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Opinion

Challenges in Restoring Mediterranean Seagrass Ecosystems in the Anthropocene

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Abstract: The intense human pressures in the Anthropocene epoch are causing an alarming decline in marine coastal ecosystems and an unprecedented loss of biodiversity. This situation underscores the urgency of making ecological restoration a global priority to recover degraded ecosystems. Meadows of the endemic Mediterranean seagrass *Posidonia oceanica* have lost more than half of their original extent in the last century, necessitating immediate conservation and management measures, supported by active restoration interventions. This paper explores new opportunities and provides specific recommendations to enhance restoration as a fundamental strategy for reversing the decline of *P. oceanica* ecosystems in the Mediterranean Sea. When a return to a historical pristine reference condition may not be feasible in the short term or desirable given current environmental conditions and uncertainty, transplanting the tolerant and fast-growing seagrass species *Cymodocea nodosa* could facilitate natural recolonization. This would occur through secondary ecological succession, benefiting the sensitive and slow-growing species *P. oceanica*. Future global and local efforts should primarily focus on proactive management to prevent further alterations by planning appropriate conservation measures in a timely manner to mitigate and reverse global changes. As a secondary step, restoration programs can be implemented with a focus on 'target-oriented' rather than 'reference-oriented' conditions, aiming to establish ecosystems capable of sustaining the future rather than replicating the historical environment.

Keywords: seagrass active restoration; reference conditions; target conditions; regime shift; phase shift; *Posidonia oceanica*; *Cymodocea nodosa*

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1. Introduction

Multiple human pressures are exerting a widespread impact on marine ecosystems globally [1], resulting in a concerning loss of biodiversity. Seagrass meadows, identified as priority coastal habitats, are particularly susceptible to these pressures. Their conservation is imperative to preserve the ecosystem goods and services they provide to humans. The global challenge of seagrass loss over the past century raises significant concerns, reflecting issues such as poor water quality, increased sedimentation and nutrient runoff due to coastal development, direct habitat destruction, physical damages from illegal fishing practices, and the impacts of climate change, including thermal anomalies and a rising sea level [2,3]. The Mediterranean Sea stands out as one of the most exploited regions in the world's oceans [4]. Meadows of the endemic seagrass *Posidonia oceanica*, which holds paramount importance in the Mediterranean, have experienced a substantial decline over the last century, with more than half of their original extent lost [5]. Thanks to enforced global measures (e.g., the European Habitat Directive, 92/43/EEC) and local initiatives (e.g., marine protected areas) implemented in recent decades, *P. oceanica* meadows have displayed encouraging signs of stabilisation or even recovery [6].

The United Nations recently launched the UN Decade on Ecosystem Restoration (2021–2030), with the goal of fostering international collaboration to restore degraded ecosystems. This approach does not replace environmental conservation but seeks to facilitate the natural regeneration of ecological components in overexploited ecosystems, with the aim of restoring biodiversity, functions, services, and capacity to fulfil human needs.

Environmental restoration can be broadly categorised into passive or active practices [7]. Passive, or natural, restoration primarily focuses on unassisted habitat maintenance and management to mitigate human pressures, enabling spontaneous recovery after disturbances are removed. However, given the high human pressures on coastal ecosystems, current passive conservation initiatives may no longer be sufficient to arrest or reverse trajectories of change ([8] and references therein). Severely degraded ecosystems might struggle to recover within a reasonably short timeframe. In support of conservation and management efforts, actively assisted restoration has experienced rapid growth since the 2000s. This approach involves direct human interventions to expedite the recovery of biological communities at a local scale, such as planting and rearing species on specific receiving sites. Given the slow natural recolonization of *P. oceanica* due to the low growth rate of rhizomes and limited sexual reproduction, active restoration is strongly recommended to counteract its decline [9].

2. Challenges in Restoring Seagrass Ecosystems in the Anthropocene

While seagrass meadows globally are experiencing ongoing decline, opportunities for recovery are emerging in certain areas due to nature- and management-driven variability [10]. Where signs of natural recolonization are observed, active seagrass restoration measures may be implemented to aid in ecosystem recovery [11].

