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Application of the Adaptive Cycle and Panarchy in La Marjaleria Social-Ecological System: Reflections for Operability

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Abstract: The adaptive cycle and panarchy are recognised tools for resilience assessment prior to establishing new management approaches aligned with Anthropocene needs. This study used the adaptive cycle and panarchy to assess the dynamics of the social-ecological system (SES) of La Marjaleria, Spain, which experienced increasing human pressure and environmental degradation in recent decades, and developed the 'adaptive curve' as a novel graphical representation of system change in the presentation of the results. Based on a literature review of historical changes in La Marjaleria, a SES analysis was performed using the adaptive cycle and panarchy, following the Resilience Alliance's Practitioners Guide. The assessment offered new insights into the social and ecological dynamics of La Marjaleria through identification of causes and consequences from a complex systems perspective. Previous land-use management in the area has generated tensions between different stakeholders and reduced environmental resilience. The systems thinking approach highlighted the complexity of change processes, offering the possibility of new routes for dialogue and understanding. The 'adaptive curve' developed as a method of illustrating interactions across scales in this study could be useful for synthesising the results of a panarchy analysis and supporting their interpretation, offering relevant departure points for future planning and decision-making.

Keywords: panarchy; social-ecological systems; environmental resilience; adaptive cycle; adaptive curve

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1. Introduction

Over the centuries, humankind has contributed to extensive environmental change and degradation [1–4]. Previous analysis of human interactions with the environment has been based on a mechanistic perspective that produces detailed knowledge about the parts of an ecosystem, without understanding what emerges as a consequence of the interactions between the parts [5,6]. In recent decades, a new approach based on the study of social-ecological systems (SESs) through the lens of complexity has gained attention [7]. The idea of resilience in ecological systems introduced by Holling [8] led to the development of the 'adaptive cycle' as a representation of the dynamics of coupled ecological and social systems, and of the 'panarchy' as the interaction between multiple adaptive cycles across different levels of scale [9]. More recently, Fath, Dean and Katzmair [10] proposed a modified version of the adaptive cycle to provide additional insights into the navigation of change in social systems. The SES perspective emphasises the intertwined nature of ecological and social systems [7,11], offers new methods for the study of SESs that are consistent with the idea of complexity, and are useful for exploring different

management approaches [12,13]. Analysis of complex system relations has been used to support management approaches, for example in urban systems [14–17]. Using the adaptive cycle and panarchy as metaphors for analysing change in SES recognises the dynamics of self-organising complex systems and the interactions between nested systems at different scales while maintaining a conceptual simplicity that helps understand processes of change and adaptation [9]. In the present study, the adaptive cycle and panarchy were used to assess the dynamics of La Marjaleria, a marshland area located on the east coast of Spain (Western Mediterranean) that has been subjected to a number of social and ecological changes during its recent history. The use of the adaptive cycle and the panarchy is expected to help improve the understanding of the multi-level dynamics of the area and offer new points of view, as in previous studies [18–25]. Furthermore, and considering the plurality of the existing complementary materials to present the results of adaptive cycle and panarchy assessments [19,22,24,25], a new graphical method to present the results is explored and tested in a La Marjaleria case study. Specific aims of the study were to (i) apply the adaptive cycle and panarchy to explore changes in La Marjaleria from a complex systems perspective; and (ii) develop a new graphical method for presenting the results of a panarchy-based assessment that enables an integration of the time dimension across scales. Since the conventional management approaches used to date in La Marjaleria have been ineffective in tackling past and present social and ecological problems [26], the adaptive cycle and panarchy were applied to obtain new insights and to uncover systems dynamics relevant to support decision-making and sustainable development.

2. Theoretical Background of the Adaptive Cycle

The adaptive cycle reflects system dynamics in four phases associated with growth, maintenance, collapse and renewal that occur in two loops. Holling [9,27] named these phases exploitation (r) when the system experiences rapid growth driven by high availability of resources and openness to new opportunities; conservation (k), when growth stops and the focus turns to efficiency; release (Ω), when a shock causes loss of identity and breaks apart the different components of the system; and re-organisation (α), when new configurations and components of the system emerge after the shock, creating opportunities for adaptation and reconfiguration. Holling [9] also developed a conceptual graphical representation of these phases of change through a figure known as the "lazy eight" model (because of its similitude with the infinity symbol) of the adaptive cycle.

During the fore-loop (r and k phases), the system grows in complexity and organization of connections (flows of matter, energy and information) between components, leading towards a stable state. During the back-loop (Ω and α phases), the system falls apart as the connections are broken, releasing the components and resources, making them available again for a new period growth. The system may grow as it was before if it is resilient. Alternatively, the parts of the system may be lost, or new parts may be added, and a new system of novel components and connections emerges from parts of the old. The combination of fore-loop and back-loop in the adaptive cycle illustrates how systems persist over time (i.e., their resilience) or how they evolve over time to become a different system. The duration of each phase of the adaptive cycle is influenced by the cross-scale interactions between systems nested within the panarchy. Previous research on the adaptive cycle and panarchy has primarily been descriptive and abstract, although its value for understanding complex systems for management purposes is growing [18–25].

