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Concept Paper

Climate Change and Active Reef Restoration—Ways of Constructing the "Reefs of Tomorrow"

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Abstract: The continuous degradation of coral reef ecosystems on a global level, the disheartening expectations of a gloomy future for reefs' statuses, the failure of traditional conservation acts to revive most of the degrading reefs and the understanding that it is unlikely that future reefs will return to historic conditions, all call for novel management approaches. Among the most effective approaches is the "gardening" concept of active reef restoration, centered, as in silviculture, on a two-step restoration process (nursery and transplantation). In the almost two decades that passed from its first presentation, the "gardening" tenet was tested in a number of coral reefs worldwide, revealing that it may reshape coral reef communities (and associated biota) in such a way that novel reef ecosystems with novel functionalities that did not exist before are developed. Using the "gardening" approach as a climate change mediator, four novel ecosystem engineering management approaches are raised and discussed in this article. These include the take-home lessons approach, which considers the critical evaluation of reef restoration outcomes; the genetics approach; the use of coral nurseries as repositories for coral and reef species; and an approach that uses novel environmental engineering tactics. Two of these approaches (take-home lessons and using coral nurseries as repositories for reef dwelling organisms) already consider the uncertainty and the gaps in our knowledge, and they are further supported by the genetic approach and by the use of novel environmental engineering tactics as augmenting auxiliaries. Employing these approaches (combined with other novel tactics) will enhance the ability of coral reef organisms to adaptably respond to climate change.

Keywords: climate change; reef restoration; gardening; connectivity; nursery; transplantation; coral repository; environmental engineering; planulae; stepping stones

1. Introduction: Advocatus Diaboli (the Devil's Advocate)

Globally, coral reef ecosystems throughout the tropics have been progressively damaged in the last century by a wide range of direct anthropogenic pressures, including over-exploitation, physical destruction, pollution, eutrophication, sediment loads from agricultural and urbanized terrestrial catchments and coastal development. On top of that, the last few decades have seen exacerbated sways of climate-change associated impacts, such as elevation of seawater temperature, extreme weather events, ocean acidification and intensifying tropical storms that cause, for example, enhanced frequency and intensity of mass coral bleaching e.g., [1–11]. Together, the above drivers directly or indirectly influence coral survival, coral growth rates, reproduction efforts, larval development and settlement, and post-settlement survivorship/development of corals [11], damaging reef ecosystems' health and resilience and reducing species abundance. The literature further attests to the decimation of key reef-building coral populations, to a dramatic shrinkage in global reef structural complexity and that many reefs experience phase shift phenomena (e.g., [3]), in addition to reefs that are continuously changing in unprecedented ways towards new ecosystem configurations and novel reef compositions that did not exist before [4]. As the major emerging sources of global reef degradation, such as coral bleaching, seawater acidification impacts and coral diseases, interact synergistically and also in concert with local/regional anthropogenic specific stressors, among them pollution, eutrophication, sedimentation, coastal development and overfishing, augmentation of existing climate change impacts is anticipated [5]. Taking the aforementioned discussion into consideration, it may seem futile to address local/regional anthropogenic impacts if global changes appear unavoidable. Thus, the need to specifically offset or mitigate the impacts of global change on vulnerable coral reef ecosystems is emerging as a high priority.

The overall degradation of coral reef ecosystems, observed on a global level, is impressive. The coral coverage in the Caribbean has been declining in the last decades by ~1.4%·year^{-1}, from ~55% in 1977 to the current ~10% average coverage [6,7], outpaced by the current rate of decline in the Great Barrier Reef, which was evaluated over the last three decades as 0.53%·year^{-1} but has increased substantially, starting from 2006, to an average rate of ~1.51%·year^{-1} [8]. Not only are coral mortality rates escalating, but the concurrent dramatic decline in coral growth rates is striking as well. Coral calcification has diminished by 15%–30% since ~1990, due to increasing thermal stress [9,10], and estimations have forecasted further decreases of up to 78% due to the greenhouse gas concentrations predicted for the year 2100 [11].

