the K phase, where resilience is low (Gunderson and Holling, 2002). The "Revolt" arrow suggests this effect-where fast and small events overwhelm slow and large ones. That effect could cascade to still higher slower levels if those levels had accumulated vulnerabilities and rigidities. An ecological example of this situation occurs when conditions in a forest allow for a local ignition to create a small ground fire that spreads to the crown of a tree, then to a patch in the forest, and then to a whole stand of trees. Each step in that cascade moves the transformation to a larger and slower level. The downward arrow labelled "Remember" in Figure 4 indicates the second type of cross-scale interaction that is important at times of change and renewal. Once a catastrophe is triggered at a level, the opportunities and constraints for the renewal of the cycle are strongly organized by the K phase of the next slower and larger level. After a fire in an ecosystem, for example, processes and resources accumulated at a larger level slow the leakage of nutrients that have been mobilized and released into the soil. The options for renewal draw upon the seed bank, physical structures, and surviving species that form biotic legacies that have accumulated during the growth of the forest. It is as if this connection draws upon the accumulated wisdom and experiences of maturity - hence the choice of the word *remember*. Examples of key variables in natural systems are given in Table 2.

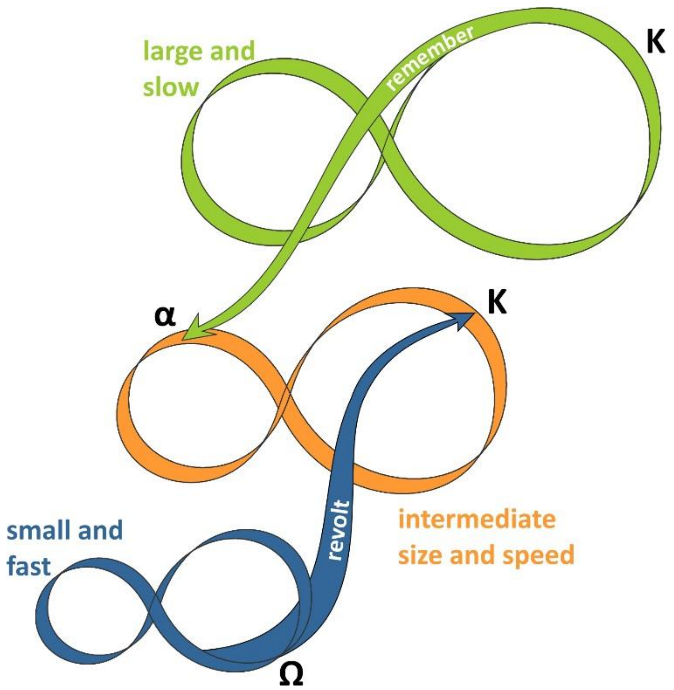


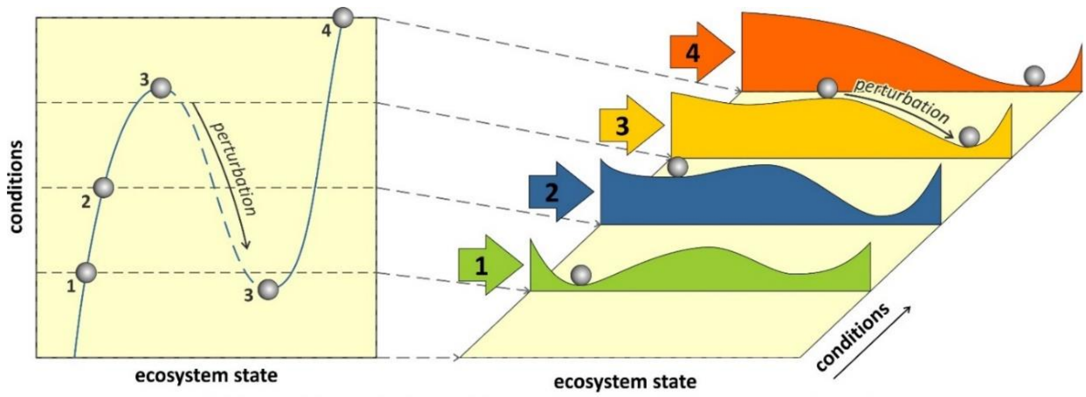
Figure 4: Panarchical connections, modified after Gunderson and Holling (2002). Three selected levels of a panarchy are illustrated, to emphasize the two connections that are critical in creating and sustaining adaptive capability. One is the "revolt" connection, which can cause a critical change in one cycle to cascade up to a vulnerable stage in a larger and slower one. The other is the "remember" connection, which facilitates renewal by drawing on the potential that has been accumulated and stored in a larger, slower cycle. Examples of the sequence from small and fast, through larger and slower, to largest and slowest for ecosystems are shown in Table 2.

Table 2: Representative Key Variables and Speeds in Seven Classes of Systems (from Gunderson and Holling (2002))

	The variables		
The system	**Fastest**	**Slower**	**Slowest**
Forest-pest dynamics	insect	foliage	tree
Forest-fire dynamics	intensity	fuel	trees
Savannah	annual grasses	perennial grasses	grazers
Shallow lakes and seas	phytoplankton and turbidity	sea grasses	grazers
Deep lakes	phytoplankton	zooplankton	fish and habitat; phosphate in mud
Wetlands	periphyton	saw grass	tree island; peat accreation
Human diseases	disease organism	vector and susceptibles	human population

3.4 Alternative states and regime shifts

Alternative stable states can be related to (and explain) surprisingly large ecosystem shifts, in which, even a tiny incremental change in conditions can trigger a large shift in some systems if a critical threshold known as 'catastrophic bifurcation' is passed (Scheffer and Carpenter, 2003). This implies that a gradual change in system parameter or in other factors might have little effect, until a threshold is reached, at which a large shift occurs that might be difficult to reverse (Scheffer and Carpenter, 2003). Changes in external conditions affect and may reshape the stability landscape and the size of the stability domain of residence, the strength of the repulsive forces at the boundary and the resistance of the domain to contraction are all distinct measures of resilience (Gunderson et al., 2009). The closer the system is to a threshold, the likelier it is to cross over and, thus, its resilience also depends on its distance from these thresholds (Walker and Salt, 2006). Alternative stable states can arise from a positive feedback in a system (Scheffer and Carpenter, 2003), while a variety of synonyms have been used to describe these dynamically favourable configurations of components, including stability domains, phase states, multiple (or alternative) stable states, or attractors (Stallins, 2005). Understanding the drivers that cause a system to cross thresholds between alternate regimes and knowing where the thresholds might lie is key to understanding and assessing resilience (Walker and Salt, 2006). Undesired shifts between ecosystem states are caused by the combination of the magnitudes of external forces and the internal resilience of the system (Gunderson et al., 2009). As resilience declines, the ecosystem becomes less resistant, and progressively smaller external events, including human actions, can cause shifts into less desired states, such as the ones summarised in Figure 5.



1	2	3	4
clear-water lake	phosphorus accumulation in agricultural soil and lake mud	flooding, warming overexploitation of predators	turbid-water lake
coral-dominated reefs	overfishing coastal eutrophication	disease, bleaching hurricane	algae-dominated reefs
grassland	fire prevention	good rains, continuous heavy grazing	shrub-bushland
grassland	hunting of herbivores	disease	woodland
kelp forests	functional elimination of apex predators	thermal event, storm, disease	sea urchin dominance
pine forests	microclimate and soil changes, loss of pine regeneration	decreased fire frequency, I ncreased fire intensity	oak forest
seagrass beds	removal of grazers, lack of hurricanes, salinity moderation, spatial homogenization	thermal event	phytoplankton blooms
tropical lake with submerged vegetation	nutrient accumulation during dry spells	nutrient release with water table rise	floating-plant dominance

Figure 5: Influence on existing conditions on ecosystem states, depicting how external forcing can affect resilience and produce instabilities (adapted from Scheffer & Carpenter, (2003)). Examples of human-induced loss of resilience (from Gunderson et al., 2009) for different ecosystems: alternate states (1, 4) and the related causes (2) and triggers (3) are given below.

3.5 Ecological resilience 'dimensions'

There are four crucial aspects of resilience (the first three can apply both to a whole system and to the sub-systems that make it up) (Gunderson et al., 2009; Walker et al., 2004):

1. **Latitude**: the maximum amount a system can be changed before losing its ability to recover within the same state (before crossing a threshold), equal to the width of the basin of attraction.

2. **Resistance**: the ease or difficulty of changing the system; deep basins of attraction indicate that greater disturbances are required to change the current state of the system away from the attractor.

3. **Precariousness**: how close the current state of the system is to a limit or "threshold" that, if breached, makes reorganization difficult or impossible.

4. **Cross-scale interactions** (i.e. Panarchy): the resilience of a system at a particular focal scale will depend on the influences from states and dynamics at scales above and below. They express how the other three attributes are influenced by the states and dynamics of the (sub)systems at scales above and below the scale of interest.

The first three 'dimensions' of resilience are related to the shape of the basin of attraction and the system state (ball), as graphically depicted in Figure 6. It is important to keep in mind that the representation of a system using the ball-and-cup analogy is referring to a specific set of conditions (in time and space) and that these dimensions are not to be perceived as static. The shape of the stability domain (basin) and of the entire stability landscape are continuously changing in response to the combined effects of natural processes and interactions and external disturbances (i.e. Figure 5), as well as the system state itself.

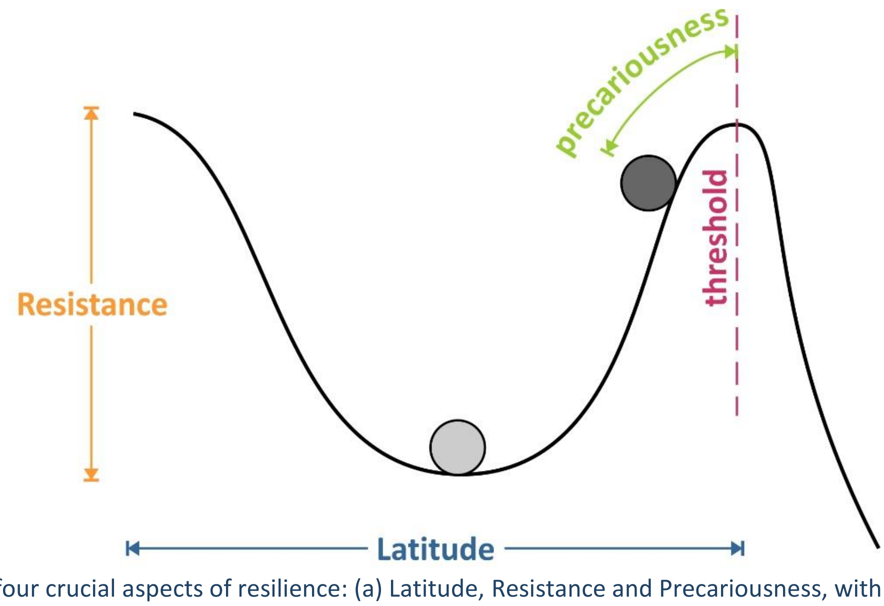


Figure 6: The four crucial aspects of resilience: (a) Latitude, Resistance and Precariousness, with respect to the dimensions of a basin of attraction.

Regarding cross-scale connections, the system can be analysed into different cycles, with respect to the related, main internal spatiotemporal scales, and expressed as a panarchy (Figure 4). The main panarchical connections that need to be accounted for and become important at times of change and renewal in the adaptive cycle (Gunderson and Holling, 2002), are the 'Revolt' and 'Remember' (Figure

4) connections. The former refers to a collapse at a lower, faster cycle that can cascade up to the next larger and slower level, triggering a crisis, especially if the upper level is at the K phase. The latter refers to the organisation of opportunities and constraints for the renewal of a lower cycle (that had previously collapsed) by the K phase of a slower and larger level. Thus, a revolt connection suggests conditions where fast and small events overwhelm slow and large ones, whereas a remember connection facilitates renewal, by drawing upon the potential accumulated and stored in a larger, slower cycle (Gunderson and Holling, 2002).

4. Transferring Resilience Theory to Barrier Island Geomorphology

4.1 Resilience terminology transference

In order to pass on from a geomorphological analysis to a resilience assessment of complex systems, a series of fundamental aspects of resilience theory need to be interpreted to geomorphological principles and/or features. Going back to the definition of resilience, it becomes evident that one needs to start from identifying the identity, functions, structure and feedbacks of the coastal barrier system:

- In terms of **identity**, a coastal barrier can be defined as a strip of sand and/or gravel, backed by a shallow coastal bay, separated wholly or partly from the mainland shore (Stutz and Pilkey, 2002).
- Its main **functions** are to support its habitats, species and anthropogenic activities and to provide storm protection and sheltering to the lagoon and its supported habitats and to the mainland (Moore and Murray, 2018).
- From a geomorphological point of view, the **structure** of a coastal barrier can be analysed using six main components or sub-environments (Davidson-Arnott, 2009): (1) mainland coast; (2) the lagoon, bay or marsh that separates barrier and mainland; (3) subaerial barrier (beach, dunes and backbarrier deposits); (4) subaqueous sediments platform (on which the subaerial barrier is built); (5) shoreface extending offshore from the exposed beach; and (6) inlets and associated tidal deltas.
- The diverse range of evolutionary pathways of barriers is a result of the complex **feedbacks** between 4 spheres: atmosphere, hydrosphere, lithosphere and biosphere (Barrineau et al., 2015).

