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Rebuilding coral reefs: does active reef restoration lead to sustainable reefs?

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The coral reefs worldwide are exposed to multiple anthropogenic threats and persisting global change impacts, causing continuous degradation, also calling for the development of novel restoration methodologies. Of the most promising emerging approaches, deriving its rationale from silviculture, is the low-cost 'gardening concept', guided by a two-step restoration operation: (a) mid-water nursery phase, where coral-nubbins are farmed and (b) transplantation of nursery-farmed colonies. Tested worldwide, at least 86 coral-species and over 100 000 colonies were successfully farmed in different archetype nurseries, and several novel transplantation methodologies were developed. A number of unanticipated emerged outcomes were the immediate establishment of coral infaunal biodiversity in nurseries, the development of nurseries into 'larval dispersion hubs' and the enhanced reproduction of transplanted coral colonies. Altogether, and in addition to envisaged results (e.g., high survivorship, fast coral growth), results attest that the gardening-toolbox could serve as a ubiquitous ecological engineering platform for restoration on a global scale.

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Introduction

The ominous status of coral reefs worldwide and active reef restoration

Once acknowledging the vital ecological importance of coral reefs and their fundamental roles in sustaining hundreds of millions of people, it is dismaying to realize that over the last four decades ca. 40% of the global coral-reef system has been lost, a process galloping at 1–2% per year [1], not considering the developing global change impacts that are exacerbated by severe anthropogenic pressures. Thus, coral reefs, while exhibiting exceptional species diversity, are poorly protected, highly degraded, and exposed to multiple persisting and envisaged threats [2,3]. The stressors, and notwithstanding all traditional conservation management measures implemented [4], would lead to loss of up to 70% of reef area within four decades or to phase shift [1].

The above causes that have led to progressive impairment of the normal course of coral-reefs life and their global contribution to humans, without proper damage control or repair, have prompted the demand for alternative active reef restoration measures, beyond the traditionally employed conservation. Restoration is defined by the Society of Ecological Restoration as 'the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed' [5]; it has also been acknowledged that restoration activities may complement [6], even substitute conservation efforts. Whereas the restoration rationale is rooted in active approaches to solve ecosystem degradation ('Ecological restoration is an engaging and inclusive process'; [5]), conservation biology endeavors preservation, counting on long-term ecological succession as the major repairing mechanism for impacted ecosystems. The literature documents that ecological restoration is a fast developing scientific discipline. Heeding the invaluable lessons gathered from the failures of traditional conservation, the declaration of the Convention on Biological Diversity that restoration of terrestrial, inland water and marine ecosystems is essential for rehabilitating the ecosystem's functioning, goods and services [6], confirms the wide scientific support of ecological restoration efforts. In fact, the extent of anthropogenic and global change impacts on coral reefs worldwide renders their active restoration as a major conceptual and practical approach, not just as assistant act to traditional conservation acts [4,7,8].

Restoration practices for degraded reefs can be broadly categorized into passive or active restoration [4,7,8]. Active restoration, or active human intervention in degraded reef sites, disputes passive restoration, the dependency on natural regeneration and repair with minimal human surrogacy. Indeed, when analyzing globally employed passive restoration measures, it is evident that the reef management acts have been imperfect, failed to ascertain the right responses to key threats, failed to yield a quantifiable return and are ineffective in ameliorating long-term impairments [summarized in 4,7,8]. More pressing is the realization that regardless of