The studies performed to date usually explore the dynamics of a system by developing a historical timeline of major events and mapping them onto the adaptive cycle as a starting point for understanding the dynamics of the focal system, as influenced by the interactions between its sub-systems and the larger environment. The Resilience Alliance [28] published an assessment guideline comprising eight different steps: (1) definition of boundaries of the focal system; (2) identification of the main issues; and (3) the key components of the system; (4) factors of change; and (5) exploration of further time and space scales. This information is then used to (6) build an adaptive cycle model and (7) explore any changes of state that

may have occurred in the focal system, together with their thresholds and transitions. The focal system assessment is complemented with an assessment of the dynamics of the upper and lower scales in order to (8) explore the cross-scale interactions and their effects in the focal system.

In some case studies, the results of the assessment are described in words, while others present complementary diagrams [22,24,25] or tables [19]. These complementary materials facilitate presentation and interpretation of the results, but are quite diverse. Moreover, while the adaptive cycle and panarchy enable users to capture the essence of system dynamics, it can be difficult to integrate changes over time across the different scales of the panarchy. Therefore, a variety of representation tools that can be applied to different assessment cases and different systems are needed to present the results of an SES assessment using the panarchy.

3. Materials and Methods

3.1. Case Study: La Marjaleria, Spain

La Marjaleria is located on the east coast of Spain, in the municipality of Castelló de la Plana (Figure 1). This area has experienced social and ecological tensions in recent decades, driven by its management, land use, ecological status and vulnerability to natural hazards [29].

Figure 1. Location of the La Marjaleria study area in the municipality of Castelló de la Plana, Spain.

Transformation of the former wetland to agricultural use started in the 14th century and advanced slowly while providing a livelihood for many generations of farmers, who historically adapted their techniques and crops to the terrain and to a growing population by learning how to work with water as part of the system [30,31]. However, major changes began to occur during the early 20th century, when the whole area was parcelled and sold for agricultural use, with new farmers entering the area without local knowledge or a sense of care [32]. This led to the emergence of rice and other irrigated cropping systems, achieved through intensive management practices. During the 1950s, economic changes at

national and global levels associated with industrial development in nearby areas reduced the attractiveness of agriculture in the La Marjaleria area [33]. Other changes at the local level, such as a growing population, improved quality of life and increasing attractiveness of the coast, led to further subdivision and sale of agricultural plots at high prices, and unleashed informal (illegal) occupation of the area [29]. This unregulated urbanisation process lasted for more than 20 years and affected most of La Marjaleria [34].

By the end of the 20th century, residential land use reached 3 houses/ha [26], and therefore the area was administratively considered a suburb of Castelló city [34]. At that time, some problems related to the unregulated urbanisation emerged, which impacted both the social and ecological subsystems: (1) lack of adequate energy grid, causing frequent energy shortages; (2) lack of sewage system and treatment, triggering groundwater contamination; (3) increased extraction of groundwater and aquifer depletion, causing terrain subsidence; (4) degradation of the irrigation network and land fragmentation caused by construction of roads, buildings and fences; and (5) introduction of ornamental plants and domestic pets in residential areas, including invasive species [29]. In addition, the unregulated occupation of the former wetland created a recurrent flooding hazard [29].

In order to address these problems, in 2006 the municipality sought to improve the liveability of the La Marjaleria area through major investments in infrastructure and services, but this attempt failed due to the global economic crisis. Nowadays, around 3000 houses co-exist in La Marjaleria, surrounded by the remaining small-scale irrigated subsistence agriculture, which proved unable to compete economically with industrial farming within the region, and an ecological system that is suffering the impacts of the unregulated urbanization process. The municipality is currently working on a second management plan to tackle social and ecological issues in La Marjaleria, allowing humans and nature to co-exist [26], but the administrative, social and environmental situation in the area is still far from being resolved and its future remains unclear. A simplified storyline of changes in the area is presented in Figure 2.