These aspects, and especially the latter two, are interrelated and linked to the panarchical scales and interactions, the dimensions and morphology of the stability domain(s) and landscape and the considered spatiotemporal scales and boundaries of the system. For a sandy barrier, for example, a potential panarchy (from larger-slower to smaller-faster) could be local society - barrier - barrier section. Therefore, an example of a revolt connection is the cascading effect of a storm-induced breach in a barrier sector that can, under circumstances, cause permanent morphological changes to the entire barrier (i.e. persisting channels that enlarge and end up in barrier splitting). This effect can, in turn, cascade to the higher level of the local society (i.e. loss of property, infrastructure, even lives). Management actions, like the artificial closure of the breached barrier sector, can assist the renewal at the lower levels after collapse, therefore give an example of a remember connection.

From the listed sub-environments, some (mainland, lagoon bay, and inlets) do not form part of the barrier body itself and others (subaqueous platform, tidal deltas and shoreface) pertain to the (permanently or temporarily) submerged part of the system. Focussing on the subaerial barrier (part above the Mean Sea Level), the considered components can be divided with respect to the principal forces acting upon them, into wave- wind- and tide-dominated parts. This division is also meaningful in terms of distinct habitats, as these parts can be simply referred to as beach, dune and marsh (BDM).

Considering the three units beach, dune and marsh, geomorphological dimensions and/or processes can be used to determine the four crucial aspects of resilience, as shown in Figure 7. The transference of the first three aspects is rather straightforward (Figure 7a and Figure 8). The **latitude** (width of the basin), or else the maximum amount a system can be changed before losing its ability to recover within the same state, should be expressed by the total width of all units (barrier and perched marsh), given that, if this width decreases below a critical value (Lat_{crit} in Figure 8), all units would have disappeared. The reason for including marsh width in the latitude dimension is to account for the presence of the

marsh platform that can assist barrier rollover. The **resistance** (basin height) can be related to the dune height, as an indicator of the difficulty of the barrier to be inundated. The **precariousness**, or the proximity of the system to a critical "threshold", over which reorganization is difficult or impossible, can be straightforwardly linked to the proximity of the (back)barrier to the mainland, given that it is a direct measure of the space available to the barrier for inland migration before it welds to the mainland. Crossing such a threshold (Pr_{crit} in Figure 8) would mean an irreversible loss of resilience (identity, functions, structure and feedbacks).

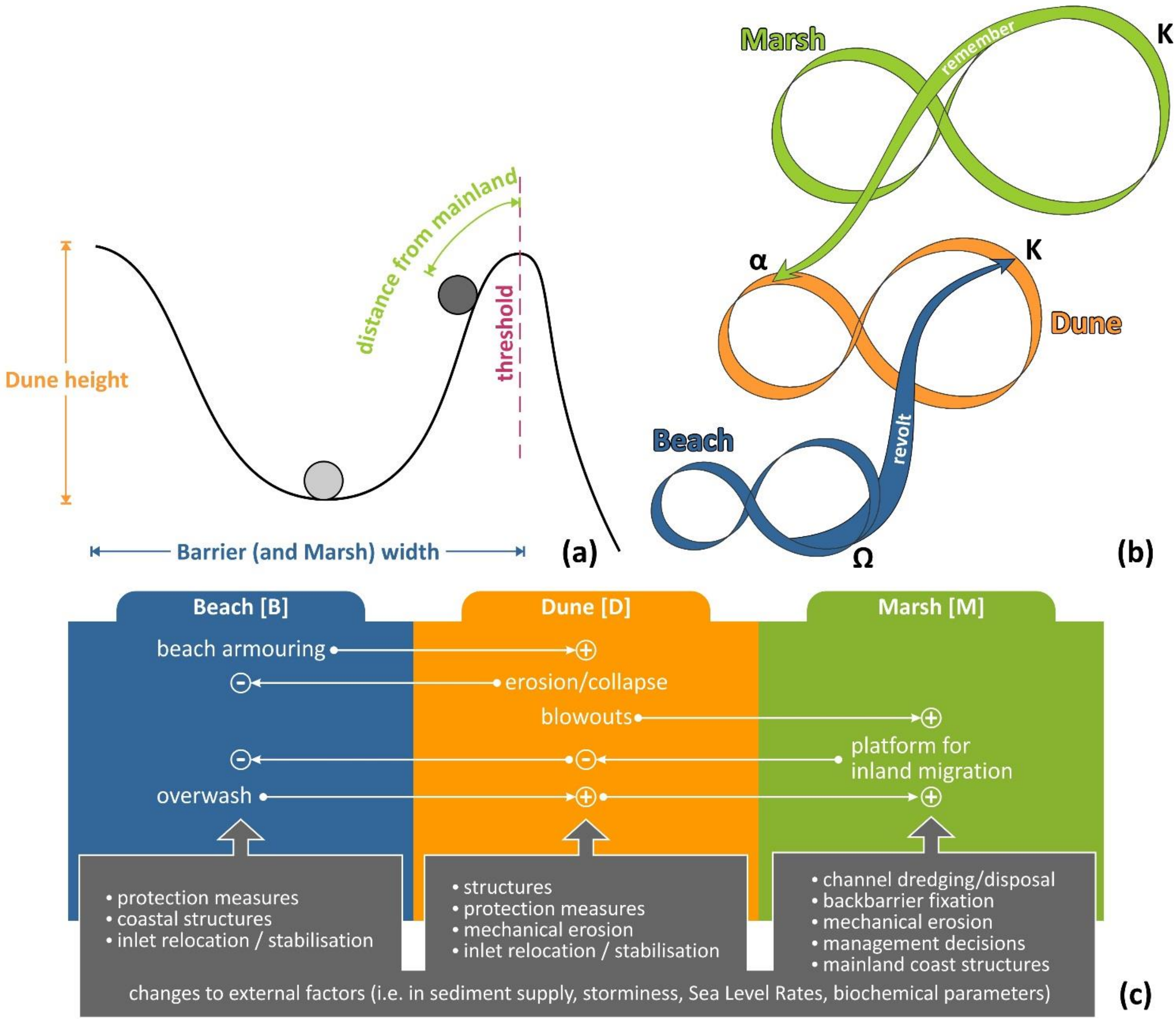


Figure 7: Barrier resilience 'dimensions' using three panarchical levels (B, D, M): (a) dimensions of a basin of attraction, (b) cross-scale interactions and (c) potential feedbacks (+: positive; -: negative) between the three levels, including human-induced ones and broader feedbacks, external to the system (grey areas).

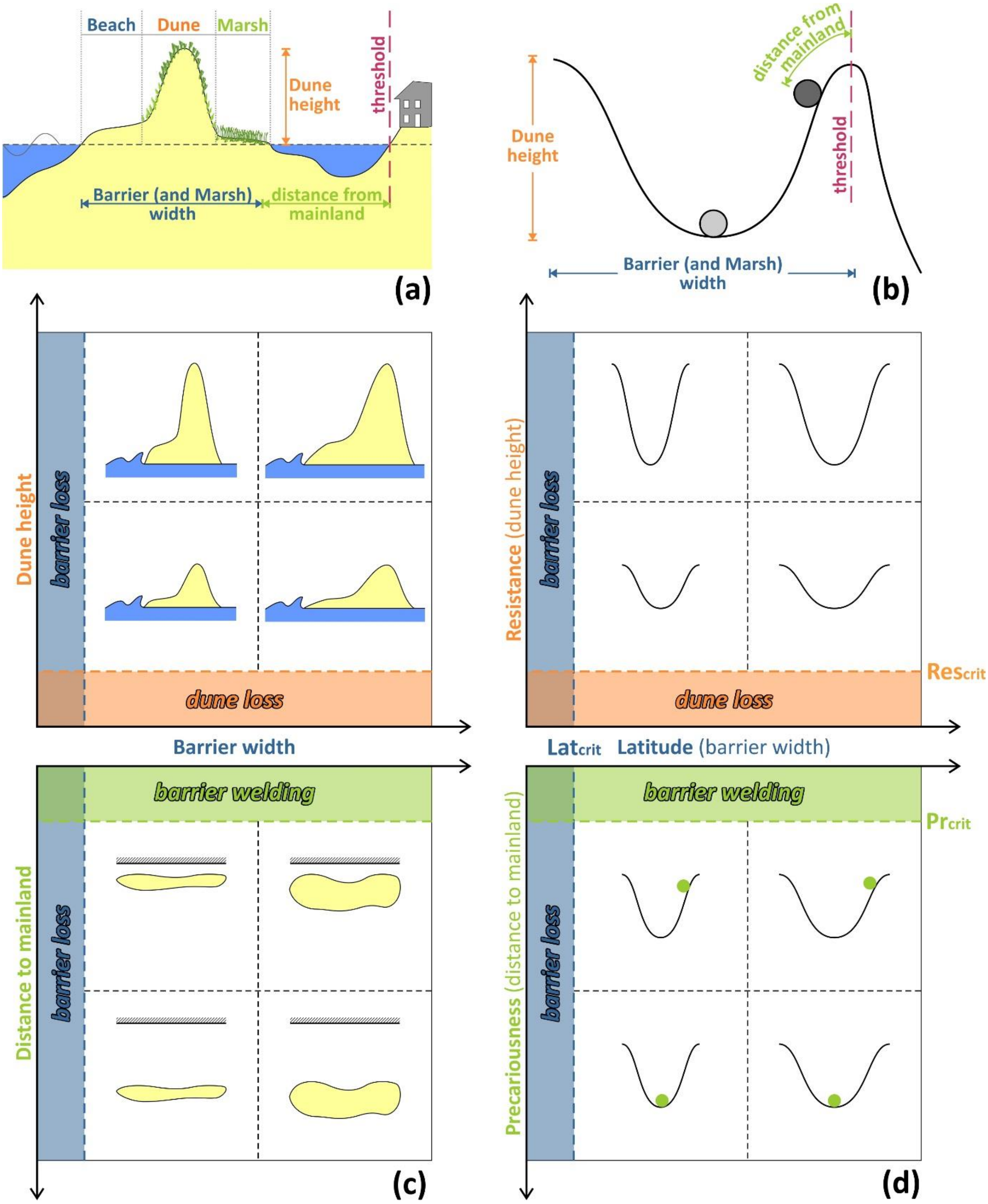


Figure 8: Passing from geomorphological dimensions (a, c) to resilience (b, d): typical barrier cross-section, where three main geomorphological dimensions (barrier width, dune height and distance from mainland) are noted (a), transference to dimensions of the basin of attraction (b) and variability of the three dimensions, in relation to coastal geomorphology (c) and in relation to resilience (d). The shape of basin (cup) is defined by the dune height and the barrier width (top part of graph in d), while the system state (ball position) is related to the available accommodation space (bottom part of graph in d). The thresholds in (c) and (d) denote loss of resilience (Lat_{crit}, Res_{crit} and Pr_{crit} are critical values for latitude, resistance and precariousness, respectively); not all thresholds can be included in the plot.

These dimensions can be used to visualise changes to the stability landscape and to assess the implications to the resilience of the system (as in the example of Figure 8d), where the different zones correspond to different combinations of the three parameters and, therefore, to different scales of resilience. For instance, a wide barrier with high dune that is far from the mainland (high resistance and resilience and low precariousness) would belong in the top-right quadrant of the upper panel of the plot in Figure 8d and the bottom-right quadrant of the lower panel of the plot.

As already mentioned, each unit corresponds to a panarchical level (Figure 7b), while examples of **cross-scale interactions** under conditions of geomorphological change are listed in Figure 7c, divided into negative (stabilising) and positive (destabilising) feedbacks. For instance, beach armouring is linked to dune growth through a weak positive feedback, as it can impede the aeolian transport of sediment from the beach to the dune, thus constituting a revolt connection between the two levels. Conversely, dune erosion or collapse delivers sediment from the dune to the backshore and thus can be characterised as a negative (remember) connection. Positive (revolt) feedback is identified during blowout events between dune and marsh as well as during overwash events that (depending on the magnitude) can cascade from beach to the dune or produce a cascading chain of positive feedbacks that can reach the marsh. Through a reversed process, the marsh can provide a platform for the inland migration of the entire sandy part of the barrier (Carrasco et al., 2008), linking beach and dune with marsh through a strong revolt (positive) connection. As humans are part of the system, their presence and related actions within and outside of the system should be considered as an upper, higher cycle of the panarchy. Here, and given that the main objective is the transference from geomorphological to resilience analysis, these impacts are presented as 'external' (Figure 7c) and no 'revolt' connection between the system and the anthroposphere is considered. Potential links include management practices and protection measures, occupation of area and exploitation of services inside the system. Regarding dynamics and broader changes outside of the system, these include factors that can potentially affect the hydrodynamic conditions, the sediment, or the biochemical balance in the system (i.e. introduction of invasive dune/marsh plant species, or predator species, or pathogens, etc.) and should be taken into account as exchanges through the **boundaries** of the system. This is in accordance with Barrineau et al. (2015) who postulate that a coastal barrier (at any spatial scale, ranging from a barrier stretch to an entire barrier chain), should be considered an open system that exchanges matter and energy between the atmosphere, lithosphere, biosphere, and hydrosphere.