Climate change impacts are difficult to evaluate as they represent highly complex trajectories. As an illustration, corals may respond to climate change with natural range expansion into areas that are nowadays deprived of coral reefs. The Japanese coral reefs are a good example, since they have extended their range northward in the last eight decades at rates of up to 14 km/year in response to rising sea surface temperatures, generating novel northern reef structures [12]. This migration rate is of an order of magnitude greater than the average natural expansion records that exist in the literature, including records of terrestrial species [13]. Similar trends were recorded in the Caribbean species *Acropora palmata*, which is expanding its geographic distribution ranges northward along the Florida Peninsula and into the northern Gulf of Mexico, concurrent with increasing seawater temperatures [14,15]. These natural coral range expansions allow reef dwelling invertebrates [16] as well as reef fish species [17] to extend their distribution ranges northward as well. These expansions may somehow be considered a mitigation of the impacts of global changes. On the other hand, predictions of climate-linked expansions in response to changes in seawater temperatures may not come to pass if the potential new latitudinal distribution sites would prove unfavorable to coral growth due to unrelated environmental factors, such as substrate availability, high sedimentation load or reduced light e.g., [18]. Furthermore, there are fears that climate-linked expansions might encourage the development of devastating biological trajectories, like the appearance of invasive species [19] and the emergence of epidemic diseases [20]. Clearly, the stochastic situations and the complexity of the ecological interactions that are developing between donor and recipient ecosystems in climate-linked site expansions may render irrelevant any expectation generalized from the limited examples known. This contradicts any ecological engineering approach for re-population of a given habitat that is customarily equipped with milestones and deliverables. Natural processes are far more difficult to foretell on both spatial and temporal scales, and human experience acquired on one site may not be relevant elsewhere [21].

Thus, what should we do in the face of the disheartening forecasts and the gloomy expectations for future reefs' statuses? The original and basic goals of all traditional reef management measures have been basically rooted in the rationale of mitigating local (this is less valid for regional or global) impacts. While aiming concurrently to reverse reef decline and strengthen the resilience of coral-reef ecosystems, the traditional reef management approaches are now acknowledging, more than ever, the notion that it is unlikely that future reefs will return to historic conditions [4]. Hence, despite all the traditional conservation management practices implemented [22,23], global change impacts will most probably lead to the loss of up to 70% of the existing reef area or to worldwide phase shift phenomena within four decades [24].

2. Active Reef Restoration—The "Gardening" Tenet

The failure of the conservation acts traditionally employed [22,23,25] has prompted suggestions of alternative effective reef management and reef rehabilitation approaches aiming to complement, even to substitute, conservation efforts. Probably the most effective among these approaches is the "gardening" concept of active reef restoration [23,26–29]. Based on principles, concepts and theories from silviculture, the "gardening" concept is centered on a two-step restoration act (the nursery phase and the transplantation phase). The first step involves the development of large stocks of coral colonies in mid-water floating nurseries; each of the farmed colonies is created from a coral nubbin. The second step entails the transplantation of nursery-farmed coral colonies that have reached suitable sizes onto degraded reef areas. In the almost two decades that passed since its first presentation [26], the "gardening" tenet was tested in a number of coral reefs worldwide, with more than 86 coral species that were successfully raised in various nursery prototypes, and it was further supported by assorted novel tested transplantation acts (Figure 1, [23]).