Figure 1

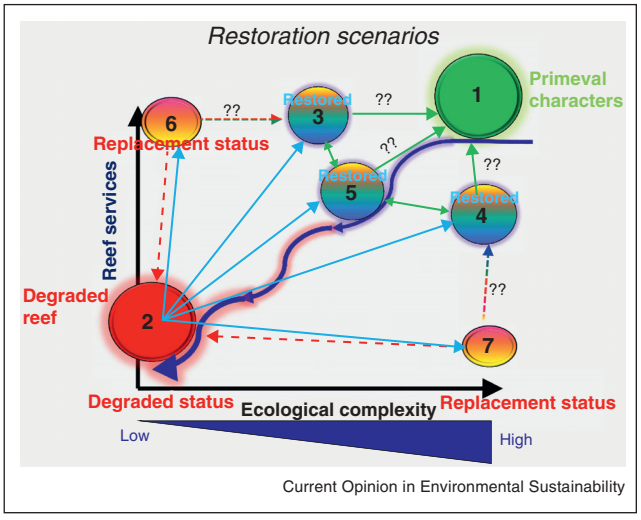

Figure depicts multiple 'restored reef-state' scenarios (circles no 3–7) showing paths from a degraded reef (low ecological complexity and minimal reef services; circle 2) toward a healthy reef (circle 1), passing through two types of unsuccessful measures (circles 6, 7) and several restored status (circles 3–5). The unsuccessful measures represent attempts **(a)** aiming to boost reef services (such as installing artificial reefs for fisheries; circle 6) or whole colonies transplantation acts [9] and **(b)** aiming to increase biodiversity, such as the concept of 'assisted colonization' [10•] (circle 7). In both scenarios it is more likely that reef environments will revert to their degraded status than advance toward a better state (marked by question marks). Three different scenarios employing the 'gardening concept' [4,7–9,12••,13,14,15•,16–23] are defined. These may result in rehabilitated reefs at different complexity/reef services states (circles 3–5) that could develop into other states and possibly (question marks) will culminate with the primeval reef status.

the implication of either practice, the restored 'reefs of tomorrow' will be different from the current or past reefs' constructions (Figure 1).

The gardening tenet

Several approaches for active restoration have been suggested; some have been subjected to intensive research manipulations. One of the first advocated methodologies was the direct transplantation of coral material (entire coral colonies and/or fragments), an approach subjected to a wide range of limitations and pitfalls, such as negative impacts on donor reefs and on transplanted coral colonies [8,9]. A comparable, more recent approach is the controversial tool of 'assisted colonization' or 'managed relocation' [reviewed in 10•], claiming active translocation of groups of species outside the species' historic range for conservation purposes.

One of the most promising active restoration approaches is the 'gardening concept' [4,7–9], which has surfaced as a means to avoid the pitfalls associated with the traditional management for coral reefs (e.g., reduced negative impacts on donor reefs, high survivorship of transplanted coral colonies, improved state of health of transplants, year round availability of transplants). This strategy, which derives its rationale from silviculture, is guided by a two-step restoration operation. The first step entails rearing stocks of small coral fragments in specially designed mid-water floating nurseries, and upon reaching suitable sizes, applying the second step, the transplantation of nursery-farmed coral colonies onto denuded reef areas. As restoration ecology is rooted in forestation, it is therefore not surprising that silviculture principles, concepts and theories, are intermingled within the 'gardening' notion and its associated activities. During the almost two decades from their first presentation [9], the two gardening tenet steps have been tested in various reefs worldwide (Table 1 discusses the nursery step; studies performed in the Red Sea, Thailand, Singapore, Philippines, Tanzania, Mauritius, Seychelles, Caribbean sites [Jamaica, Florida keys, Colombia, Belize, and more], Japan, Taiwan, Hawaii; much of the outcomes is still unpublished [3,11,12••,13,14,15•,16–23]).

The nursery phase of the 'gardening concept' has been drawing the most scientific investigation, conceptually and technically addressed in detail, with at least 86 coral species farmed in underwater nurseries, worldwide (117 species when total farmed species in all nurseries is considered, Table 1; only species from literature and personal communication are listed). Issues, such as nursery structure, nursery types, nursery's set-up, shape and construction, nursery location, maintenance subjects, coral species cultured (types, numbers) and genotypic considerations, spacing of farmed coral colonies, realistic number of generated and farmed colonies, duration of the nursery phase, growth rates of farmed corals, longevity of farmed colonies, pest control and economic considerations are some of the topics studied recently. The second phase of transplantation, which is still in its infancy, has also revealed promising results ([12••,13,14,15•], unpublished). The major conclusion which emerged from the above studies is that the application of active restoration protocols may enhance reef recovery [4,7,8].

The results obtained from various reefs worldwide cumulatively have revealed that the gardening tenet, with modifications and adjustments per local conditions, can be used as a ubiquitous management instrument for rescuing reefs from the on-going degradation (Box 1).

What has been learnt recently from nursery/transplantation acts?

Studies [11,12••,14,15•,16–23,24•] have already revealed that farmed corals not only compete successfully with natural colonies' performance, but also exhibit improved health status, being free of parasites and diseases (developed and maintained under controlled conditions), with