From geomorphology to resilience of barrier islands: transferring concepts from theory to application

De geomorfología a resiliencia de islas barrera: transfiriendo conceptos de la teoría a la aplicación

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Abstract: Ecological resilience is a multi-faceted concept that is open to various interpretations, giving rise to confusion over terminology and concepts, especially across scientific fields. The present work is attempting to clarify resilience principles and concepts and bridge the gap between theory and application in the case of geomorphic systems, like barrier islands. Under this reasoning, we analyse the main aspects of ecological resilience theory and transfer them to the field of coastal geomorphology, using geomorphic environments and dimensions of barrier islands. Three panarchical levels are proposed (beach, dune, marsh), corresponding to different habitats and spatio-temporal scales of change. Based on these, the four crucial aspects of resilience, latitude, resistance, precariousness and cross-scale interactions are determined. Data from a barrier inland migration was used as a paradigm for an adaptation process, showing that the proposed geomorphic dimensions effectively capture the changes in the stability domain, while the emergence of new regimes and tipping points and the transition trough the phases of the adaptive cycle and changes to the cycle itself were effectively conceptualised.

Keywords: ecological resilience; alternative states; thresholds; panarchical levels; barrier rollover

Resumen: *La resiliencia ecológica es un concepto multifacético abierto a multiples interpretaciones que han generado cierta confusión en torno a la terminología y los conceptos asociados a la misma, especialmente entre áreas científicos. Éste trabajo pretende aclarar los principios y conceptos de resiliencia y cerrar la brecha entre teoría y aplicación en el caso de sistemas geomorfológicos como las islas barrera. Bajo este razonamiento, analizamos los aspectos principales de la teoría de resiliencia ecológica y los transferimos a la geomorfología costera, utilizando los ambientes geomorfológicos y las dimensiones de islas barrera. Así, proponemos tres niveles panárquicos (playa, duna, marisma), correspondientes a distintos hábitats y escalas de cambio espacio-temporales. Basados en estos niveles, determinamos los cuatro aspectos fundamentales de resiliencia: latitud, resistencia, precariedad e interacciones entre escalas. Datos de un 'rollover' fueron utilizados como paradigma de adaptación, demostrando que las dimensiones geomórficas propuestas capturan efectivamente los cambios en el 'paisaje de estabilidad', mientras que el surgimiento de nuevos regímenes y puntos de inflexión, así como, y la transición a través de las fases del ciclo de adaptación y los cambios en el propio ciclo fueron conceptualizados efectivamente.*

Palabras clave: *resiliencia ecológica; estados alternativos; niveles panarquicos; rollover de barrera*

INTRODUCTION

Resilience has multiple levels of meaning, used with different objectives and over a broad contextual frame, leading to divergent conceptions and ambiguous uses of terminology and to an increasingly diluted and unclear specific meaning of the term (Brand and Jax, 2007). Distinct views and definitions seem to coexist even within disciplines, while, across scientific fields, the differences are even more significant (Piégay et al., 2018). It becomes clear that the term has been used ambiguously, for fundamentally different intentions, leading to resilience being increasingly conceived as a perspective, rather than a clear and well-defined concept (Brand and Jax, 2007). At the same time, increasing interest is noted within the research community regarding ecological resilience (Flood and Schechtman, 2014), concept gaining ground over more rigid views of natural systems. This work focuses on clarifying resilience terminology, identified as one of the main emerging issues for bridging the gap between geomorphology and resilience (Thoms et al., 2018), and on applying these principles and concepts to express the resilience of coastal systems. Geomorphic parameters of barrier islands are used here to express key resilience aspects, using multi-decadal data from an inland-migrating barrier.

MAIN ECOLOGICAL RESILIENCE CONCEPTS

Two are the main schools of thought on resilience, the engineering, focussing on recovery and return time after a disturbance, and the ecological, concentrating on how much a system can be disturbed and still persist without changing function (Miller et al., 2010). These differences are fundamental, with the engineering concerned with maintaining efficiency of function and the ecosystem one on maintaining existence of function (Gunderson and Holling, 2002). The ball-and-cup analogy (Fig. 1a) is often used to represent these views. The cup represents the 'basin of attraction' (or regime), defined by all possible values of system variables of interest, and the ball represents the state of the system at a given temporal point. Engineering resilience considers a single basin, focussing on if the ball can remain at its bottom, whereas ecological resilience accepts multiple basins and focuses on whether the system can remain within the current basin. Thus, engineering resilience considers no thresholds and expresses the ability to resist departure from equilibrium (bottom of the basin) and minimise return time after disturbance (Flood and Schechtman, 2014). On the contrary, identifying and understanding thresholds is paramount in ecological resilience thinking and, even though recovery time can also be important, the ability of the system to recover at all is much more relevant.