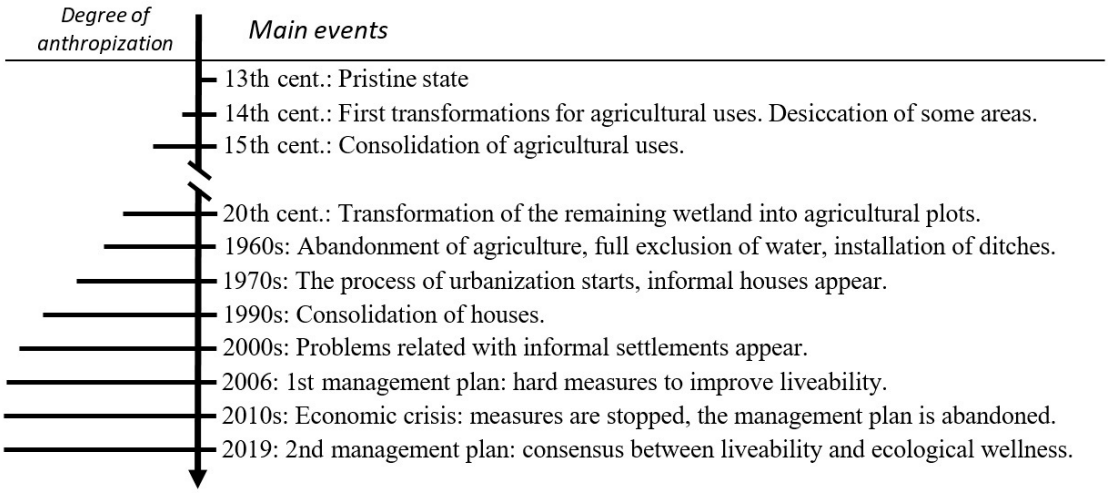

Figure 2. Timeline of socio-economic and environmental changes in La Marjaleria, Spain.

For the purposes of the SES assessment of La Marjaleria, the time boundaries of the system were defined by the historical record from the 14th century (Figure 2). Prior to 1950, La Marjaleria was agricultural land and major policy changes from 1950 onwards disrupted the former structure and function of the previously stable arable landscape. Definition of the spatial boundaries of the SES was based on a combination of the historical record of the wetland area ecological boundaries and the recent social planning boundaries in which land use transformation took place. The total area of the SES is 7.8 km^2, distributed at 2–7 m a.s.l.

3.2. Adaptive Cycle and Panarchy Methodology

The adaptive cycle and panarchy were used to analyse changes in the study area following the Resilience Alliance practitioners' guide [28], departing from the information collected for the system's storyline through a process of a scientific and official (government) literature review. The eight methodological steps comprise Sections 1.1–3.1 described in the guide [28]; however, they were reduced into five for operational purposes, as follows:

(1) Definition of the SES. This includes the main storyline of the system and the definition of the spatial and temporal boundaries of the focal system. This corresponds with Section 1.1 of the Resilience Alliance's guide [28].
(2) Initial exploration of the focal system dynamics. Specific information about the changes in the system over time and the causes of those changes was extracted from the storyline and was highlighted. This represents the foundation for subsequent adaptive cycle and panarchy analysis. This corresponds with Sections 1.2 and 1.3 in the Resilience Alliance's guide [28].
(3) Definition of levels of scale in the system. After exploring the system's history and identifying the most relevant drivers of system change, corresponding changes are structured into levels above and below the focal level. This represents Section 1.4 in the Resilience Alliance's guide [28].
(4) Construction of a mental model of change using the adaptive cycle. Major events during the history of the focal system representing different phases of change (r, K, Ω and α) were mapped on the adaptive cycle. In this study, we mapped changes on the adaptive cycles that represented each level of the panarchy. This step corresponds with a modification of Section 2.1 in the Resilience Alliance's guide [28].
(5) Interactions between the panarchy levels. In order to understand the relationship between the adaptive cycles at different levels of scale identified in step (4), the impact of changes recorded in each level on the overall system was investigated. The aim was to understand how system dynamics were conditioned by each level's dynamics and affected the state of the focal system. This corresponds with Section 3.1 in the Resilience Alliance's guide [28].

A new tool to present the results of the adaptive cycle-panarchy assessment was developed (Figure 3), by incorporating the time variable in a graphical approximation of the "Lazy eight" model [9] to illustrate how a system moves through the four phases of change (r, K, Ω and α) over time. The illustration is based on a three-dimensional adaptive cycle of three variables [9]: "potential for change" ("range of future options" [9]), "connectedness" ("internal controllability of a system" [9]) and "resilience" ("adaptive capacity" [9]), reduced to a two-dimensional model with time on the horizontal axis and the inverse relationship between connectedness and resilience reported by Allison and Hobbs [20] on the vertical axis. The "potential for change" variable can be deduced [9] to be higher in the late k or α phases, and to fall dramatically when the system shifts to Ω or r phases. We consider that this arrangement, which we named the "adaptive curve", maintains the essence of the adaptive cycle.