4.2 Spatial-Temporal scales

In general, when passing on from geomorphic to resilience analyses, spatiotemporal scaling can become key. Scaling issues need to be addressed early on, in the sense that the number of panarchical levels and of the considered feedbacks is highly dependent on the level of analysis and, in turn, the considered spatiotemporal detail needs to be oriented towards the objective of the analysis. For example, considering faster changing cycles (i.e. dune plant seasonal cycles), or very detailed spatial discretisation, in a multi-year geomorphological resilience analysis would be pointless. Conversely, disregarding a level could lead to feedbacks, thresholds and potential alternate states being overlooked, thus involving high possibilities of unexpected forms of future system organisation. For coastal systems, the spatiotemporal **scales** involved are the relevant compatible levels for geomorphological analysis (Larson and Kraus, 1995), ranging from meso- to mega-scales, depending on the prevailing forcing factors (Figure 9). Thus, the resilience to individual storms should be analysed at spatial levels ranging from barrier sectors (<1 km) up to an entire barrier and at temporal scales of

several hours to a few days, whereas climate change analyses should be multi-decadal to centennial and extend from a single barrier to the whole barrier system. It is noted that the individual barriers (i.e. BDM) have inherent spatiotemporal scales, in the sense that the same forcing conditions are expected to affect the units at distinct temporal scales (Figure 9). For example, the response of the marsh to a rising sea level is expected to be slower than that of the beach. Thus, these units range from smaller and faster changing units (i.e. beach) to larger and slower ones (i.e. marsh) that can be readily converted to panarchical levels (Figure 9b).

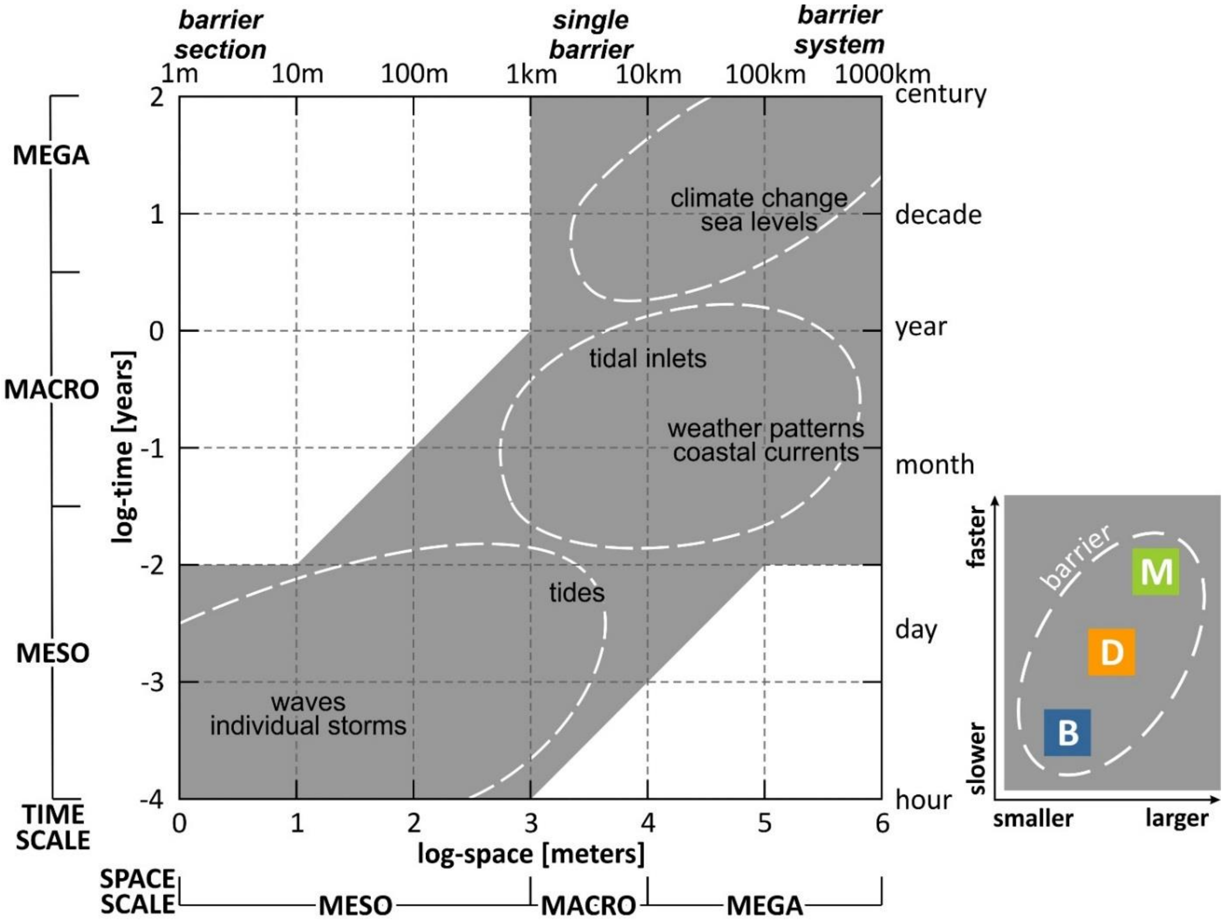


Figure 9: Relevant spatiotemporal scales for the resilience assessment of barrier islands: indicative response scales, with reference to distinct drivers of change, are noted (dashed white curve). The legend (right) denotes the inherent scales for the main morphological units (B: Beach, D: Dune and M: Marsh). Compatible spatial/temporal scales (grey area) are from Larson and C. Kraus (1995).

4.3 Thresholds and regime shifts

Human-induced pressures (e.g., reduction of longshore drift) together with natural disturbances (e.g., storms) can gradually reduce the resilience of the barrier and cause shifts to less desirable regimes. Furthermore, the dynamics after a disturbance or even a regime shift is crucially dependent on the self-organizing capacity of the complex adaptive system (Folke, 2006). Especially for the case of barrier systems, it becomes evident that the rollover process is a perfect example of the ability to '*re-organize while undergoing change*'. A variety of external factors can trigger this response, such as sediment inflow reduction combined with storm impacts, rising sea levels, hurricane incidence, etc.

Figure 10 shows a conceptual representation of the changes to the stability landscape and the characteristics of regimes during barrier rollover and recovery. Let us assume a system (R1) that is initially (Figure 10-1) resilient, away from any imminent threat (low precariousness; K phase). A change in the sediment inflow to the system through its boundary (assuming an open system) could reduce its resistance to storm impacts and initiate a landward migration, during which sediment is driven in the lagoon-side, where it remains as submerged deposits, creating a new regime (R2; Figure 10-2). The precariousness of R1 increases, as the system moves closer to the tipping point between R1 and R2 and the barrier enters in the release (Ω) phase. If the external factors persist (i.e. press disturbance) and storm overwash continues, the system will eventually cross the tipping point from R1 to R2, with complete inundation of the barrier and increase of sediment deposited in the sand flats (Figure 10-3). Thus, the system enters the reorganisation (α) phase, accumulating resources with loose internal structure. Some of the sediment may leak away (e.g. offshore cross-shore losses) during this phase of high uncertainty. Drawing upon the sand stored in the lagoon side (i.e. forming a platform), the system may recuperate, flipping back to R1, with the barrier forming once again and regaining barrier widths (Figure 10-4) while migrating landwards. By this point, the system enters the exploitation phase, with rapid growth (increasing connectivity) and low resistance. If the external conditions allow it, the system gradually passes on to a more mature and complex internal structure (i.e. dune fixation and growth; marsh development), expressed by deepening and widening of the R2 basin.

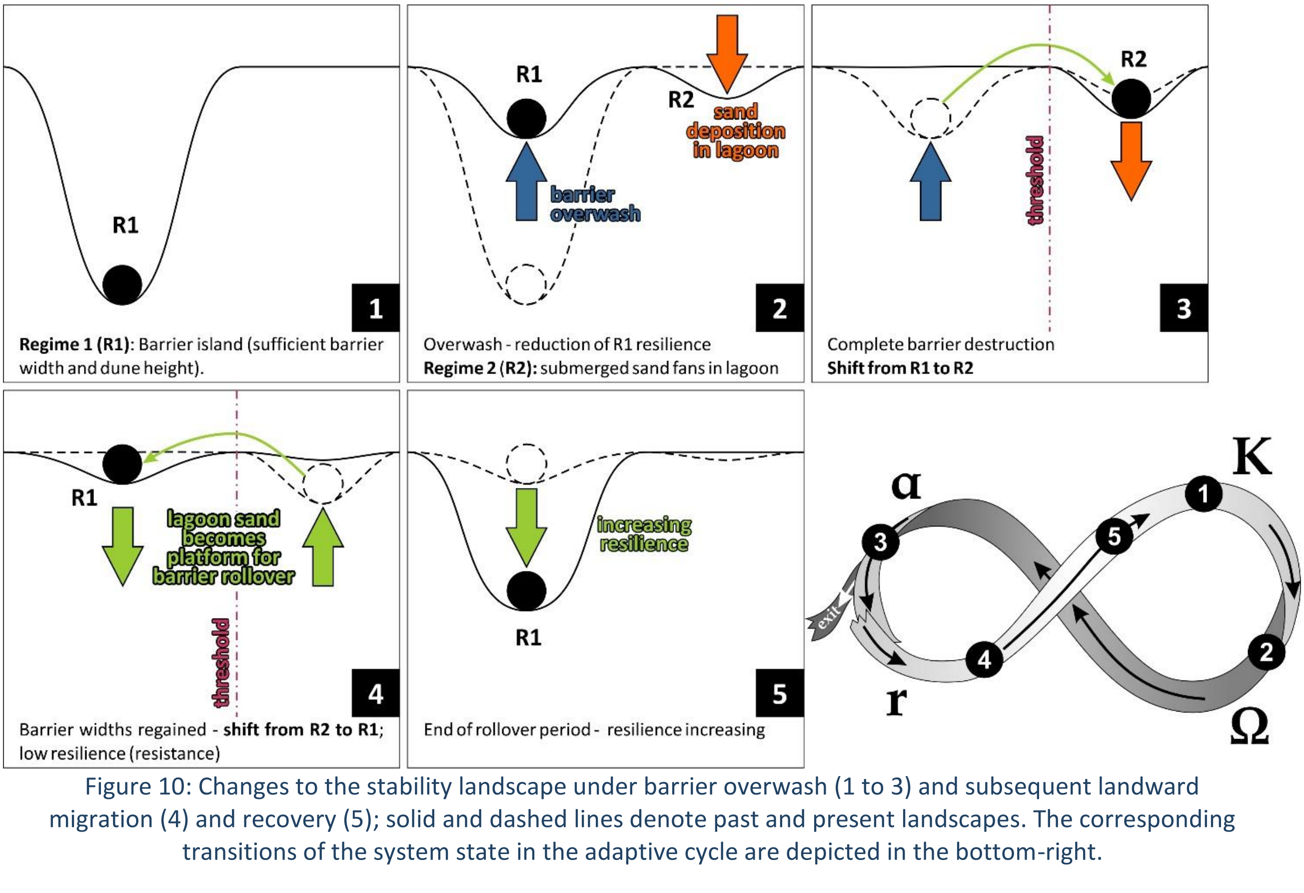


Figure 10: Changes to the stability landscape under barrier overwash (1 to 3) and subsequent landward migration (4) and recovery (5); solid and dashed lines denote past and present landscapes. The corresponding transitions of the system state in the adaptive cycle are depicted in the bottom-right.

Of course, the sequence, presented and discussed, is simply one potential evolution of the stability domain. The inherently unpredictability of the reorganisation phase regarding the surviving components that will control subsequent renewal (Gunderson and Holling, 2002), makes it highly likely that unexpected organisation forms arise in the next phase, such as the alternative scenarios after the

first stages of a barrier rollover, presented in Figure 11. For example, the maturation or growth of a barrier after its stabilisation (i.e. development of perched marsh) could be expressed with an expansion of the fore-loop of the adaptive cycle. Contrastingly, the leak of a significant amount of sediment, and depending on the prevailing conditions (i.e. storm impacts, backbarrier lagoon depths), makes it likely that the accumulated resources are insufficient to support the barrier reorganisation. Thus, it is likely that the system never crosses back to the initial barrier regime (R1), or that it temporarily crosses back, but the available resources are insufficient for providing stability (i.e. to cope with rising sea levels). In the latter case, a gradual contraction of the adaptive cycle would be expected, which (potentially after several cycles of regeneration and reconstruction) would eventually lead to merging of the barrier with the mainland.