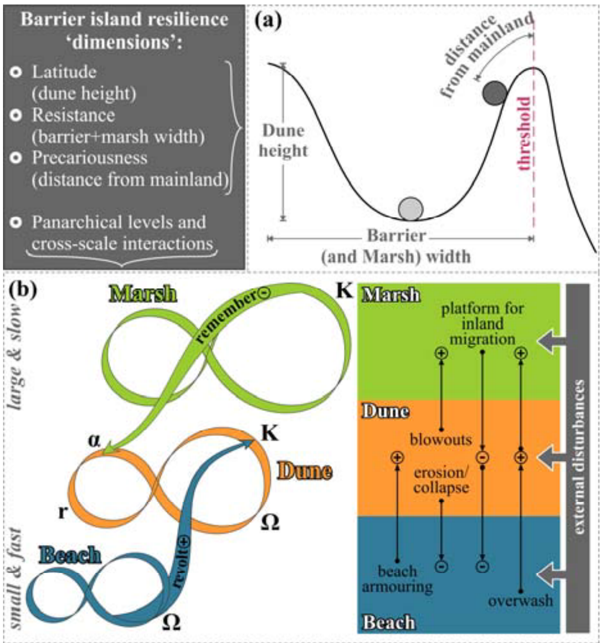

FIGURE 1. *Main aspects of resilience: Latitude, resistance and precariousness, expressed by the ball-and-cup analogy (a) and panarchy with cross-scale (revolt and remember) interactions (b), as translated for the case of barrier islands.*

Ecological resilience is 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; Walker et al., 2004). The ecological concept focuses on avoiding to cross a threshold into an alternate and possibly irreversible new state, and on regenerating after disturbance (Miller et al., 2010).

Four are the crucial aspects of resilience (Gunderson and Holling, 2002; 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 difficulty of changing the system, equal to the basin depth; **3) Precariousness**: how close the current system state is to a limit or "threshold" that, if breached, makes reorganization difficult or impossible; and **4) Cross-scale interactions**: influences from (sub)systems at scales above and below the particular focal scale.

The first three aspects, applicable to both the whole system and to the sub-systems that compose it, are related to the shape of the basin of attraction (cup) and the position system state (ball) (Fig. 1a), which are continuously changing, in response to the combined effects of natural processes and interactions and external disturbances. Cross-scale interactions (Fig. 1b) are based on the "*panarchy*" theory, put forward by Gunderson and Holling (2002), and its relation to the adaptive cycle. Theory holds that complex adaptive systems do not tend towards some equilibrium configuration, but, instead, pass through the series of the four characteristic phases of the adaptive cycle (Fig. 1b; Gunderson and Holling (2002)): exploitation (r), conservation (K), release (or "creative destruction", Ω) and renewal or reorganization (α). Two panarchical cross scale interactions are the most significant ones, termed "*revolt*" and "*remember*" (Fig. 1b). They differ in terms of direction within the panarchy and of the feedback nature (destructive or creative) and become important at times of change and renewal in the adaptive cycle. "*Revolt*" refers to a collapsing lower-faster cycle, whose impacts may cascade up to the next higher-slower level, potentially triggering crisis, especially if the upper level is at the conservation (K) phase. "*Remember*" refers to the reorganisation of a previously collapsed lower cycle, 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).

RESILIENCE AND BARRIER GEOMORPHOLOGY

Based on its definition, it follows that, to assess ecological resilience of a geomorphic system, one must start from identifying its identity, functions, structure and feedbacks. For a barrier island, these can be:

Identity: strip of sand and/or gravel, backed by a shallow coastal bay, separated wholly or partly from the mainland shore. **Functions**: provide support to

habitats, species and human activities and storm protection and sheltering to the lagoon, its supported habitats and the mainland. **Structure**: a potential subdivision for the subaerial barrier can be wave-, wind- and tide-dominated parts (or simply beach dune and marsh). **Feedbacks** are highly linked to the considered structure.