The adaptive curve (Figure 3) illustrates how the system moves through the different phases of the adaptive cycle, with ascending slopes representing the fore-loop (phases r and k) of the adaptive cycle, descending slopes representing the back-loop (phases Ω and α) and the inflection points on the curve representing transitions between fore- and back-loops. The horizontal time arrow on the centre of the y-axis separates phases with low resilience and high connectedness (phases k and Ω) from phases with high resilience and low connectedness (phases r and α). The upper limit of system growth is represented by a horizontal line labelled "carrying capacity", and the lower limit of system collapse is represented by a horizontal line labelled "loss of potential". The adaptive curve thus illustrates cycle of growth, collapse and renewal over time.

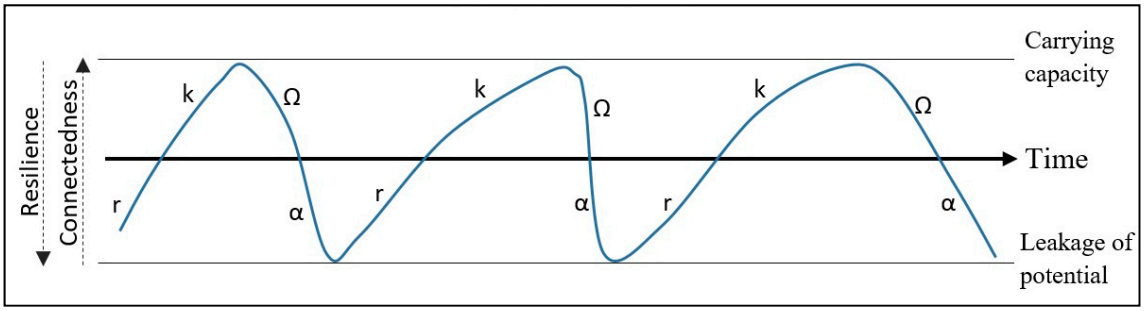

Figure 3. Explanatory diagram of the 'adaptive curve', including the four phases (r: exploitation, k: conservation, Ω: release, α: re-organisation), the variables (resilience and connectedness), and the conceptual upper and lower limits of the system (carrying capacity and loss of potential).

Carrying capacity is determined by growth-limiting factors in social-ecological systems and "loss of potential" represents the leakage of resources from the system that takes place during a re-organisation phase [9,27]. The upper line is a conceptual representation of the limits to growth of any organic system and the lower line represents a point beyond which the identity and characteristics of the system are lost and the system enters a new degraded state. Neither line represents an absolute limit of the system, rather they may be interpreted as an approximation of the boundaries that will apply to any real system when studied.

The "length" of each phase on the horizontal axis indicates the approximate duration of that phase. The inflection points on the curve represent "deeper" or "shallower" navigations of the system through re-organisation and conservation phases, and thus the resilience and connectedness of the system. As with Holling's adaptive cycle and panarchy [9], the adaptive curve is a heuristic model designed to enable stakeholders in a system to develop a qualitative understanding of systemic change over time.

In this study, the definition of the different phases of the adaptative cycle, the establishment of the limits of the system and the proposed adaptative curve model are based on a literature review of historical and current changes in the social and environmental systems in La Marjaleria.

4. Results

Departing from the storyline presented in Section 3.1, the adaptive cycle and panarchy were applied to develop a mental model of change in La Marjaleria over the past 70 years.

4.1. Mapping the History of System Change on the Adaptive Cycle

Given the history of the La Marjaleria, residents were regarded as the primary component of the subsystem and the local and national government authorities were regarded as the primary component of the larger environment within which changes in La Marjaleria's land use occurred. Actors at both levels were responsible in different ways for land use changes in the recent past. Residents started the process of urban sprawl, unleashing the land transformation and the associated impacts onto La Marjaleria, and the authorities were responsible for the land use planning and the legal and administrative management of the area. These actors still retain high capacity to influence the current situation and future changes in the system.

The assessment of system dynamics is summarised in Tables 1–3. Because of difficulties in setting exact dates, historical changes in the system were described for broad periods. Table 1 summarises the dynamics of the focal system, departing from the stable mature agricultural system (k phase), which collapsed (Ω phase) due to economic reasons and loss of profitability [32,33], the land abandonment and emergence of new land uses (α phase) during uncontrolled and growing urban sprawl period (r phase) [29,34]. The urban land uses were consolidated with the administrative brake to the urban sprawl (k phase) after the 1990s, leading to a regime shift [26].

Table 1. Summary of the different phases of change identified in La Marjaleria and mapped on the adaptive cycle.

Phase No.	Adaptive Cycle Phase	Event or State	Period	Description
0	k	Consolidated agricultural system	1950s	Agriculture is the foremost land use and the main livelihood of local farmers.
1	Ω	Agricultural collapse	Mid 1960s	Abandonment of agricultural activity due to limited profitability. Degradation of the agricultural systems.
2	α	New land uses emerge	1960s–1970s	Houses self-built by the landowners appear. A new market based on land sales develops.
3	r	Residential expansion	1970s–1990s	Land sales bring new people and houses, leading to rapid transformation of the area. Urban sprawl proceeds.
4	k	Urban consolidation	1990s–present	Urban sprawl ceases. Concerns about lack of urban infrastructures and services emerge. Social and physical networks develop.