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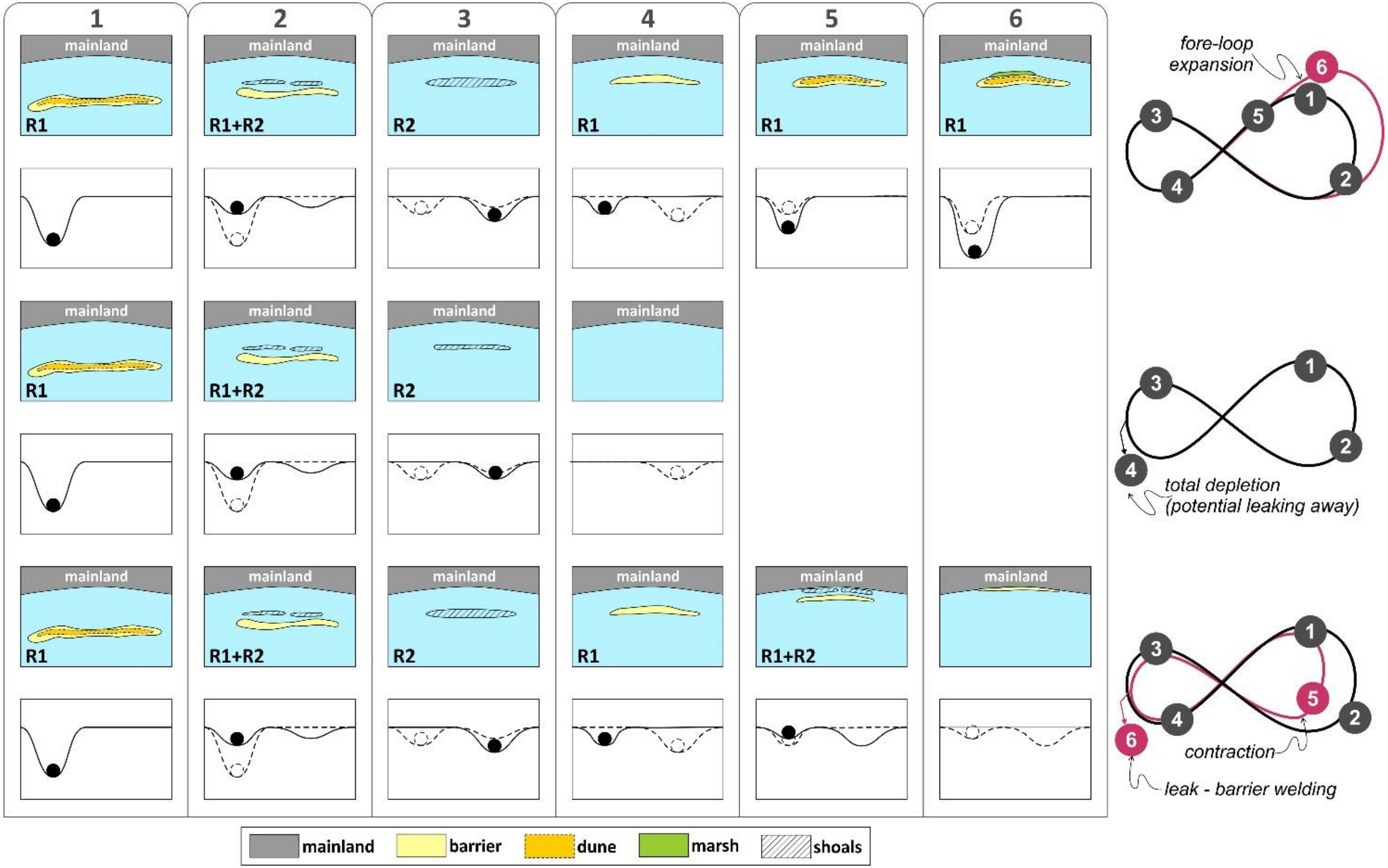

Figure 11: Evolution of regimes and states under alternative scenarios during barrier rollover; stages 1 to 2 are the same in all three cases and the changes of the adaptive cycle are given in the right.

4.4 Barrier states and evolution

To assess the multi-decadal geomorphological resilience of barrier islands, we propose using the geomorphological units of Beach, Dune and Marsh (BDM), as indicators that express distinct environments (wave-, wind- and tide-dominated, respectively) of the subaerial barrier, corresponding to distinct spatiotemporal scales of change. The data were used to determine the widths of the three morphological units (B-D-M), using a common baseline and the digitised coastlines, delimiting the selected morphologies as follows:

i) **Barrier**: wave dominated part, delimited by the ocean-side and the backbarrier coastlines, both corresponding to the same water level (ca. MHWL);

ii) **Dune**: wind dominated part, delimited by the dune line in the ocean-side (ca. MHHWL) and the backbarrier line in the lagoon-side (ca. MHWL); and

iii) **Marsh**: tide dominated part of the backbarrier, delimited by the backbarrier coastline and the marsh edge line (both in the lagoon-side). These limits correspond to the levels between MWL and MHWL.

Splitting barrier evolution to these three units expresses the inherent scales within the barrier, since the same forcing conditions are expected to affect these units at different scales (faster to slower: B-D-M). For example, the impacts of a storm, relative to its severity, are expected to affect a barrier in a BDM sequence (first the beach, then the dune and then the marsh). Similarly, the time needed to rebuild these units post-destruction increases within the same sequence (faster to slower: BDM) and, therefore, the higher the presence of units in the barrier, the higher its maturity, organisation level and complexity. Therefore, the barrier can exist in various combinations of units, which can be expressed by their absence or presence. Expressing the presence and the absence of a unit within the BDM sequence and using the values 1 and 0, respectively, can be used to simplify the distinction between potential barrier states or changes between them and, therefore, to simplify the resilience analysis. Using this 'coding', the potential barrier states range between 111 (all BDM units present) and 000 (no units present) and the transition between then under destructive or constructive regimes can be viewed as the scheme below (Figure 12).

As analysed previously, these units can be used as panarchical levels to analyse the ecological resilience of the system and the feedbacks between them (Figure 7c). For example, the presence of a perched marsh can assist barrier rollover by providing a platform for the migration, providing a negative feedback (or 'remember' connection) from the marsh to the barrier. Conversely, an overwash event from the beach and the dune can drive sediment to the marsh that could induce drowning, showing a case of a positive feedback (or 'remember' connection), where a destructive process can ascend to higher levels and potentially lead to their collapse. Potential shifts between system states under constructive and destructive processes are listed in Table 3.

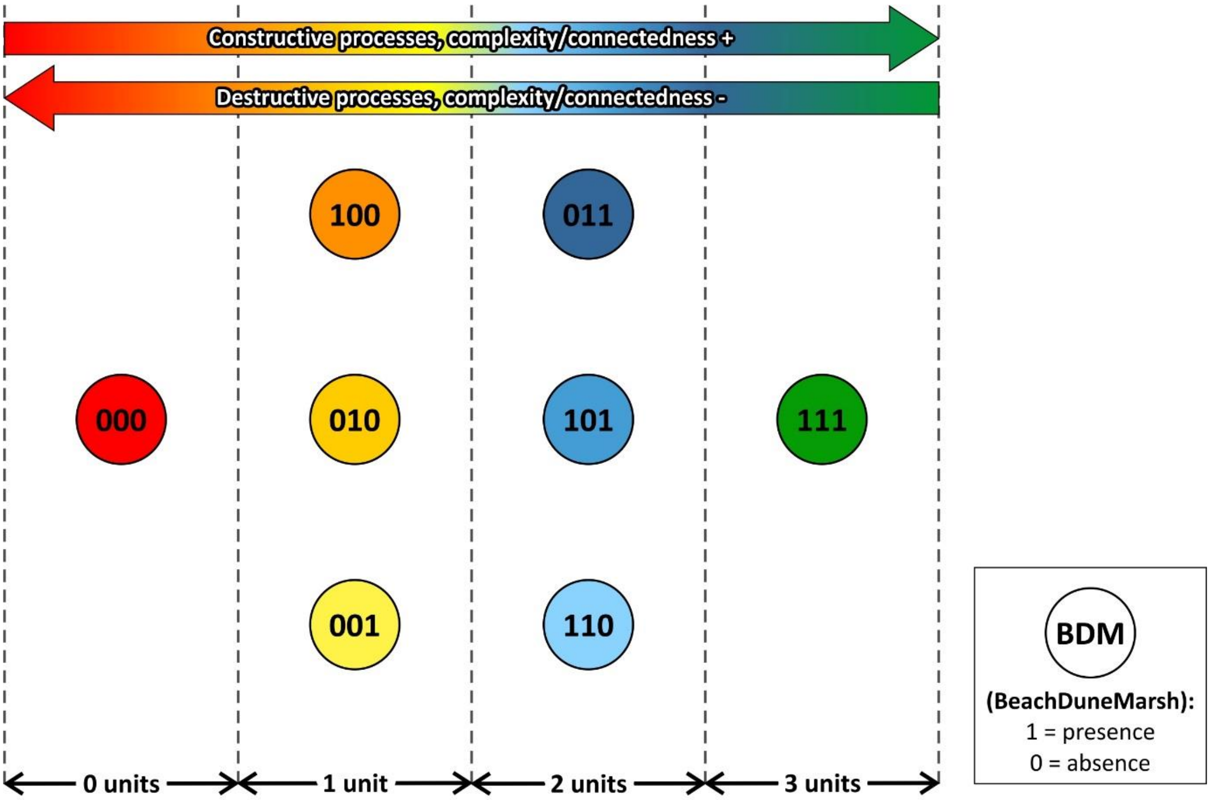

Figure 12: Conceptual scheme of alternative states, considering the BDM panarchical levels. Dashed lines present thresholds under destructive natural processes. Some states (e.g., 001 and 101) are short-term.

Table 3: Examples of destructive (storm impacts) and constructive (only considering gains in environmental units) processes causing BDM state changes.

	Regime/change	Potential BDM changes	Initial	Final
Destructive	collision	beach loss; dune present	111 110	011 010
	overwash	marsh burial	111 011 101	100 100 100
	blowouts (or overwash)	aeolian (or marine dune) erosion	111 011 010	101 or 100* 101 or 100* 100
	inundation	barrier drowning/breaching	111, 011 or 101 110, 010, 100 or 001**	000 or 001 000
Constructive	swash or dune erosion/collapse	beach growth	011 010	111 110
	aeolian sediment transport	dune growth	100 101	110 111
	overwash	marsh growth	100	101

** marsh burial happening at the same time*

*** change from 001 to 000 can also come from wave erosion*

4.5 Resilience trajectories

The variation of latitude, resistance and precariousness can be used to visualise the resilience trajectory of a barrier over a wide range of timescales and disturbances, relating changes to the shape of the basin of attraction, shown on the top part of Figure 8d and the system state, shown at the bottom part of the Figure 8d. Only three thresholds are noted on the graph (Figure 8d), related to critical values of dune height, barrier width and distance from mainland. However, more thresholds, not directly identifiable by the variability of the parameters on the graph, such as the loss of a function (e.g. of beach or marsh), do exist and need to be accounted for when assessing resilience. The barrier should be considered resilient, as long as its trajectory does not cross any threshold, since then the barrier would maintain its functions, structure, identity and feedbacks. This entails characterisation of each point in the trajectory (mapped environments and characteristics) in terms of environments and identification of thresholds related to a loss of function. The barrier should be considered resilient as long as its trajectory does not cross any threshold (the barrier maintains its functions feedbacks and identity). Assuming for simplicity that the functions whose thresholds are not directly identifiable in the plot (e.g. beach and/or marsh loss) are maintained during a disturbance, the barrier should be considered resilient as long as the trajectory falls within the white-shaded area of the plots in Figure 8d. This view is far different from the 'classical' trajectories of the engineering approach that are restricted to regaining pre-disturbance barrier dimensions and characterising recovery as 'partial' or 'full' (e.g., in Masselink and Van Heteren, 2014). Such a rigid view is incompatible with the ecological resilience principles, which are more flexible and, probably, better represent the evolution of natural systems. We postulate that post-perturbation recovery should be viewed in terms of reorganisation and adaptation, accounting for maintaining the existence of functions, or the ability to regain them. If no thresholds are crossed, morphological changes should be interpreted as transformations of the stability landscape.

5. Application of concepts to the Ria Formosa barrier system

5.1 Barrier rollover and recovery: the case of Cabanas and Cacela

The barriers of Cabanas Island and Cacela Peninsula in Ria Formosa underwent significant changes after the stabilisation of the updrift (Tavira) inlet with jetties (Figure 13). Due to the highly dynamic response of the barrier subsystem and the scarcity of survey data, the analysis is spatiotemporally restricted by the available topographic/altimetric data, corresponding to a zone of 5 km directly downdrift from the Tavira Inlet (rectangle in Figure 13) and to 5 dates: 1952, 1976, 1985, 2001 and 2011. The coastlines changes (Figure 14) show that initially (1952) the subsystem included only Cacela Peninsula, while the reduction of the longshore sediment transport by the jetties induced significant erosion to the peninsula and subsequent (after 1976) formation and gradual growth of Cabanas Island (Figure 14a and b). Due to this high alongshore variability, especially between 1952 and 1976, the only zone with barrier presence in all years is a stretch of around 1 km, located 2 km downdrift from the jetties (2-3 km; dashed rectangle in Figure 14). Therefore, the collected morphological evolution data (unit widths, dune height, backbarrier distance from mainland) from this barrier section (2-3 km) are used to visualize the changes in the stability domain, regime shifts and the respective evolution of the adaptive cycle during the barrier rollover and recovery. The broader area (0-5 km in Figure 14) is used to investigate potential scaling issues (i.e. masking of bifurcation events) due to the along-barrier averaging of morphological data, by comparing results from the two zones.

Figure 13: The Ria Formosa barrier system and the Cabanas-Cacela subsystem (zoomed image). The analysis focuses on the 2-3 km stretch, noted with an orange rectangle.