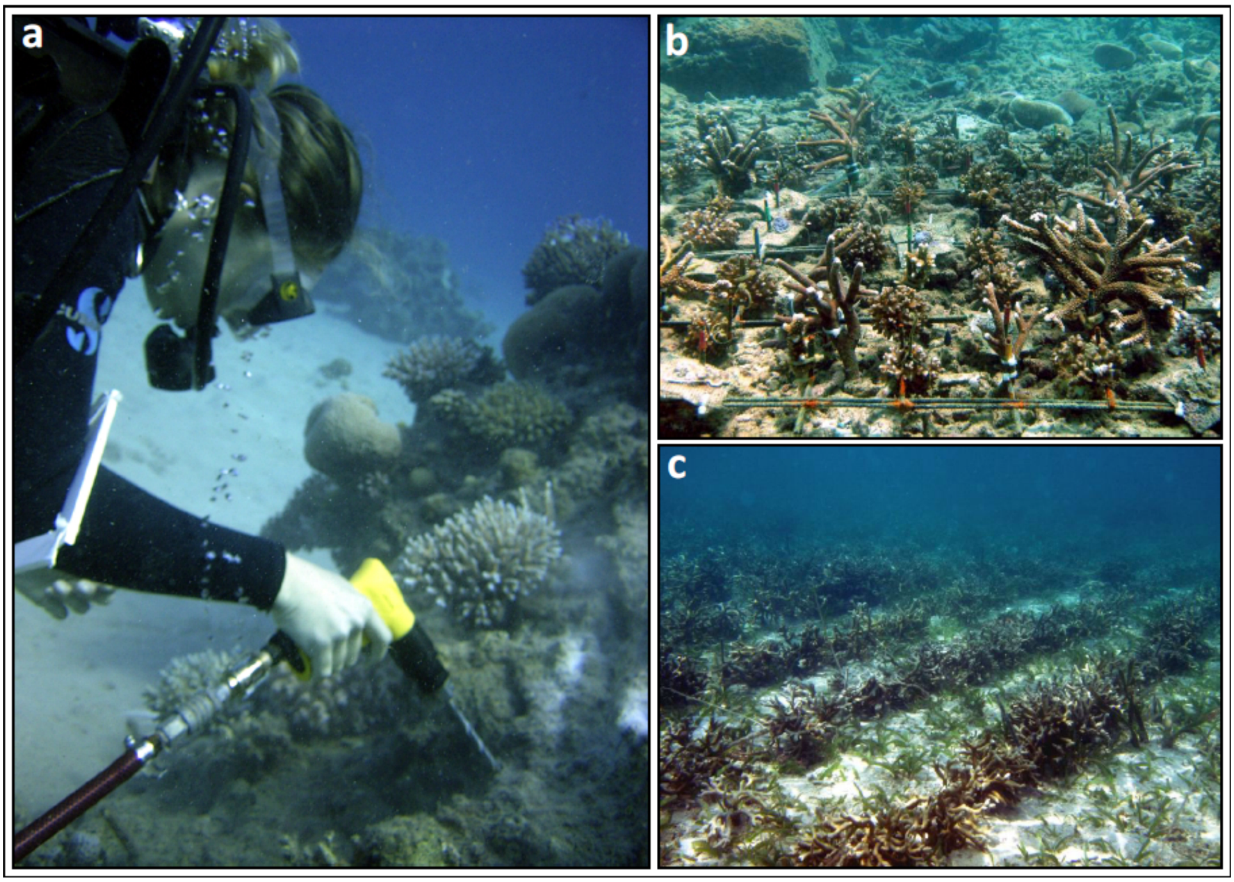

Figure 1. Part of the transplantation protocols associated with the "gardening" tenet of reef restoration. (**a**) Transplanting coral colonies from Eilat's nursery (the Red Sea, Israel) onto hard substrate. The plastic pegs covered with the farmed coral colonies (6–9 cm diameter each, initiated from 1 to 2 cm fragments that were nursed for 8–14 months) were manually cleaned of fouling organisms using scrub sponges and scratching tools and cemented into pre-drilled holes (made by pneumatic drills powered by pressured air from SCUBA cylinders) at fixed distances of 20 cm. This new transplantation practice enabled coral attachment on horizontal as well as vertical substrates, allowing maximum transplantation coverage of the target area without any required prior preparation of the substrate, while inflicting a negligible impact on substrates adjacent to the transplants (photograph by Y. Horoszowski-Fridman). (**b**) Transplantation of nursery farmed corals on rubble: Iron meshes (20 × 20 cm holes), usually used for cement floors, were each cut into 1 × 1 m square units and immobilized by iron bars inserted at each of the four corners and a single centered bar. Several units were put next to each other on the sea floor to create larger transplantation areas. Metal segments measuring 4 cm were cut out of the mesh bars, leaving 8 cm on each side, and then the last 3 cm of the left bars were bent upwards vertically to create a "peg", leaving 10 cm distances between the "pegs". Corals were tied to the pegs using cable ties (photograph by G. Levi). (**c**) Transplantation of "rope nursery" [30] corals onto soft bottoms in Thailand: The ropes carrying the farmed coral colonies were cut into 2 m long segments, laid on the soft substrate and connected to pre-inserted iron bars by cable ties, preventing excessive movement. The figure presents sparse transplantation where the ropes were put in parallel to each other, at 50 cm distances (photograph by G. Levi).