Table 2. Adaptive cycle phases of change in national and local government (the upper level of the panarchy) that influenced change in La Marjaleria.

Phase No.	Adaptive Cycle Phase	Event or State	Period	Description
0	k	Traditionalist society, autarky	Until 1950s	Governance based on self-sufficiency and traditional values, agriculture is the core of the economic activity for national subsistence.
1	Ω	Crisis of the national economic model	1950s	Self-sufficiency policies create an economic crisis at national level; the agriculture-based economy is no longer profitable.
2	α	Reformism (period of transformation)	Early 1960s	Opening of borders to foreign investments; the economic model is based on industrialisation and services such as tourism and leisure.
3	r → k	Economic growth	1960s–1970s	Reformism generates a period of economic growth and social transformation; the "American way" is imposed and a strong middle-class appears.
4	Ω → α	End of dictatorship (transition period)	Late 1970s–1980s	The dictatorship ends and democracy emerges, bringing a process of social, institutional, administrative and political transformation at national level.
5	r	Consolidation of democracy and emergence of the new society	Late 1980s–1990s	Democracy is fully operative, public institutions recover their management capacity and start tackling pending issues.
6	k	Institutional stability	2000–2008	Period of administrative, social and economic prosperity, with liberalism and land speculation as economic motor.
7	Ω	Economic crisis	2008–2010	Global economy collapses, high unemployment and social discontent emerge. Liberalism is blamed. Period of economic austerity experienced at all levels.
8	α	Social movements	2010–2012	Massive social actionsarise from discontent with politicians and liberalism as causes of the crisis. New visions of social unity appear. The political panorama changes radically at the national level.
9	r	The new era of sustainable cities	2012–present	The new political approach based on social responsibility and sustainability brings new management values and ideas.

Table 3. Adaptive cycle phases of change in the social system (the lower level of the panarchy) of La Marjaleria social-ecological system.

Phase No.	Adaptive Cycle Phase	Event or State	Period	Description
0	k	Agricultural economy	1950s	The inhabitants are farmers earning their living from agriculture.
1	Ω	Crisis of agriculture	Early 1960s	Economic reforms associated with the global market reduce the profitability of small-scale agriculture. Old people continue to farm while young people seek employment in the city.
2	α	Pursuit of new economic opportunities	Late 1960s	Consolidation of new economic sectors in industrial and services reconfigures the relationship between people, land and economy. Majaleria residents can work in the city and landowners in seek new ways to use the land.
3	r	New land uses emerge	1970s	Young former residents of La Majaleria become resident in the city where they work. With external income sources and consolidation of a new culture of leisure, the area becomes desirable for low-density housing. The first summer houses are built (illegally) by wealthy people from the city.
4	k	Intensification of residential use	1980s	As demand for houses increases, owners start dividing and selling their parcels at high prices. New neighbours arrive and residential use intensifies.
5	Ω	Problems of urban sprawl appear	Early 1990s	The high concentration of housing creates environmental problems. Legal issues of housing development are addressed for the first time by the authorities.
6	α	Social union of the households	Late 1990s	Neighbours organise themselves in associations to defend their interests, align their property development with the law and bring urban infrastructure to the area.
7	r	Infrastructural improvements start	2000–2008	The municipality responds to social concerns by developing a management plan. The social service infrastructure is provided for the first time to improve the living conditions for residents and summer house owners.
8	k	Brake on the system	2008–present	The management plan is abandoned due to the economic crisis. The problems of urban sprawl remain to be addressed by a second management plan.

The upper level of the panarchy describing La Marjaleria as an SES included dynamics related to external management of the system by government and society at the local and supra-local levels (Table 2). Departing from Franco's autarchic regime (k phase), it involved an initial period of economic crisis (Ω phase, late 1950s), followed by a period of openness to foreign investment (α phase, 1960s–1970s) that generated economic prosperity (r and subsequent k phase) [35]. The end of the dictatorship (Ω phase, 1970s) caused by Franco's death and a rising social movement against authoritarian regimes [36] ended up with the emergence of democracy in Spain (α phase, late 1970s–1980), which entailed social and institutional transformation at the national level, and that coincided with a period of prosperity (r and subsequent k phase, 1980s–2000s) [35,37]. However, the global economic crisis in 2008 led to a new period of collapse (Ω phase), followed by new ideas (α phase) and management principles (r phase) based on long-term sustainability (2010s).