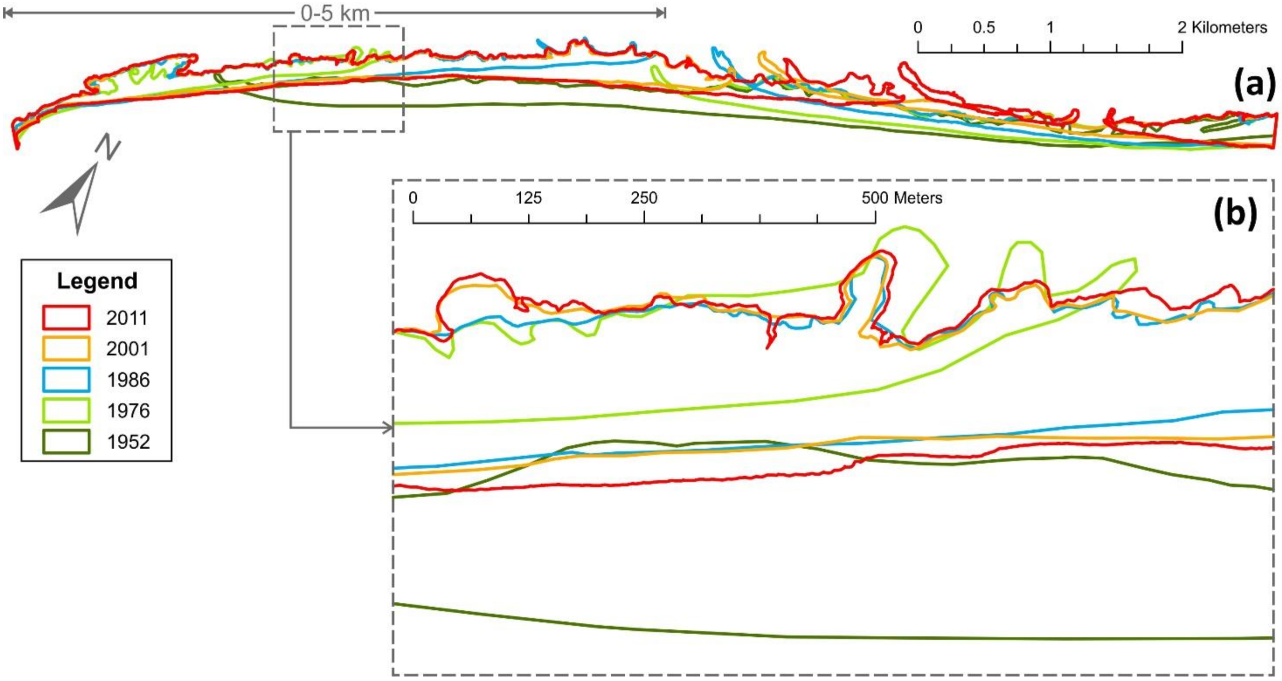

Figure 14: Coastlines of the Cabanas-Cacela barrier subsystem where the 5 km stretch of Cabanas is noted (a) and zoomed detail of the coastline variability in the study site (2-3 km downdrift the Tavira jetty; b).

The changes to the stability landscape for the barrier stretch of 2-3 km are given in Figure 15 for the five years of available data, based on the terminology described previously. Between 1952 and 1976, there is strong contraction of the stability domain in terms of both latitude (barrier width) and resistance (dune height) as well as increase of the precariousness (reduction of the distance from mainland). These changes are related to the morphological changes in the area between these dates, involving breaching of a new inlet (around 1961), followed by erosion of the extremity of the peninsula and gradual eastward growth of the Cabanas Island (around the late 1960s). During the process, the whole barrier section drowned, pushing sand into shoals that facilitated the regrowth of the island landwards. Therefore, a regime shift took place in the barrier stretch between 1952 and 1976, most likely around the mid to late 1960s, changing the system state from barrier (in 1952) to submerged shoals. By 1976, the system had flipped back to the barrier state; however, no data were available to visualise the change in the stability landscape of Figure 15 and the regime shift is simply noted as a flip to R2. Theoretically, these regime shifts should be similar to the one schematised in Figure 10. The average depth of the shoals could express the resistance of the submerged shoals' regime, as a measure of the sediment that needs to be vertically accreted for the deposits to become subaerial and, therefore, to flip back to the barrier regime. The initial stages of the barrier recovery in 1976 show a shallow and narrow regime with increased precariousness due to the migration of the barrier closer to the mainland (1976 versus 1952; Figure 15b). From 1986 onwards, the changes to the landscape are mostly related to shape, with significant widening and deepening of the cup, while the precariousness appears mostly stabilised.

In terms of the changes and phases of the adaptive cycle, the evolution corresponds to the one depicted in the top panel of Figure 11, with the initial 1952 morphology (stage 1 in Figure 11) passing on to a creative destruction and reorganisation phases during the regime shift (R2 in late 1960s; stages 2-3 in Figure 11). Barrier recovery in 1976 is most likely in the phase of exploitation (r-phase; stage 4 in Figure 11), while, comparing the domains of 1952 and 1976, the leak of potential (sediment; characteristic of the α-phase) during the passage from K to r is obvious. After 1986, an expansion of

the fore-loop is expected (stage 5 to 6 in Figure 11), due to combined shoreline progradation, backbarrier stabilisation and perched marsh development.

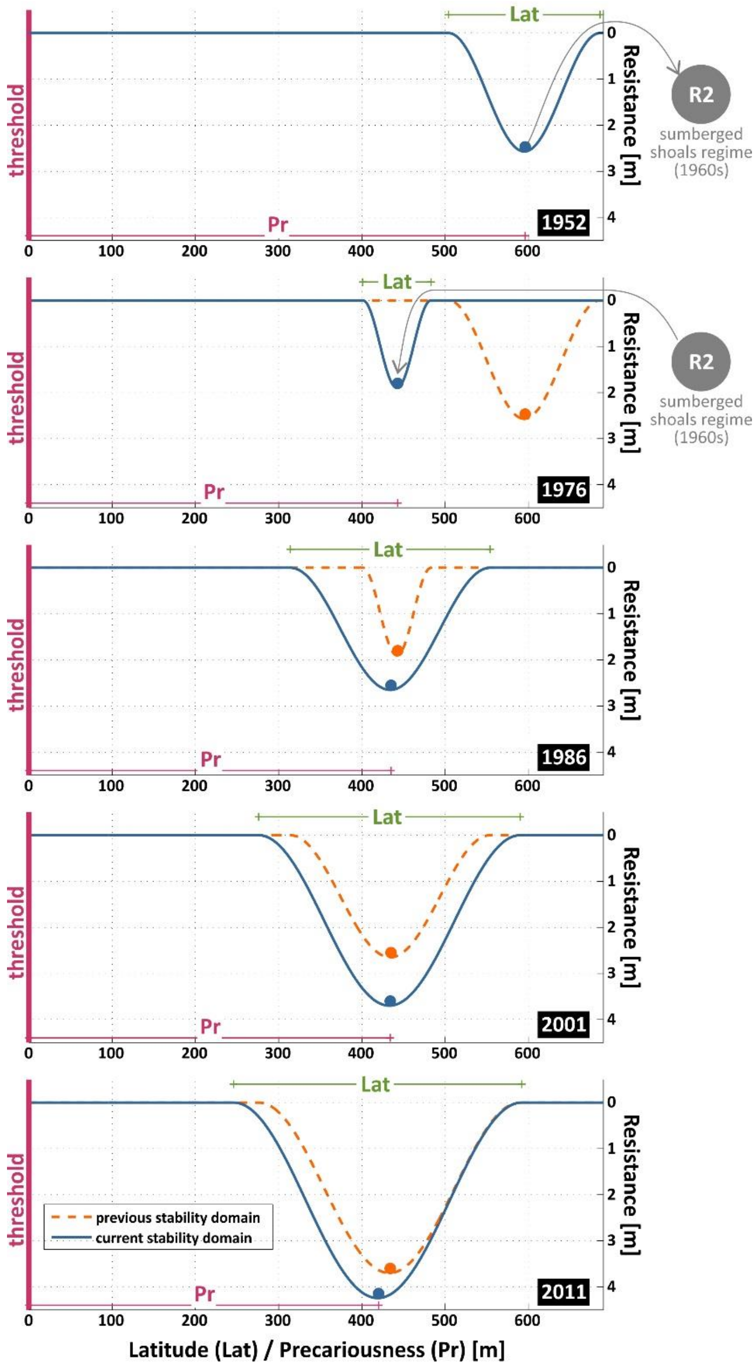

Figure 15: Evolution of barrier stability landscape from 1952 to 2011 (top to bottom), using the ball-and-cup analogy, with the width and height of the cup to express latitude (Lat) and resistance, respectively and the proximity of the ball (system state) to the threshold (purple line; mainland coast) to express precariousness (Pr). The morphology of the previous stage (except for 1952) is noted with a dashed orange line and orange ball. The regime shift to submerged shoals (R2), taking place in mid to late 1960s (data unavailable) is noted with a grey arrow in the 1952 and 1976 graphs.

These altimetric and topographic data between 1952 and 2011 were used to visualize the resilience trajectory of the stretch over a multi-decadal geomorphological evolution scale, shown in Figure 16. The axes minima are set to zero and the related thresholds are shown (set to Lat_{crit}=20 m, Res_{crit}=2 m and Pr_{crit}=100 m), in accordance with Figure 8d. The trajectory has been slightly modified, to represent the flip to a submerged shoal regime around the mid to late 1960s (setting latitude and resistance values to zero and assuming no change in precariousness). The regime shift that took place between 1952 and 1976, probably during the mid to late 1960s, forced the system into a submerged shoal regime (SSR), losing all four resilience criteria. By 1976, the system regained the beach state, with a shallow and narrow basin, however at a more precarious position. From 1986 onwards, the system started to recover, passing from beach to beach-dune and, after 2001, to a beach-dune-marsh structure, with significant widening and deepening of the basin, while the precariousness appears mostly stabilised.

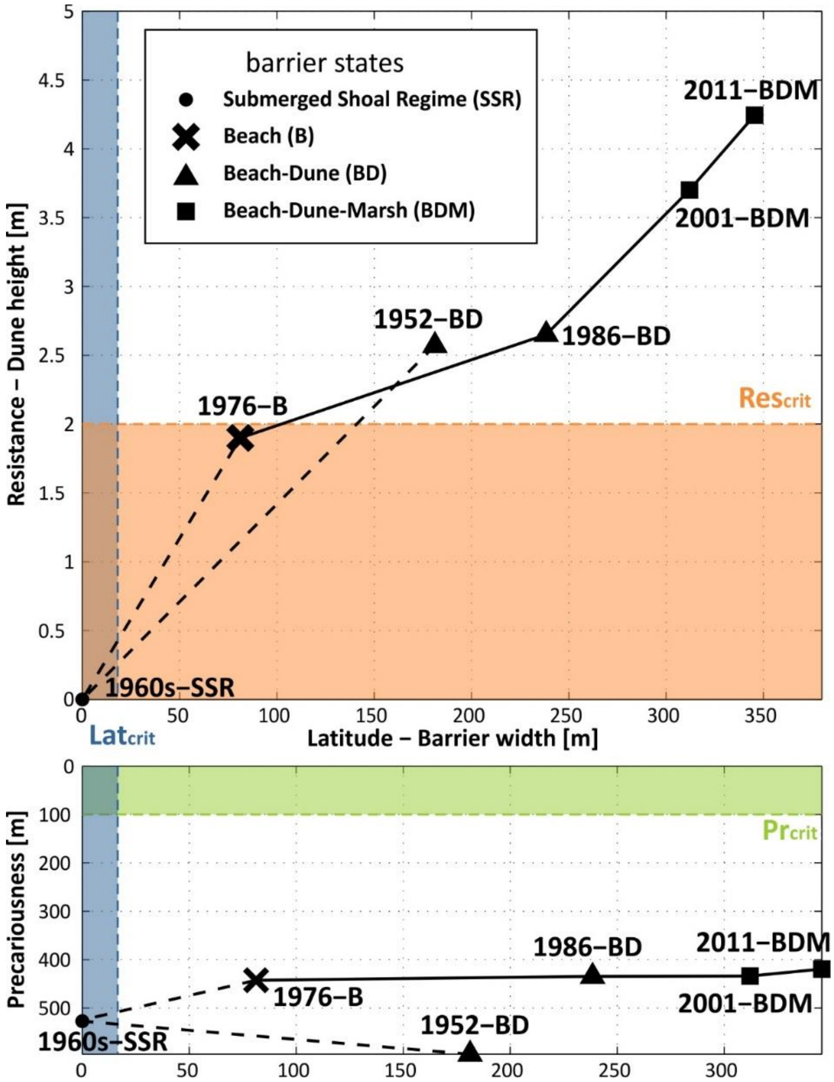

Figure 16: Evolution of resilience trajectory (combinations of resistance, latitude and precariousness) for the multi-decadal evolution of Cabanas-Cacela (2-3km in Figure 14; symbols denote different barrier state and dashed line the loss of resilience). Critical thresholds for the three parameters are noted, while the trajectory has been modified to express the flip to the submerged shoal regime (SSR).

When seen from a geomorphological prism, the perturbation caused by the anthropogenic disturbance in the system (reduction of sediment inflow) involved strong changes to the morphological characteristics of the barrier and a period of full destruction. However, applying the principles of resilience, the same data advocate for the system's ability to reorganise and effectively adapt to the new conditions of reduced longshore drift, even though in a more precarious position than before, to regain its environments (beach and dune) and to develop a new one (marsh). This highlights the differences in views and conceptions between scientific fields and hints to the challenges that need to be overcome before achieving interdisciplinary understanding (and cooperation) in resilience analyses of physical systems.

5.2 Resilience assessment based on multi-decadal geomorphological evolution

5.2.1 Geomorphological data as resilience indicators

The previously analysed approach and concepts on resilience assessment are applied to the barriers of the Ria Formosa barrier system, using geomorphological data for the period of 1952 to 2014. More information on the available data and the methodology applied can be found in (Kombiadou et al., 2019) and in the EVREST report on Task 3.

Only flights with full coverage of the barrier were used to calculate geomorphological unit areas and that, given that elevation data were not available, the analysis was restricted to a planimetric basis.

5.2.2 Barrier states and resilience dimensions

The steps of the BDM barrier state and resilience analysis are presented using the example of Cabanas Island and Cacela Peninsula (hereafter C-C), the barrier subsystem with the most significant morphological changes in Ria Formosa. Initially, the calculated unit widths (per 100 m cross-shore sector) were used to identify the spatiotemporal variability of BDM states in the barrier. The summarized results for C-C (averaged per 500 m) are shown in Figure 17. The results can effectively visualise the constructive and destructive processes in the barriers, as for example the barrier breaching between 1958 and 1972 over the transects 4 to 8 and its subsequent recovery (1972 to 1986), or the natural maturation of the barrier over transects 1 to 10, with gradual marsh establishment (1985-2005).