The specifically developed tool-box applications of the "gardening" concept have already shown ([23,27,31–34] and unpublished) that active reef restoration may reshape coral reef communities (and associated biota) in such a way that novel reef ecosystems, with novel functionalities that did not exist before, may be developed. Clearly, the function of such novel reef ecosystems could deviate markedly (through elements such as species compositions, biodiversity, engineering capacities, goods and services) from that of existing reef systems; they may still provide the same valuable goods and services to society, or perhaps offer different ones.

3. Active Reef Restoration—An Applied Tool for Mitigation of Global Change Impacts

In practice, mitigating the impacts of a local/regional stressor might be a more straightforwardly achievable goal than mitigating global change impacts that seem to be inevitable [5]. Climate change impacts, while they are mounting novel threats to coral reef ecosystems, also pose challenges for innovative conservation retorts. Given the substantial alternations already recorded in reef-ecosystems worldwide, it may be advisable to evaluate the tool-box developed for reef restoration (based on forestation in terrestrial habitats; [35,36]) in order to discover how active reef-restoration methodologies [23,26–29] can be harnessed to ameliorate the impacts of climate change in a new approach—Developing the novel "reefs of tomorrow".

It was already suggested [23] that the active reef restoration approach can serve as a ubiquitous ecological engineering platform for actions performed on a global scale, using tools that incorporate selected ecological engineering aspects (e.g., [33,37]) and ecological engineers. As allogenic and autogenic ecosystem engineers are particularly susceptible to global climate change [38], assessing the prospective effectiveness of the engineering capacities in reef restoration necessitates a comprehensive understanding of the engineering capabilities of this approach and of the ways corals function as primary reef ecosystem engineers. The "gardening" concept may further harness the capabilities of other coral reef species (fish and invertebrates) that respond differently to a range of climate global change drivers (e.g., by increasing/decreasing their relative distributions), thus contributing differently to future reef ecosystems [39,40]. Hence, it is suggested here that the future of coral reefs, on the local, regional and global levels, may depend on the specific restoration acts employed, some of which definitely use various "ecological engineering" tools. As an example, the simple act of enhancing a population turnover within administrated reef ecosystems may, in turn, considerably augment coral resistance to diseases, a reef destruction driver that is directly associated with global change and other anthropogenic impacts [41]. Thus, the leading rationale for using active reef restoration as an applied tool for global change mitigation should be based on the notion that "restoration efforts once focused on past conditions should become more forward-looking" [42].

4. The "Gardening" Approach as a Climate Change Impact Mitigator

Global climate changes are expected to impose ever increasing challenges to traditional coral reef maintenance measures, and to novel approaches such as the "gardening" tenet as well [31]. Many aspects of the gardening approach and of active reef restoration are still in their nascent stages [23]. Thus, while dealing with climate change scenarios, two "gardening" logics can be formulated. The first is to refrain from the use of coral species/coral genotypes that are less tolerant of climatic conditions in favor of using coral material that would withstand the anticipated climate change conditions better [23]. This approach, indeed, deals with the construction of novel coral reef communities (on the species and the genetic background levels) that are more impervious to global change conditions [43,44] but do not necessarily reflect the coral assemblages in existing coral reefs. The second logic calls for maintaining the highest available genetic coral diversity in nurseries, including endangered and threatened species that are seemingly "less tolerant" to climate change drivers. For any scenario, when harnessing the "gardening" tenet as a climate change impact mitigator, the following four management approaches can be considered:

4.1. Take-Home Lessons

As more medium and large scale restoration acts are activated, valuable take-home lessons will accumulate. A unique example is a study performed in Bolinao, the Philippines, on a reef restoration operation that used nursery farmed coral colonies and coral transplants over the course of two years (Table 1; [31]). During this relatively short period, two sets of nursery farmed coral colonies (>6800 and >5400 corals colonies from 7 and 8 coral species, respectively) and a single transplantation event (*ca.* 1200 colonies from 6 coral species) were generated. All of these activities were severely influenced by series of environmental catastrophes/stressors that included an extremely tempestuous southwesterly monsoon season, record precipitation (causing mass coral mortality in transplants), a category "4" typhoon, two super-typhoons, three regular typhoons, two tropical depression storms and a combined event of elevated seawater temperature, unusually low tide and high radiation, which caused mass coral bleaching in transplants and nursery farmed coral colonies [31]. These severe weather events have resembled forecasted future scenarios associated with global change impacts [1,2] and, as expected, increased mortality and reduced growth were recorded in both nursery settings and transplants (Table 1; [31]). In spite of these losses, several important take-home lessons were learned, altogether providing insights into how to withstand global change impacts and how to improve the yield of coral nurseries and the survivorship of transplants [23,31]. For the nursery phase of the "gardening" approach, improved nursery management tactics, such as the possibility of lowering the nursery bed into deeper water during critical periods (storms, increased water temperatures/irradiation doses) in order to reduce the effects of environmental forces, could prevent mortality/bleaching in nursery farmed corals, impacts recorded simultaneously in naturally growing shallow water colonies (unpublished). Also, as mortalities of nursery farmed corals display species-specific and genotype-specific rates [31,32], choosing more robust genetic variants and more resistant species is an important key step in the road to success (see below). For the transplantation phase of the "gardening" approach, transplantation of nursery farmed corals during favorable periods of the year and in habitats that support coral growth (e.g., avoiding fresh water seepages [31]) may dramatically increase survivorship.

Table 1. Two years of follow-up outcomes of coral reef restoration activities (based on the "gardening" concept) in Bolinao (the Philippines), in the face of frequent natural catastrophes that represent anticipated global change impacts (following [31]). CN = coral nurseries; CT = coral transplantation; SWM—South-west monsoon.

Date	Restoration Act	Environmental Catastrophe/Stressor	Major Monitoring Outcomes
August 2005	Populating CN; >6800 fragments		High survivorship of fragments
September	Monitoring CN		Normal coral growth in CN
October	Monitoring CN		Normal coral growth in CN
November	Monitoring CN		Normal coral growth in CN
December	Monitoring CN		Normal coral growth in CN
January 2006	Monitoring CN		Normal coral growth in CN
February	Monitoring CN		Normal coral growth in CN
March	Monitoring CN		Normal coral growth in CN
April	Monitoring CN		Normal coral growth in CN
May	Monitoring CN	Category "4" typhoon (*Caloy*)	Increased mortality and colony detachments in nursery farmed corals
June	Monitoring CN		Post typhoon reduced growth in CN
July	Preparation for CT		
August	CT, about 1200 colonies	Heavy precipitation causing seepage of fresh-water from reef ground	Mass mortality (*ca.* 50%) of transplants near freshwater seepages
September	CN repopulated; >5400 fragments	Rough SWM season starts	
October		SWM season; super-typhoon *Paeng*	Extremely tempestuous season causing mass mortalities in CN and transplants
November	Monitoring transplants	SWM season; super-typhoon *Reming*	Variable mortalities at specific site locations
Dec	Monitoring CN		Still impacts from the last typhoon
January 2007			
February	Monitoring transplants		Survivors grow well, reduced mortality
March	Monitoring CN		Normal coral growth in CN
April			
May	Monitoring transplants		Survivors grow well, reduced mortality
June	Monitoring CN	Unusual elevated seawater temperature, extreme low tide and high radiation	Major bleaching event. Increased mortalities. Significant high partial mortalities in CN and transplants. Reduced growths
July	Monitoring CN and transplants		Many colonies recovered the bleaching.