Considering beach, dune and marsh, as the three panarchical levels of analysis, the four crucial aspects of resilience and the potential feedbacks can be expressed by geomorphological dimensions, as shown in Fig. 1. The transference of the first three aspects is rather straightforward (Fig. 1a). **Latitude** (basin width) should be expressed by the total width of all units (sandy barrier and perched marsh). **Resistance** (basin height) can be related to the dune height, as an indicator of the difficulty of the barrier to be inundated. **Precariousness** can be linked to the proximity of the backbarrier to mainland (space for inland migration). Crossing such a threshold (welding with mainland) would mean irreversible loss of resilience (identity, functions, structure and feedbacks). Scaling issues are key and need to be addressed early on, given that the panarchical levels and feedbacks are highly dependent on the level of analysis and, in turn, the spatiotemporal detail needed is case-specific. For example, considering faster changing cycles, or very detailed spatial discretisation, in a multi-year geomorphological resilience analysis would be pointless. Conversely, disregarding a level could, potentially, lead to feedbacks, thresholds and alternate states being overlooked, which could entail high possibilities of unexpected forms of future system organisation.

APPLICATION TO BARRIER ROLLOVER

The proposed morphological dimensions are tested using data from Cabanas and Cacela barriers in Ria Formosa (S. Portugal; Fig. 2), where the reduction of longshore drift by jetty construction in the updrift Tavira Inlet forced the barrier subsystem to a rollover. Due to its dynamic response and scarcity of elevation data, we focussed on a stretch of 1 km (Fig. 2a: dashed-grey rectangle) where barrier is present in all 5 periods with data availability (1952, 1976, 1986, 2001, 2011).

The changes to the stability landscape, based on the terminology described previously, are given in Fig. 3a, utilising elevation data and barrier and marsh mappings. Strong contraction in the stability domain, in terms of both latitude (barrier width) and resistance (dune height), is noted from 1952 to 1976, along with increase of precariousness (reduction of distance from mainland). A breach took place between these dates (around 1961), drowning the whole barrier section (southeast edge of Cacela Peninsula) and pushing sand into shoals in the backbarrier lagoon, shoals that facilitated the regrowth of the barrier (as Cacela Island) landwards. Thus, it becomes obvious that a regime shift took place between 1952 and 1976 (likely mid to late 1960s), however, no data are available to document the changes. Therefore, the changes to the stability domain during the shift from barrier to submerged shoals regime (SSR) could not be assessed and the shift is simply noted as a flip to SSR in Fig. 3a. Theoretically, the average depth of the shoals could express the resistance of the SSR, as a measure of the sediment that needs to be infilled for the deposits to become subaerial and, therefore, cross the threshold back from shoal to barrier. By the early 1970s, the system regained the barrier regime state, with a shallow and narrow basin, and, from 1986 onwards, changes are mostly related to shape, with significant widening and deepening of the basin, while the precariousness appears mostly stabilised (Fig. 3a). In terms of the adaptive cycle (Fig. 3b), the initial 1952 morphology passed though the phases of creative destruction and reorganisation during the regime shift (SSR, late 1960s). Barrier recovery in 1976 is probably in the exploitation (r) phase, given that the leak of potential (sediment; characteristic of α-phase), during passage from K to r, is obvious, from the domains of 1952 and 1976 (Fig. 3a). After 1986, expansion of the fore-loop is expected, due to shoreline progradation, backbarrier stabilisation and perched marsh development.