Three sectors (West, Central and East) were identified by analysing the similarity of neighbouring transects in terms of morphological evolution and grouping transects with high correlation of unit widths. The widths of the units and the distance to mainland (distance between backbarrier and mainland coastlines), averaged among the three sectors of the barriers are given in Figure 18, with the colour coding of the points to denote the system state of the sector. The dominant barrier state of each sector was determined using the most abundant state (in cases of equal presence of two states, the most mature one was selected as characteristic). Comparing Figure 17 and Figure 18, it can be seen that the main shifts of each sector are represented appropriately (i.e. the destruction of the C sector between 1958 and 1972). In terms of resilience dimensions, the values effectively express the recuperation through the increase of latitude (i.e., increase in barrier width) in the W and C sectors,

with concurrent reduction of the E one. All sectors show an increase in precariousness (reduced accommodation space), which, however seems stabilised after 1986.

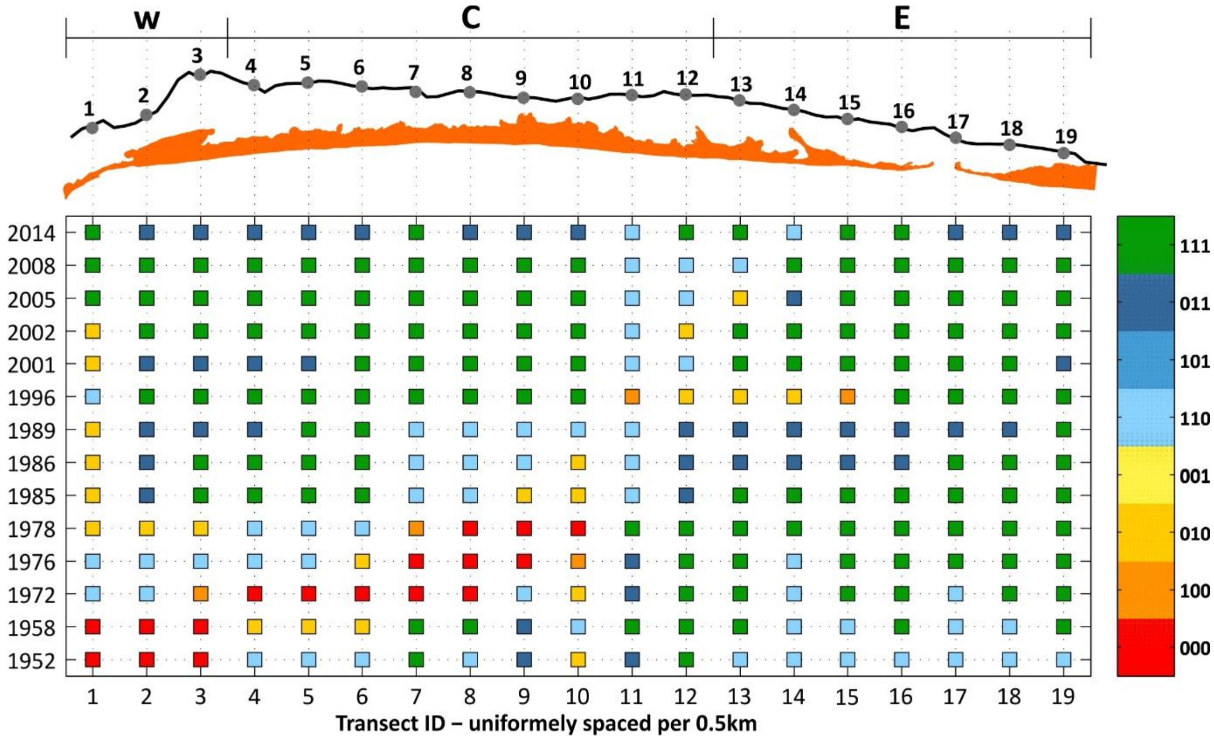

Figure 17: Changes to the barrier state (BDM, defined as before) along the stretch of C-C (x-axis; map of 2014 given above) for all the available flights (y-axis).

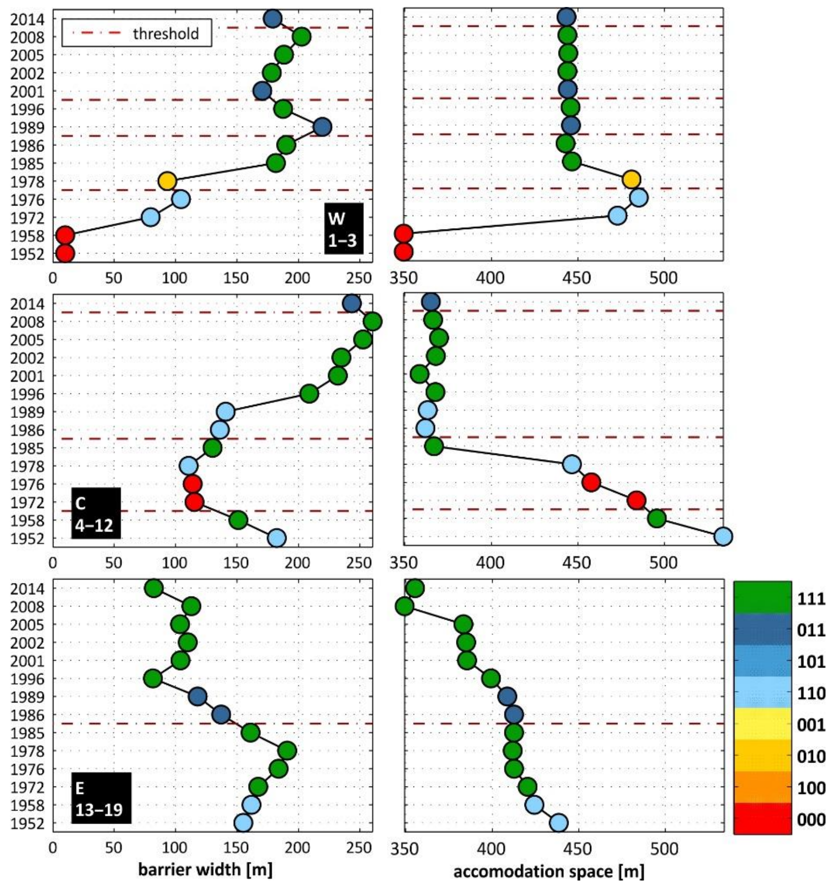

Figure 18: Changes to BDM barrier state (circle colour with reference to the colour bar) and the evolution of average barrier width (left) and distance to the mainland (right) for the three sectors of C-C (top to bottom: 1-3, 4-12 and 13-18; see map in Figure 17). Dashed lines denote threshold crossing.

The results of the spatiotemporal evolution of barrier state and resilience dimensions along barrier sectors for the barriers of Ancão, Barreta, Culatra, Armona and Tavira are shown in Figures 19 to 23, respectively. Individual sector shifts, which represent crossing thresholds, are represented only in cases where they are extensive enough to be characteristic for the entire barrier, or when the changes are persistent in time. For example, the beach loss shift of Ancão W in 2005-08 appears on the entire barrier only in 2009-14 (Figure 24), when the central part also loses beach (see Figure 19).

Figures 19 to 24 proved that the proposed representation method is a concise and accurate way of representing the evolution and resilience of barriers. They enable a visual reading of barrier evolution through time, its variability alongshore, the gain, maintain or loss of barrier environments, the location of threshold crossings, the maturation or disruption of barriers, recognition of evolutionary paths, and facilitate barrier comparisons. The most common situations considering both individual sectors and entire barriers are 111 and 011, which are barriers with beach-dune-marsh (111), that change into a beach loss state (011) after storms, that will eventually regain the three units (Figures 19 to 24). Breaching or inlet migration situations (000) occurred in all barriers and are well represented by the BDM barrier states identified, with less occurrences on the barriers of Armona (Figure 22) and Tavira (Figure 23). It was noticed that the state 001 was absent during this period, considering the data sampling characteristics, which means that this was an uncommon situation, with a short duration, not properly characterised on a multi-year analysis.

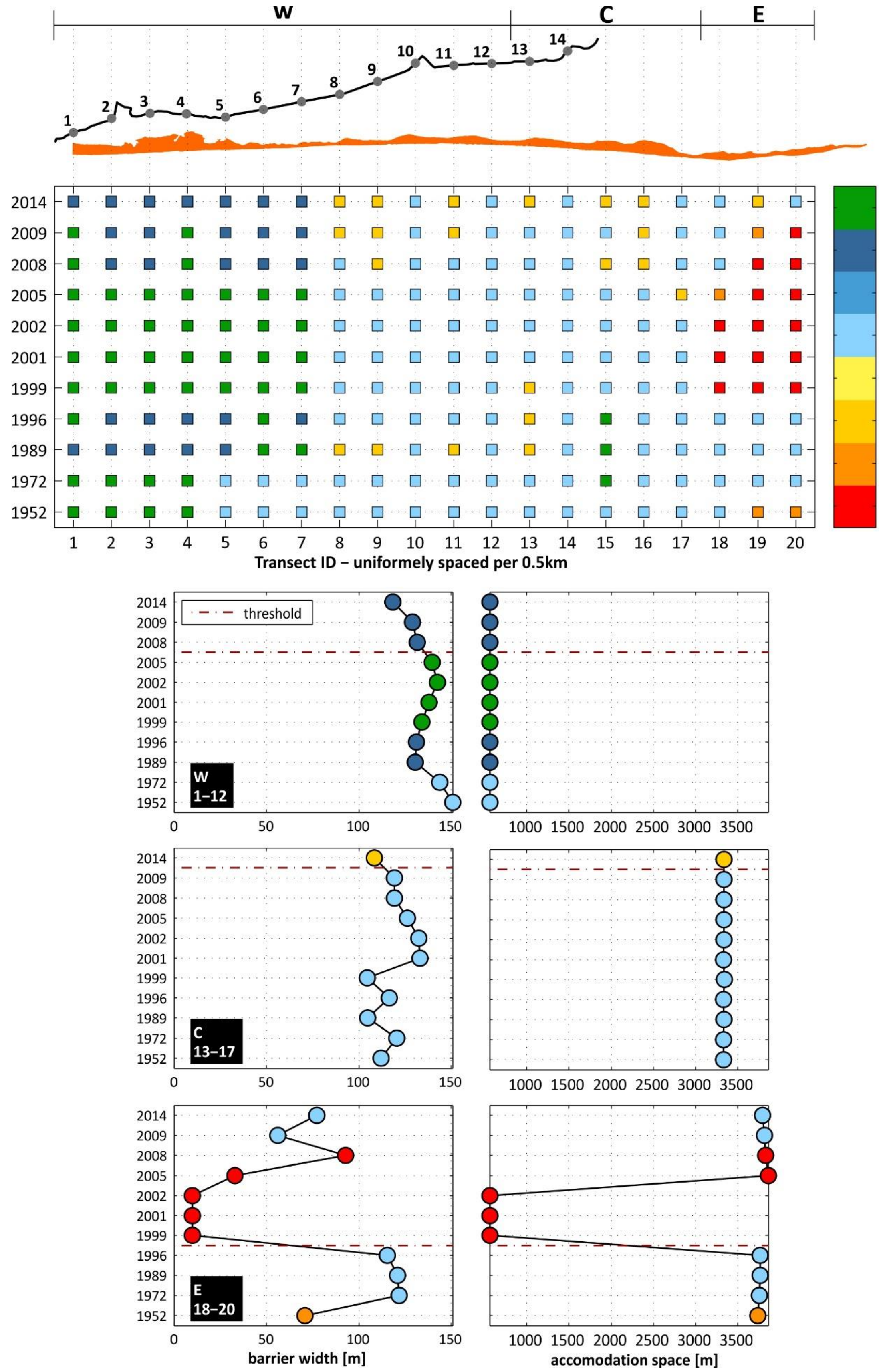

Figure 19: Changes to the BDM barrier state (with reference to the colour bar) in Ancão along barrier transects (top panel) and in barrier sectors (bottom panel, showing average barrier width and distance to mainland values; dashed lines denote threshold crossing).