The social subsystem of La Marjaleria is regarded as the lower level of the panarchy in this social-ecological assessment. This includes the individual and collective behaviours of neighbours and households, and how their relationship with the area has developed over time (Table 3). Departing from the stable agriculture economy (k phase), the most remarkable changes came with abandonment of agriculture (Ω phase) and subsequent urbanisation (α and subsequent r phase) driven by national level economic reform in the 1960s, its consolidation (k phase) and the appearance of administrative, social and ecological problems (Ω phase), and the neighbors' response through civil unrest and associations (α phase) [29], which caused the implementation of the management plan (r phase) that finally could not be effectively implemented (k phase).

4.2. Using the Panarchy and Adaptive Cycle to Illustrate Cross-Scale Interactions

After assessing the dynamics of each level through the adaptive cycle (Section 4.1), a cross-scale analysis was undertaken to explore interactions between the scales to illustrate how changes in scales conditioned the evolution and current state of the focal system. The panarchy was developed by plotting the adaptive curve of each level (Figure 4). The vertical arrows in Figure 4 represent the most relevant cross-scale interactions affecting the trajectory of change at other levels of scale.

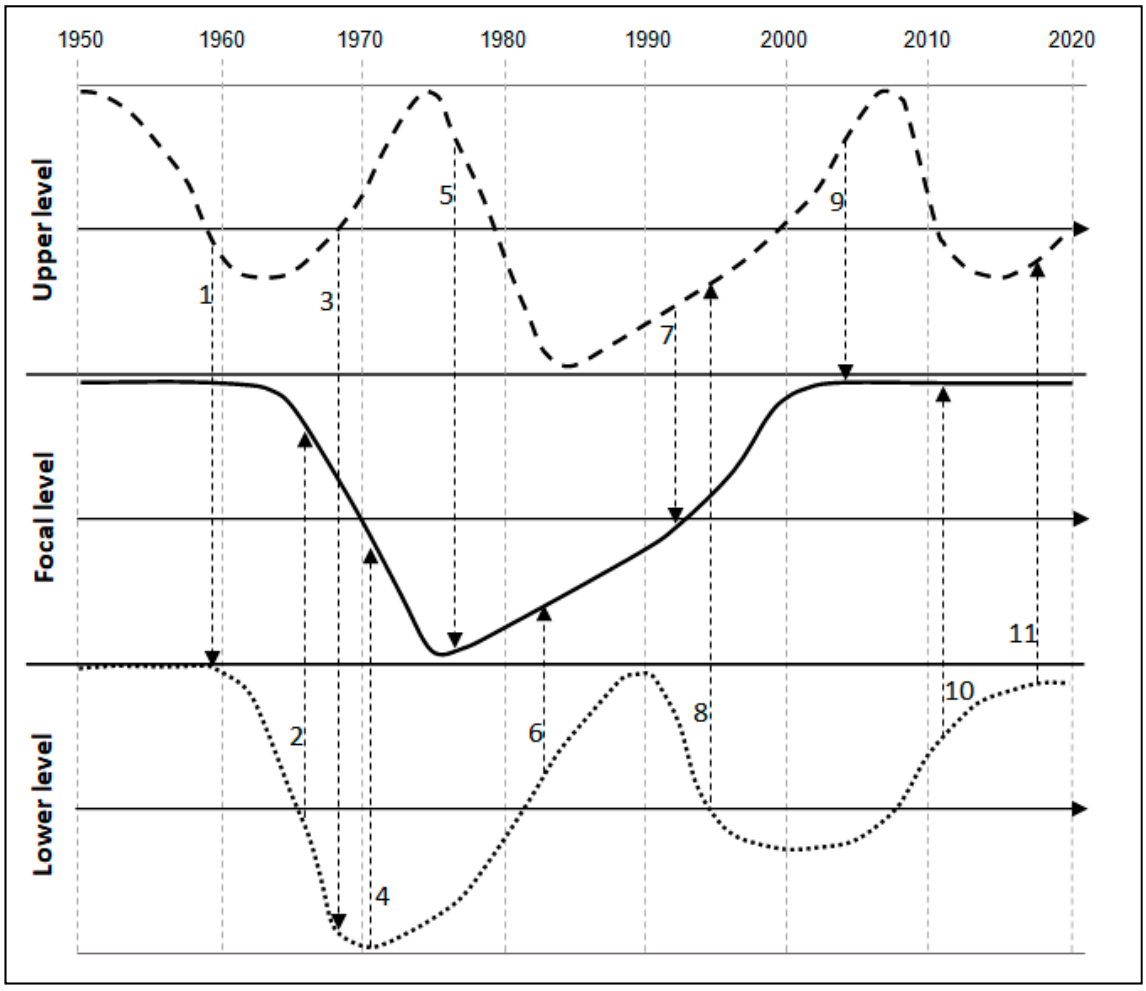

Figure 4. The adaptive curves that illustrate changes and cross-scale interactions in the social-ecological system assessment of La Marjaleria. The numbers beside the vertical arrows indicate the order of interactions between levels.