Examining the original definition of ecological restoration, which aims to "return an ecosystem to a close approximation of its condition prior to disturbance by reestablishing pre-disturbance functions and ecosystem processes, and related physical, chemical, and biological characteristics, and allowing reintroduction of indigenous species" [12], it is evident that the primary goal is undeniably the restoration of the ecosystem to its pristine reference state. However, contemporary environments shaped by human activities often exhibit significant changes in biophysical conditions, referred to as regime shifts, leading to profound alterations in the ecosystems' state, known as phase shifts. In instances of strong regime and phase shifts, the possibility of reverting ecosystems to their previous state is diminished [13], and the pristine reference state becomes an idealised goal [14]. Attempts to restore irreversible losses to their former historical condition are likely to be challenging or even impossible [15].

Therefore, any restoration plan should aim for 'target-oriented' rather than 'reference-oriented' conditions, focusing on the re-establishment of ecosystems capable of sustaining the future, not necessarily replicating the historical environment [16]. In a world characterised by continuous change, the imperative is to develop robust novel ecosystems that can perform effectively [14]. Additionally, the return to historical references assumes an almost unlikely static configuration of nature and stability in ecosystems. Ecosystems and biological communities undergo constant changes in response to environmental variability and species interactions. What was observed in the past may not necessarily be replicated in the future. In the Anthropocene, ecosystems are strongly influenced by disturbance, heterogeneity, and the existence of multiple stable states [17], aligning with the non-equilibrium perspective of the new 'Ecology of Change', which has replaced the old 'Equilibrium Ecology' developed in the twentieth century.

While achieving past reference conditions may prove impractical, gaining insight into the historical variability of ecosystems is invaluable for understanding trajectories of change and predicting the future arrangement of ecosystems. This knowledge is essential for establishing specific targets that replicate some observed states from the past. Without a comprehensive understanding of both the baseline condition of species and habitats and the causes of their degradation, identifying achievable restoration targets and assessing restoration success can be challenging [8]. Historical data for seagrass meadows are scarce and are often affected by the sliding-baseline syndrome [18], hindering an accurate estimation or conception of the true extent of loss in certain areas [19].

3. Exploring New Opportunities for *Posidonia oceanica* Restoration

Successful restoration interventions are feasible only in environments with sustainable ecological regimes and where major pressures, including those arising from climate change, are effectively mitigated [20]. The contextual factors, such as the degree of human pressures and habitat type, in which the restoration activity is implemented, prove more critical for achieving success than the methodology employed [8]. According to an expert judgement procedure [21], certain factors are deemed essential in the initial selection of a suitable site for restoration, namely (i) threats, encompassing activities that have damaged ecosystems (e.g., anchoring and pollution); (ii) logistic factors, including permit request and proximity to donor sites; (iii) abiotic factors (e.g., suitable substrates); and (iv) socio-economic factors (e.g., support from stakeholders). Biotic factors are considered desirable, including the historical presence of the species, connectivity among populations (i.e., the presence of natural corridors), and control over predation and invasion by competing and alien species. Suitability modelling for seagrass restoration is emerging as an effective and widely adopted method for identifying environmentally suitable restoration sites [22,23].

What is the sustainable target for *Posidonia oceanica* restoration projects? While returning to the pristine reference condition is often challenging, there has been a history of inappropriate transplanting operations of *P. oceanica* at sites where the species has never been present before [24]. Recognising the need for feasible, target-oriented interventions, proactive management becomes essential to prevent further alterations. This involves planning timely and appropriate conservation measures to mitigate and reverse the effects of global change.

The Ligurian Sea (NW Mediterranean) serves as an iconic marine region where *Posidonia oceanica* meadows have lost about half of their original extent since the mid-19th century due to intense coastal development [25]. Since the 1980s, the decline has slowed down due to enforced conservation actions, and recent years have shown signs of natural recovery, especially in marine protected areas [26]. These positive developments pave the way for promising active restoration interventions [27]. Clearly, de-artificialising the Ligurian coastline is not a viable solution to address the main causes that triggered the disappearance of and ecosystem shifts in many *P. oceanica* meadows [28]. Therefore, alternative solutions must be considered where the original environmental regime cannot be restored, and multiple alternative trajectories of change may lead to unpredictable endpoints [16].