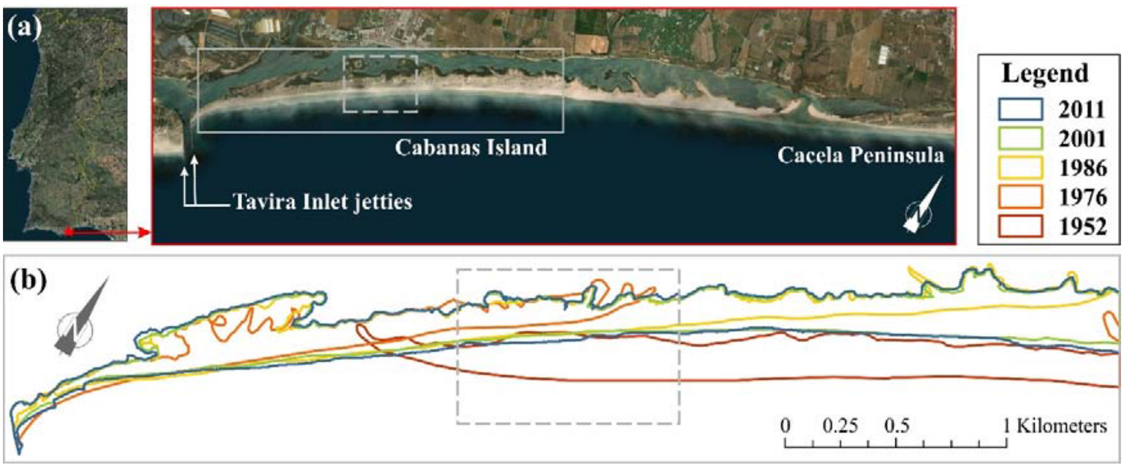

FIGURE 2. *Location of Cabanas Island and zoomed image (a) and changes to barrier morphology (coastlines are MHWL) between 1952 and 2011 (b). The dashed grey line denotes the stretch with barrier presence for all the dates with available elevation data.*

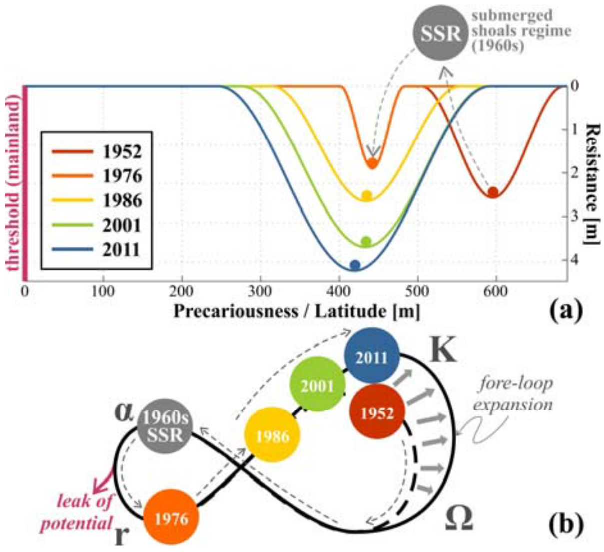

FIGURE 3. *Changes to the stability domain during the rollover and recovery of Cabanas, showing the main resilience 'dimensions': latitude (basin width) and precariousness (distance from mainland) are shown in the horizontal axis and resistance (basin depth) is given in the vertical axis (a) and related phases and changes of the adaptive cycle (b). Due to lack of data, the changes during the flip to a submerged shoal regime (SSR) could not be assessed in (a).*

DISCUSSION AND CONCLUSIONS

Ecological resilience, a topic receiving increasing scientific interest, is, by definition, multifaceted and open to various interpretations. The interdisciplinary nature of natural systems and the distinct interpretations by different scientific fields makes it even more difficult to reach consensus regarding concepts, terminology and applicability on resilience. Motivated by the need to clarify concepts and to initiate a dialog regarding the resilience of geomorphic systems, the present paper analyses the main principles and facets of ecological resilience, clarifies concepts and attempts to transfer them to the field of coastal geomorphology. Concepts are "translated" using geomorphic environments and dimensions of barrier islands. Three panarchical levels are proposed to express the main resilience aspects (beach, dune, marsh) and potential feedbacks between them are identified. Even if limited by data availability, the proposed geomorphic dimensions are consistent with the theory, effectively expressing the system recovery, through deepening and widening of the domain of attraction and expansion of the fore loop of the adaptive cycle.

It is interesting to point out that, when seen from a geomorphological prism, the changes to the Cabanas-Cacela barrier in the late 1960s, involved significant shifts in morphological characteristics and a period of full barrier destruction. On the other hand, through the prism and 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 differences in views between scientific fields and hints to the challenges that need to be overcome before achieving interdisciplinary understanding (and cooperation) in the area of sustainability and resilience of natural systems. We hope that this work provides a step forward toward this direction, contributing to translating resilience concepts into detectable and measurable geomorphic/physical units, adaptable to any geomorphic system.

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