In 1950 La Marjaleria was in a conservation phase, characterised by the existence of a stable, consolidated and efficient agricultural system. The first shock occurred with the collapse of the national economy, forcing changes in economic policy that caused small-scale farmers to lose profitability and abandon their farms in late 1950s (arrow '1' in Figure 4). Abandonment of farms represents a release phase in the focal system (arrow '2'). The new economic opportunities that emerged from the economic reform in 1959 (upper level) brought changes in the social system involving a greater emphasis on individual wellbeing and a culture of leisure and consumerism that became evident from 1965 onwards (arrow '3'). These new social conditions translated into a new appreciation of the La Marjaleria area based on its desirability for housing driven by its proximity to the sea, its rural character and its lack of recognized economic or productive value by landowners.

The first houses in the area were built by local landowners, triggering the beginning of a transformation process (arrow '4'). Urbanisation was slow and discrete at the beginning, but collapse of the dictatorship in 1975 and subsequent institutional and administrative reform at the national level created a window of opportunity for the growth of urban sprawl, as the government lacked the means to prevent unplanned development of the area (arrow '5'). Landowners obtained revenue through sub-division and sale of their properties to foreigners seeking a summer house in the area. Unregulated subdivision and summer house construction created a new identity of the area (arrow '6').

As the new administrative organisation of the government and the democratic institutions were consolidated after the dictatorship (Table 2), the government slowly recovered its ability to control development in La Marjaleria. Urban expansion was stopped and the land uses were stabilised during the 1990s (arrow '7'). The ecological degradation (e.g., the over exploitation and contamination of groundwater and the introduction of invasive species) became evident, and the government developed a management plan for the area. Householders, through neighbourhood associations, took an active part in shaping the management plan and safeguarding their interests (arrow '8' in Figure 4). The management plan finalised in 2006 aimed to provide major investment in social service infrastructure to improve the living conditions for residents and summer home owners in La Marjaleria (arrow '9'). However, with the global economic crisis in 2008, implementation of the management plan was abandoned and conservation of the area was determined by households (arrow '10'). The municipality is now working on a new management plan, in collaboration with local neighbourhood and citizen associations (e.g., AA.VV. La Marjaleria, Associació d'Amics de la Marjal de Castelló) through participatory processes (arrow '11'). The municipality expects the new plan to consider both social and ecological subsystems, for the long-term sustainability of the area.

5. Discussion

5.1. Understanding the Dynamics of La Marjaleria SES

Changes in La Marjaleria SES were highly conditioned by a strong top-down governance approach where changes at the lower and focal levels emerged in response to changes at the upper level and illustrate the effect of external drivers on social-ecological system dynamics [38]. Rigid top-down governance impedes development of adaptive capacity [39], adaptive governance [40] and creates vulnerability [41]. Despite the appearance of civil associations at the lower level, the existing structure does not address the dependency of La Marjaleria, maintaining the system in an "addiction trap" [42].

While hierarchical management played a prominent role in the development of the system in La Marjaleria, another determining factor was land ownership. An ownership model based on small-scale privately-owned plots facilitated transformation of the system, as it permitted fast and uncoordinated changes by individual property owners that spread rapidly across the whole system, illustrating the self-organising property of complex systems [42]. This ownership pattern, together with the planning law (Soil Regime and Urban Planning Law, 1956), which allowed construction of buildings for agricultural

purposes but not for residential purposes, enabled urban sprawl while obstructing the application of control measures. This example of cross-scale mismatch [43] illustrates how fast, small-scale changes can overwhelm the response capacity of the slower upper level, resulting in system change.

The combination of the strong top-down approach and the land ownership pattern established ideal conditions for transformation of the focal level once the upper level entered into the second back-loop and control mechanisms could not be applied effectively (Figure 4). At the same time, the top-down management policy prevented the learning and development of adaptive management practices such as installation of drainage and sewage treatment needed to address ecological degradation issues, and which eventually impacted the social system.

La Marjaleria entered a rigidity trap from 2006 when the government's management plan for development of infrastructures failed [29], and no bottom-up alternatives that could fill this management gap appeared. A rigidity trap undermines the general resilience of a system, as it diminishes the capacity to adapt to shocks [9] or smoothly navigate the adaptive cycle through continued innovation in response to external change [10]. Systems that have lost the capacity to respond can be regarded as brittle, or fragile and vulnerable.