The other common Mediterranean seagrass, *Cymodocea nodosa*, is a ruderal species [29], demonstrating lower sensitivity to environmental degradation compared to other seagrasses. While *P. oceanica* has experienced a significant decline in the Ligurian Sea, *C. nodosa* has consistently increased over time, mirroring the positive trend observed in artificial structures along the coastline [25]. As a pioneer species in the primary ecological succession of *P. oceanica* [30], *C. nodosa* rapidly colonises soft sediments, a creating favourable environment for the settlement of *P. oceanica*.

A reconstructive restoration strategy aims to reintroduce a substantial portion of the desired habitat, potentially mimicking natural successional dynamics [7]. The restoration of a degraded *P. oceanica* meadow to its original pristine state may be somewhat unrealistic. Priorities should shift towards supporting ecosystems that demonstrate greater resistance and resilience to environmental changes and disturbances, even if they represent a modified version of the desired state [31]. Strategic transplantation of *Cymodocea nodosa* should be carefully planned in coastal areas where significant regime shifts have occurred and cannot be promptly reversed. This approach aims to enhance the natural recovery of *P. oceanica* through secondary ecological succession.

Evidence also suggests that *C. nodosa* thrives in warmer sea waters [24]. Its seeds germinate rapidly, and meadows grow quickly, making it an ideal species for restoration in the Anthropocene. Understanding the natural evolution of degraded ecosystems should be mandatory for planning successful restoration interventions. Embracing the role of *C. nodosa* in the secondary succession of *P. oceanica* requires a shift in perspective, moving beyond the restoration of a single species to a comprehensive ecosystem-level approach. Recognising the importance of addressing the complexity of ecological interactions across systems is crucial in this attempt [8].

4. Final Remarks

In the current Anthropocene scenario, characterised by rapid environmental changes, our management efforts and conservation endeavours should prioritise the development of more resilient ecosystems for the future, proposing innovative and practical strategies for their restoration [32]. Historical reference conditions must be considered in light of the challenge of restoring degraded ecosystems to reset ecological processes to defined pre-disturbance conditions. Caution is necessary when designing restoration interventions aimed at rebuilding past ecosystems where irreversible regime shifts have occurred.

In the context of seagrass restoration, the challenges of space and time persist. Many studies remain experimental, focusing on small spatial and temporal scales. The majority of seagrass restoration projects in the Mediterranean Sea have addressed relatively small areas (usually <1 ha, spanning a few hundred meters), failing to match the large scale of human disturbance. A broader restoration scale, at the seascape level [33], has been theorised to be advantageous for overcoming the stochasticity associated with a variable environment and providing a critical mass to enhance positive density-dependent feedback, initiating self-facilitating processes [34].

Most of the literature focuses on the short term, typically ranging from one to five years [24] and references therein, with longer-term studies being comparatively rare [35]. Achieving certainty regarding the success of restoration interventions for the endemic Mediterranean seagrass *Posidonia oceanica* remains an ongoing challenge. Furthermore, for restoration to be successful, it must effectively re-establish ecosystem functions and services to enhance human well-being [36,37]. This emphasises the imperative for consistent, long-term monitoring—spanning more than decades—to comprehend the trajectory of restoration, evaluate the effectiveness of methods and procedures, consolidate results, and perceive the recovery of ecosystem services. Additionally, local populations can play a pivotal role in supporting adaptative management through public engagement and citizen science initiatives [14].

While the restoration of degraded ecosystems is seen as a solution to mitigate the impacts of climate change [38], the success of restoration efforts faces challenges from extreme events like heatwaves [39] and severe storms [40]. Seagrass restoration programs will be implemented in the context of a rapidly changing climate, under a projected scenario of increased intensity and frequency of extreme climate events, along with an increased likelihood of pathogen outbreaks in a multi-hazard situation [41].

It is crucial to acknowledge that, in certain locations, managing multiple pressures may be insufficient to prevent additional seagrass loss. Investing time and money in restoration programs in these areas could be counterproductive, especially considering that seagrass transplanting is the most expensive restoration method globally [24]. We cannot deceive ourselves into thinking that planting millions of seagrass shoots and investing a substantial amount of money in this strategy will resolve our environmental problems. To achieve the goals of the UN Decade on Ecosystem Restoration, projects will require careful planning and feasible designs, adaptive and inclusive approaches, and proactive management to maximise their success relative to costs. It is imperative not to delay real solutions that prevent further damage to the remaining healthy and resilient seagrass meadows.

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