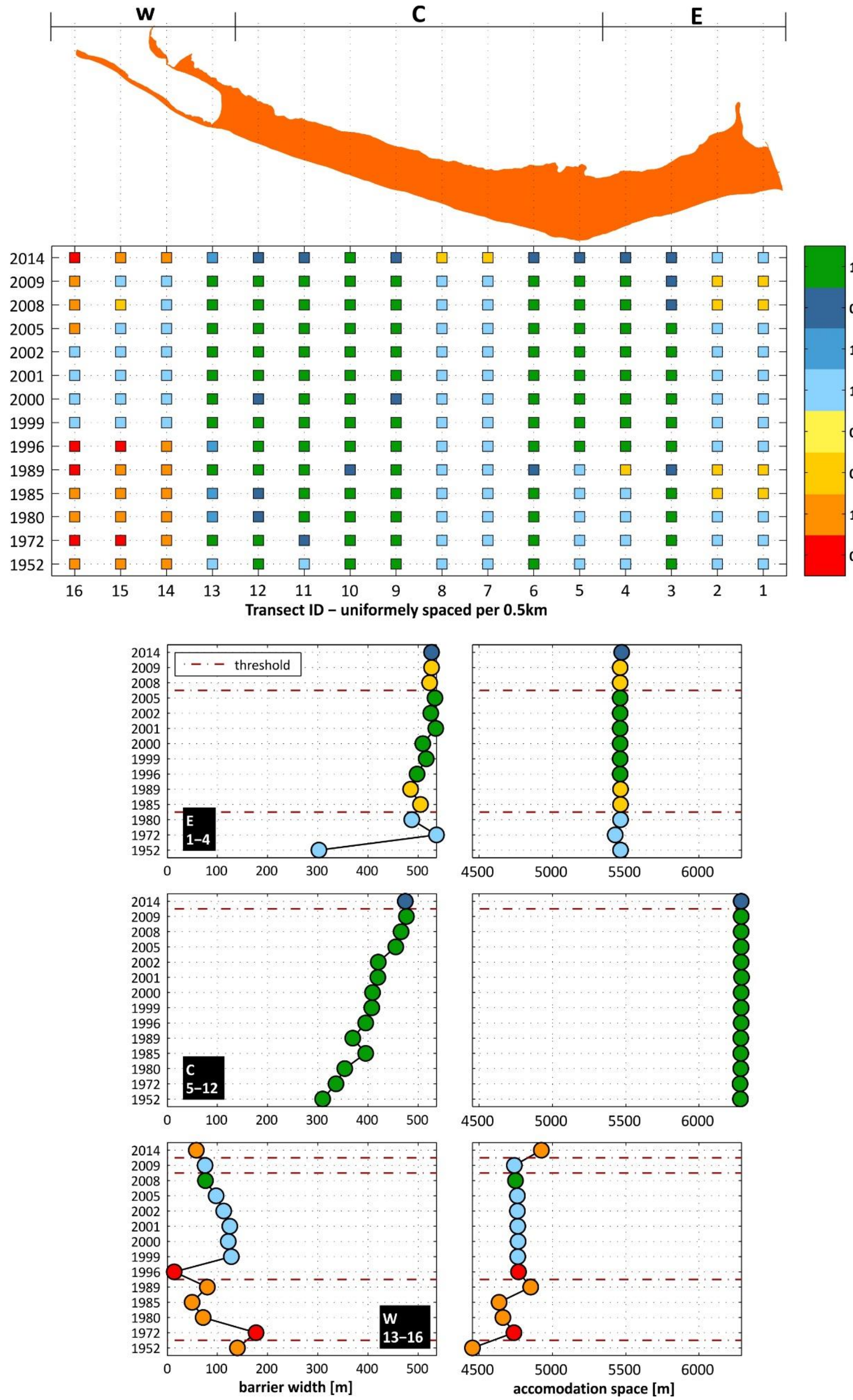

Figure 20: Changes to the BDM barrier state (with reference to the colour bar) in Barreta along barrier transects (top panel) and in barrier sectors (bottom panel, showing average barrier width and distance to mainland values; dashed lines denote threshold crossing).

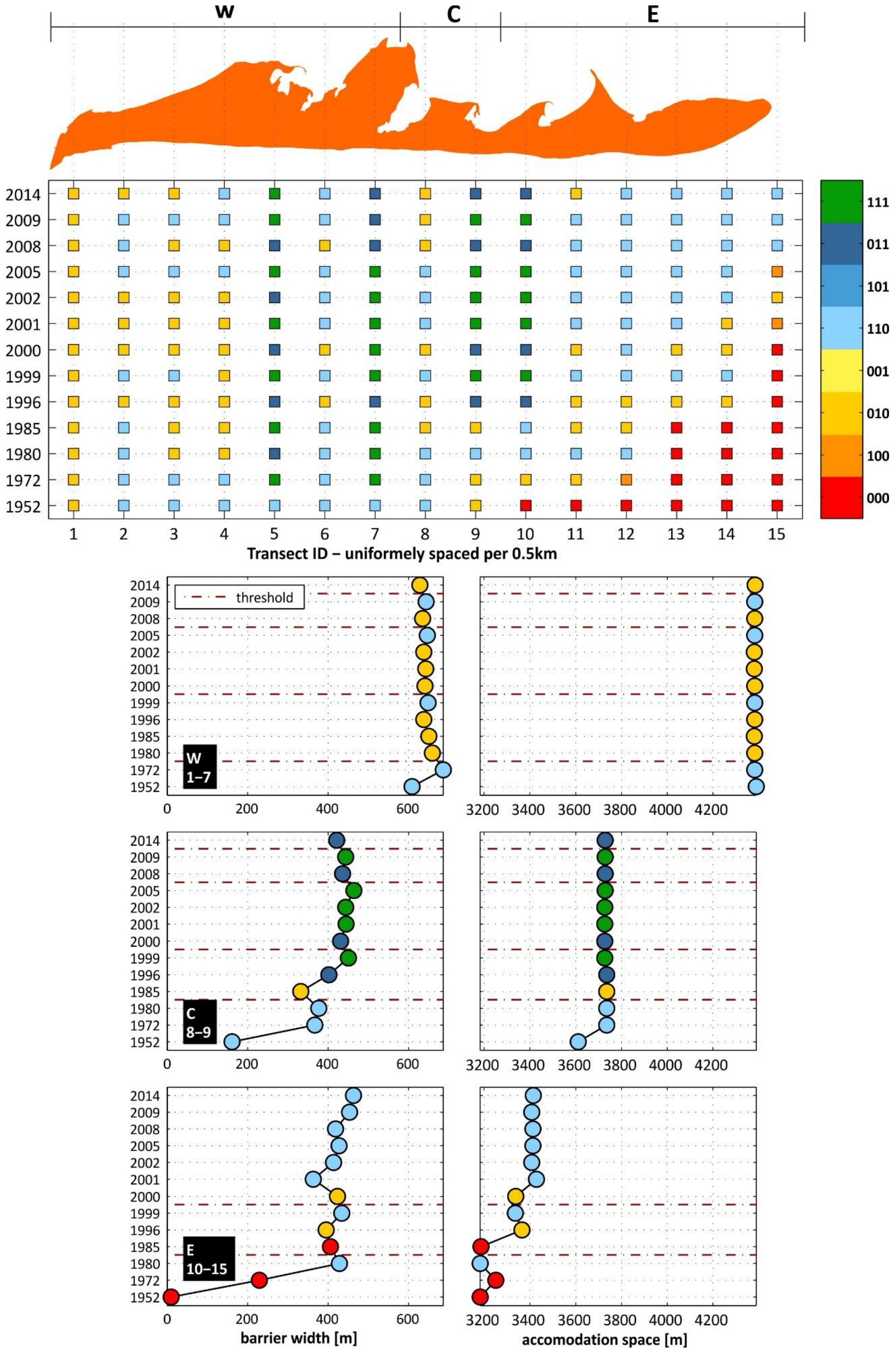

Figure 21: Changes to the BDM barrier state (with reference to the colour bar) in Culatra along barrier transects (top panel) and in barrier sectors (bottom panel, showing average barrier width and distance to mainland values; dashed lines denote threshold crossing).

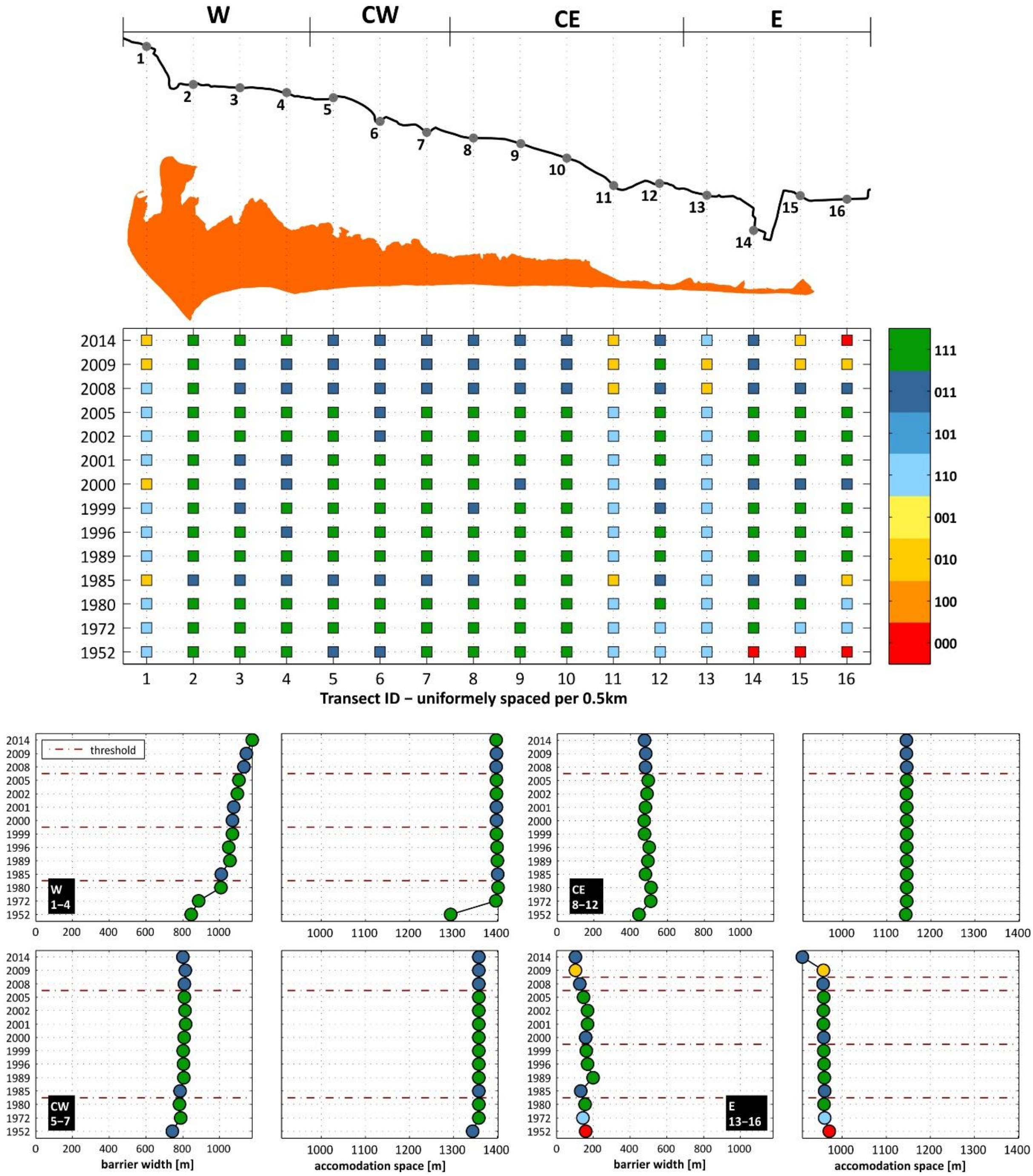

Figure 22: Changes to the BDM barrier state (with reference to the colour bar) in Armona along barrier transects (top panel) and in barrier sectors (bottom panel, showing average barrier width and distance to mainland values; dashed lines denote threshold crossing).

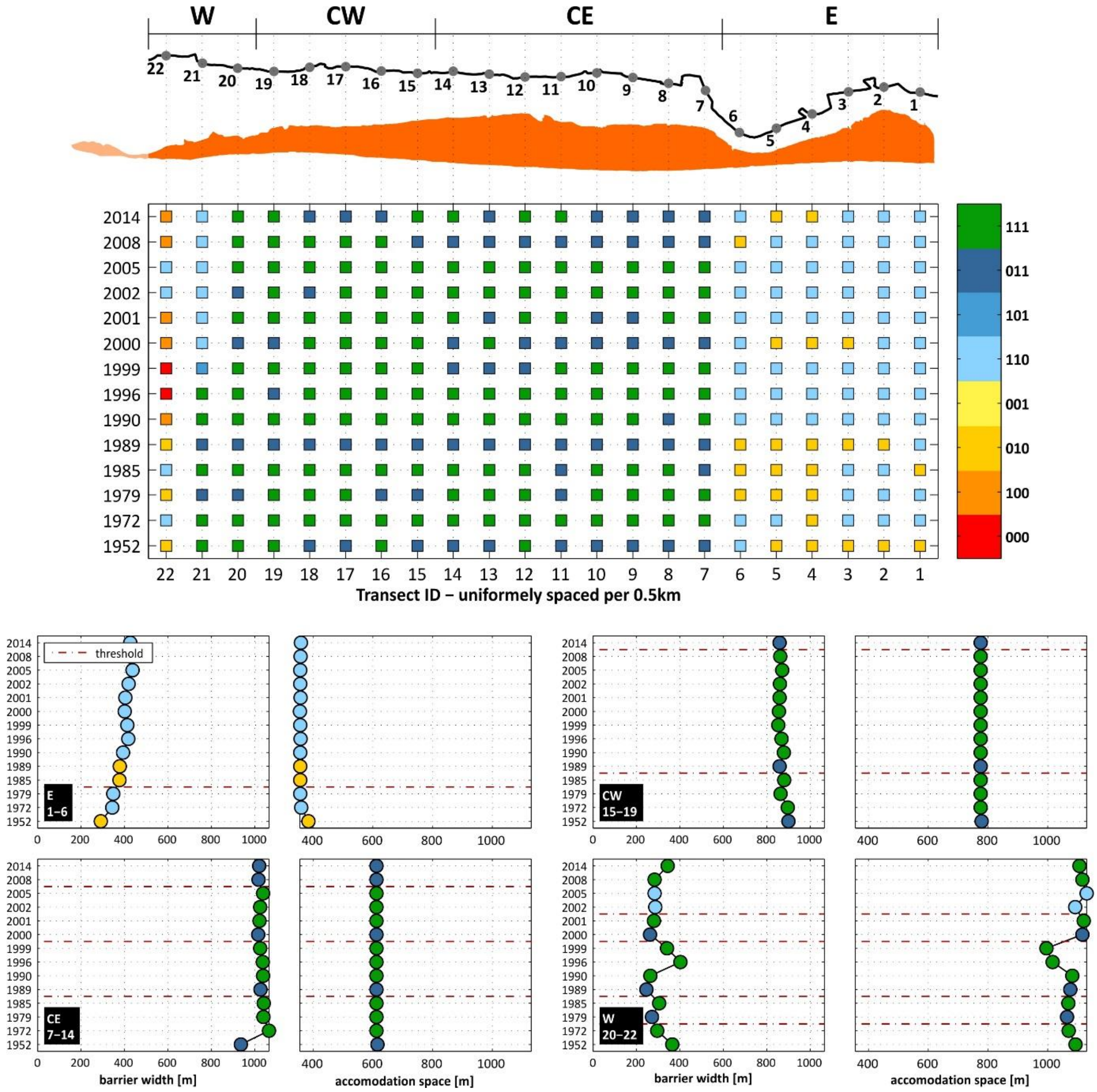

Figure 23: Changes to the BDM barrier state (with reference to the colour bar) in Tavira along barrier transects (top panel) and in barrier sectors (bottom panel, showing average barrier width and distance to mainland values; dashed lines denote threshold crossing).