Degradation of the ecological system (e.g., groundwater pollution, invasive species, loss of biodiversity, soil subsidence, eutrophication of surface water [29]) emerged as a major problem in La Marjaleria, which persists because of the rigidity trap. The rigidity trap also impacts the social system by preventing residents from legalising their homes and the development of social services and economic activities, and obstructs the ability of residents to self-organise and address social and ecological issues. An inability to self-organize ultimately reduces the capacity for adaptation to future shocks [44].

There is a high level of general discontent among La Marjaleria residents because of the inability of government to solve the legal situation of housing in the area and the continued degradation of the ecological system that increases flood risk with its associated economic and social impacts [29]. Although the new management plan aims to tackle most of these problems [28], it is not being applied yet and may not be sufficient without the support of residents [45].

While this study illustrates the potential of a systems assessment to provide a foundation for the design and application of new management approaches for La Marjaleria, the limitations of the study also need to be considered. These include the lack of on-site data collection and involvement of stakeholders in the description of the system's history and current state, which in this case were based solely on a bibliographical review. This can raise some subjectivity in the assumptions made regarding the periodization of the phases in the adaptative cycle. Involvement of stakeholders is of key importance in a SES analysis, as it enables a common understanding of the complexity of a system by planners, specialists and local residents, thereby reducing the tendency for "wicked problems" to occur as a consequence of incomplete knowledge or disagreements amongst stakeholders [12]. The development of such was beyond the scope of this study and should be addressed in future work.

5.2. Challenges in Use of the Adaptive Cycle and Panarchy

Use of the adaptive cycle and panarchy requires analysis of much information and identification of a representative set of variables to characterise a system's dynamics. According to Holling [9], the variability of a system can be effectively reduced to a handful of variables for management purposes. However, identifying these variables may be challenging and somehow considered subjective, and in this context the Resilience Alliance guidelines [28] can be helpful. Another difficulty in application of the SES framework to planning tasks is the definition of the "system". Complex systems are not fixed entities, but rather defined "ad hoc" in each case, which conditions the results obtained. This requires mindful consideration of the problem-solving nature of the panarchy [9], and careful application of the mental model that emerges from a collaborative assessment

process. The complex and dynamic nature of SESs require practitioners to monitor the outcomes and impacts of interventions in order to validate the effectiveness of their theory of change, and to apply an adaptive management approach [9,45]. During monitoring, it is necessary to have a transparent participatory process to ensure a relevant degree of representativeness of stakeholder diversity in the system and to help foster self-criticism and debate, laying the foundations for a better understanding of how the system changes in response to management. As mentioned in Section 5.2, this stakeholder involvement should be considered in further research to improve the application of the adaptive cycle and panarchy in the La Marjaleria case study.

5.3. Reflections on the Adaptive Curve

The 'adaptive curve' aims to capture the representativeness of the adaptive cycle phases in a system, while also accounting for change over time. Because of this, the same considerations that affect the adaptive cycle and panarchy also apply to the adaptive curve. It must be noted that the adaptive curve is not intended to be a model or a theory for system change, but a complementary tool to facilitate visualisation of the system's dynamics in the context of the adaptive cycle and panarchy framework.

In future work, the adaptive curve needs to be applied in other case studies for assessment of its usefulness in different contexts. For example, there may be challenges in the representation of systems in which navigation of the phases of the adaptive cycle does not follow Holling's "Lazy eight" structure [9]. There is also a risk of the graphic representation being interpreted as a quantitative diagram of the variables of resilience and connectedness represented on the vertical axis, although the comparison of the state of these variables in the system is merely qualitative, which might be confusing when comparing different representations for different systems. These limitations are denoted in the adaptative curve developed for La Marjaleria (Figure 4), whose representation can be considered subjective. The limitations need to be overcome in order to avoid misunderstandings and misinterpretations of the adaptive curve. Overall, the intended purpose of the adaptive curve is to facilitate an understanding and interpretation of the results obtained from SES assessments and to better support decision-making to enhance sustainable development.

6. Conclusions

Land transformation and associated social and environmental problems in La Marjaleria, Spain, were assessed using the adaptive cycle and panarchy. This systems analysis provided new perspectives on the historical changes in the SES of La Marjaleria, highlighting the importance of interactions across the scales of nested complex systems and their influence on the direction and rate of change of the system. The adaptive cycle and panarchy can support the design of management interventions that recognise these interactions and enhance the ability of managers to avoid undesirable change in a system, or to transform a system which is in an undesirable state.

Use of the adaptive cycle and panarchy to assess the status and trends of an SES is challenging for non-experts and requires a sound understanding of the system being assessed, and the application of concepts of systems thinking. The Resilience Alliance guidelines [28] offer useful directions for assessments, even by non-experts. We developed the 'adaptive curve' as a complementary tool for illustrating cross-scale interactions and their influence on system change over time. It is designed to present schematic and synthesised information, as a complement to written descriptions. However, further research and testing are required to determine whether this usefulness extends to different SESs.

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