The overall state and averaged characteristics for each barrier of the system are given in Figure 24. The characteristic state for the entire barrier was defined after calculating the coverage of each environment (B, D & M) along the island and assigning it as present (1) for values greater or equal to 50% and as absent (0) otherwise.

It can be noted that regarding thresholds in entire barriers, these are exclusively related to the loss of Beach (i.e. due to storm incidence). Therefore, the identified threshold crossings and related regime shifts, at the scales of an entire barrier, correspond to loss of the most dynamic and variable unit of the three. This means that these shifts and perturbations are ephemeral and that the system rebounds shortly after the relaxation of the disturbance.

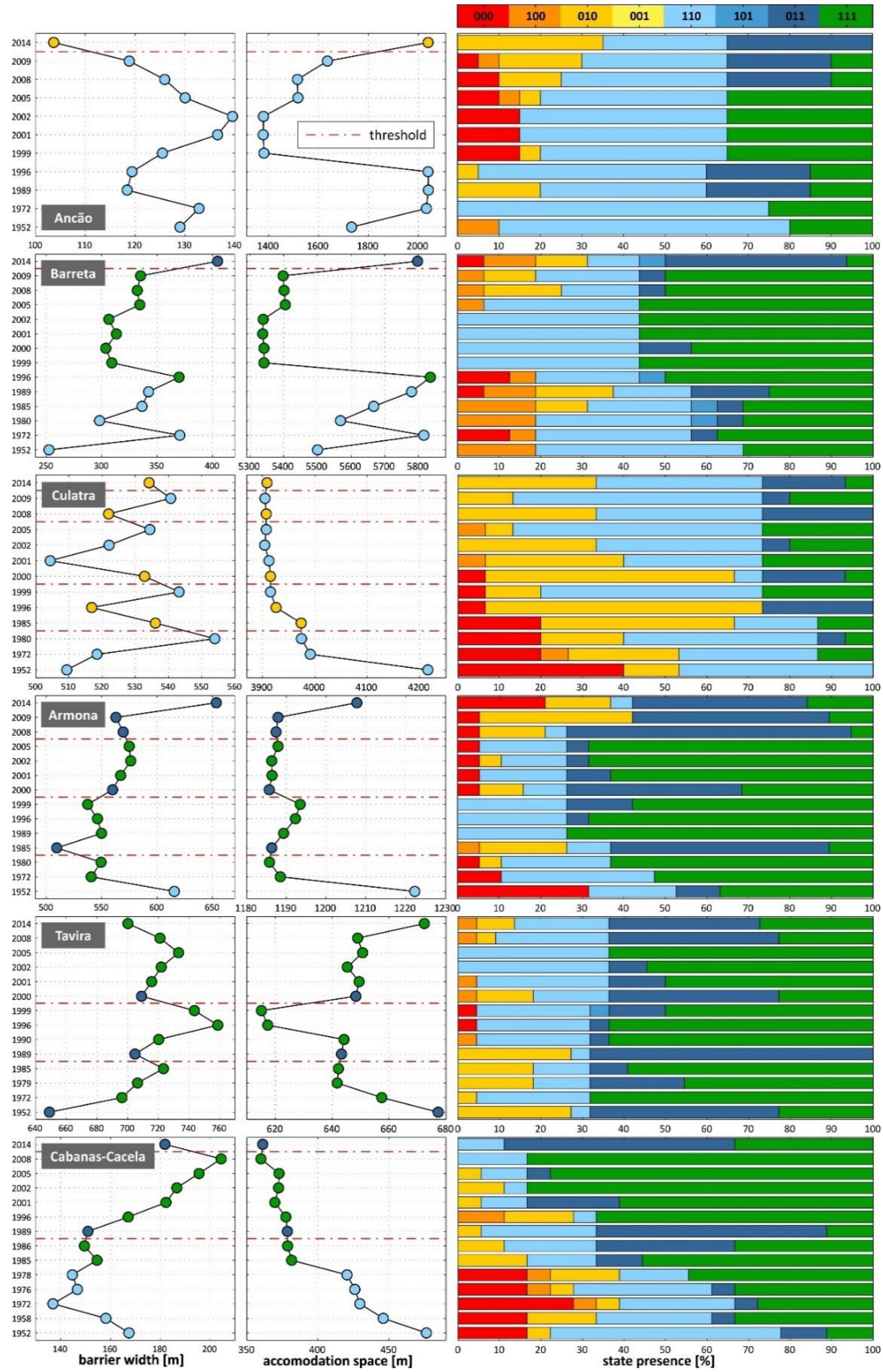

Figure 24: Changes to the BDM barrier state for Ria Formosa. Left to right: State changes with relation to barrier width and distance to mainland (circles) and percent of BDM state presence (bars). Top to bottom: the barriers from west to east.

Regarding the evolution of resilience states and dimensions for the entire barriers (Figure 24), it can be noted that:

- **Ancão** appears mainly at a 110 state (with a single flip to 010 in 2014 due to beach loss), with a tendency for latitude reduction. This is most likely the combined impact of narrowing and inlet migration. Inlet migration affects accommodation space as well, due to the increase of distance to mainland from W-E.
- **Barreta** is generally growing and maturating, passing from a state of 110 to 111 after 1996, with no significant changes to the resilience dimensions. The changes shown are mostly reflecting the influence of the W sector, directly affected by the Ancão inlet position (C and W sectors show increasing trends, see Figure 20). The single shift in 2009-2014 is due to storm beach erosion.
- **Culatra** is flipping between states 110 and 010 throughout the period of analysis. The thresholds are mostly crossed in the W-C part and correspond to beach loss (see Figure 21) that is likely influenced by the reduction of longshore drift by the Faro-Olhão jetties (Kombiadou et al., 2019). The variability in latitude values is generally low, while the reduction in accommodation space is due to the elongation of the island and the lower distance of the E part to the mainland.
- **Armona and Tavira** show a very similar behaviour. They are generally wide and mature barriers, with only storm-related thresholds that lead to fluctuating states of 011 and 111.
- **C-C** show that only two thresholds are characteristic for the whole barrier subsystem, in 1986-89 and in 2008-14, corresponding to a flip from 111 to 011. From these, the flip of 2008-14 is present in the W (1-3) and C (4-12) sectors (Figure 18) and, therefore, it was extensive enough to be characteristic of the entire C-C barriers. The 1986-89 is present only over the W sector (1-3), which is short (1.5 km length) and thus it cannot have dominated the averaging process. The other sectors show a threshold in 1985-86, from 111 to 110 in the C part and from 111 to 011 for the E (Figure 18). So, even though the averaged BDMs do not necessarily follow the largest sector (which here should be the C, 4-12), the assessment for the barrier does represent the dominant changes accurately (see Figure 17, where the change from 111 to 011 in 1985-86 can be identified). On the other hand, important shifts in sectors, like the shift from 111 to 000 in 1958-72 for the central part (4-12) are not represented when accounting for the entire barrier. Thus, spatial averaging has limitations and it is directly linked to the meaning of specified resilience (of what to what).

6. Final Remarks

Three panarchical levels are proposed (beach, dune, marsh), in accordance with the related system's spatiotemporal scales of change, and potential feedbacks between them. The dimensions of the three proposed levels are used to define the related dimensions of the basin of attraction: resistance, latitude and precariousness. Dune height is used to express resistance and the joined width of barrier (beach and dune) and marsh (when present) is considered representative of the latitude of the regime. The proximity of the backbarrier to the mainland is proposed as a measure of the system's precariousness, considering barrier welding to mainland as a situation with low possibility for the barrier to bounce back from. Drawing upon the adaptive nature of the barrier island rollover process itself, we used it as an example to conceptualise the potential changes to the stability landscape and the adaptive cycle. These hypotheses were tested using data from an actual barrier stretch that migrated landwards as a result of sediment starvation. Even if limited by temporal data availability, still, we found that the proposed geomorphic dimensions agree with the conceptual scheme. The evolution of the stability landscape showed evidence of having crossed a threshold during the full inundation of the barrier, with leak of potential (sediment) indicative of a passage from the reorganisation to the exploitation phase. The proposed dimensions expressed the subsequent recuperation of the system effectively, with deepening and widening of the domain of attraction, which is also indicative of a fore-loop expansion of the adaptive cycle of the system following backbarrier stabilisation.

When passing on from geomorphic to resilience analyses, two issues become key: spatiotemporal scaling and how natural evolution is accounted for. Scaling issues need to be addressed early on, in the sense that the number of panarchical levels and of the considered feedbacks is highly dependent on the level of analysis and, in turn, the considered spatiotemporal detail needs to be oriented towards the objective of the analysis. For example, considering faster changing cycles (i.e. dune plant seasonal cycles), or very detailed spatial discretisation, in a multi-year geomorphological resilience analysis would be pointless. Conversely, disregarding a level could lead to feedbacks, thresholds and potential alternate states being overlooked, thus involving high possibilities of unexpected forms of future system organisation through, mainly positive, feedbacks that have been unaccounted for. Additionally, and regardless of the level of analysis, it is important to consider the natural evolution of a system when accounting for regimes and thresholds. When analysing the morphodynamic changes of barrier islands, the natural migration of an inlet, for example, cannot be considered as evidence of instability. Therefore, the morphological change of a sector from barrier to inlet needs to be considered critically when analysing for resilience. This can be a result of a breaching event, thus signifying an actual flip to an alternate state, but it can also be part of the natural barrier evolution, either because the inlet crossed the sector during its natural migration, or because the old inlet reached its limiting position (gradually got infilled and lost its efficiency) and a new inlet opened at the location of the sector in question. Similarly, the growth of a marsh in the backbarrier is related to a change in the functions of the system, and thus would mean crossing of a threshold. However, this should not be considered a flip to an alternate state, but an evolution of the state itself, as proposed here by the inclusion of the marsh width to the latitude of the basin. This is in accordance with the understanding that 'thresholds exist at multiple scales, but not all result in a shift to an alternate state' (Parsons et al., 2009).

Depending on the specific resilience of the study (of what to what), which is directly linked to spatiotemporal scales of analysis, resilience can be assessed from stretches of a few tens of meters (essentially along transects, with no averaging) to averaged values over sectors or entire barriers.

However, in areas of high (spatial and/or temporal) variability in resilience dimensions, scaling issues on spatial averaging can arise, masking regime shifts that could potentially be important. In such cases, and depending on the focus of the specific resilience sought, it might be necessary to divide in sectors and analyse states, thresholds and resilience dimensions separately in each sector.

Regarding the analysis of the multi-decadal evolution of the barriers of Ria Formosa:

- The identified regime shifts and thresholds in terms of entire barrier refer to the faster-and-smaller cycle of the BDM panarchy (B loss) and, therefore correspond to the unit with the highest temporal variability and ability to regenerate. Therefore, overall, the barriers of the system can be characterised as resilient.
- Higher-order thresholds have been identified in barrier sectors (e.g. loss of all 3 units in sector C of C-C between 1958 and 1972; Figure 18), which indicate temporal loss of resilience. However, the posterior recuperation (regeneration of all three units by 1985) indicate the ability of the system to 'to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same functions, structure, identity and feedbacks' (migrating landwards as an adaption to the new conditions of reduced longshore drift). Therefore, the response of the system at the analysed temporal scales can be characterised as resilient, also at the level of individual barrier sectors.
- Sectors directly influenced by inlets show the highest variability in resilience dimensions and frequent shifts in barrier state. However, taking into account the natural evolution of a migrating inlet, this is to be expected within the zone of inlet migration. For example, the breach of a new inlet after the old one reached its limiting position (gradually got infilled and lost its efficiency) (e.g., shift from 110 to 000 in Ancão E from 1996 to 1999; Figure 19) is part of the migration cycle. When assessing the resilience of a barrier sector and identifying regime shifts, such issues need to be taken under consideration and the morphological change of a sector from barrier to inlet needs to be considered critically. Similarly, the growth of a marsh in the backbarrier is related to a change in the functions of the system, and thus would mean crossing of a threshold. However, this should not be considered a flip to an alternate state, but an evolution of the state itself, as proposed here by the inclusion of the marsh width to the latitude of the basin.

The proposed methodology is robust, applicable over a wide range of spatial and temporal scales and is one of the few to link geomorphological evolution of barrier islands and ecological resilience theory, providing a clear translation of resilience concepts into detectable and measurable geomorphic units, adaptable to any system. The approach allows assessing resilience through reorganisation and adaptation, far from pre-specified dimension criteria (i.e. pre-disturbance barrier dimensions), in a manner suitable for natural systems.

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