4.2. Genetics

Corals reveal species-specific and genotype-specific tolerance and growth capabilities under different environmental stressors (e.g., [31,32]), many of which are genetically controlled. The genetic variation of coral populations has already been acknowledged as a potential reservoir of resilience to climate change conditions [23,44]. The genetic repertoires presented by marine organisms at any specific time/location further possess also variants that are not perfectly adapted to current environmental settings but would be better suited to future environmental conditions, as these variants underwent some adaptation processes (resulting in characteristics such as resistance to high seawater temperatures [44]). A newly revealed potential source of "climate change adapted" coral material is those coral colonies that survived environmental insults (e.g., high temperature events, mass coral bleaching [31]), where modified levels of genome epigenetics increase tolerance to otherwise lethal conditions, carrying stable epigenetic changes across multiple generations [44,45].

Thus, whenever possible, efforts should be made to choose the right genetic/epigenetic variants from the natural populations that showcase a wide range of "positive" alleles and epigenetic changes. It should nevertheless be noted that very little is known about the ways genotypic variations are generated [44] or about how genetic variance and genetic repertoire influence adaptive global changes competency [46,47]. Yet, when identified, valuable genetic variants can be actively amplified through the "gardening" approach by farming coral genotypes under *in situ* nursery conditions in the various types of nurseries that were already developed and tested [23]. While this was not tested yet under controlled conditions, variants that are resilient in the face of global change impacts can go through specific breeding programs in the nursery that will further increase the distribution of "resilience alleles" in coral transplants.

4.3. Repository for Coral and Reef Species

Public zoos and aquaria may be used as a special tool in preserving biodiversity. However, while the number of threatened terrestrial species saved from extinction by zoos is low [48], the "gardening" approach, primarily the use of underwater coral nurseries, may be further considered under the "Noah's ark" paradigm as genetic repositories for local species [49]. Thus, coral nurseries may be used for a wider range of purposes than just the traditional tool to supply reef-managers with coral colonies for reef restoration [23,50].

Coral nurseries could be used as genetic repositories for future coral reef restoration acts, combating the impacts of major natural catastrophes and creating climate refugia [49] for dominant and rare reef species. This approach would be essential primarily for rearing rare coral reef species that, though highly vulnerable to habitat loss and climate change like other rare species [51], may consistently support functionally important, distinct and vulnerable reef ecosystem performances, as was demonstrated for rare reef fish species [52]. Thus, "to protect species that are locally rare, since they tend to support the more vulnerable functions and increase the level of functional diversity within communities" [52] necessitates the development of novel ecological engineering approaches that address rare species maintenance alongside reef restoration acts. Furthermore, rare/less abundant species under current reef conditions may be the species of choice for reef restoration under future conditions, as already forecasted for terrestrial reforestation [53], an effective and adaptive forward-looking climate change response-strategy.

It has already been documented that floating coral nurseries, in addition to introduced farmed coral colonies, can provide habitat for a wide range of native species assemblages (including other coral species), all successfully recruited from plankton [50]. Thus, the novel ecological engineering approach is the employment of mid-water coral nurseries as a biodiversity management instrument (one that is not used for terrestrial nurseries), harnessing the outcome, e.g., the development of these nurseries into floating ecosystems, essentially "oases" of life in the blue waters. The different mid-water coral nursery prototypes that were in use for prolonged periods of several years have developed ecological sustainability characteristics, due to continuous introductions of reef associated organisms, such as herbivorous species, coral dwelling organisms, coral symbionts, coral colonies, fish and invertebrates [50,54]. Thus, when inserting these developing "floating reefs" into protected locations, such as deeper depths during major storms or bleaching events, as well at a distance from shallow near-shore coral reefs that are pruned to withstand anthropogenic impacts, these floating reefs, with their biological contents and when carefully maintained, can be developed into repositories and active depositories of coral species and other reef biota (e.g., [49]). This would preserve and enhance the species/genotypic diversity of depleted reef assemblages for any future need, including reef restoration measures, aimed at boosting coral reefs' resilience. It is our view that the use of coral nurseries as active depositories for coral reef assemblages is superior to other suggested notions, for example assisted colonization [55], or to the use of high-latitude coral reef communities as climate change refuges for vulnerable tropical coral reef species [56]. Furthermore, the opportunity to develop nurseries into small refugia for reef assemblages will insure the conservation of species with unknown but potentially key ecological functions, such as the "Sleeping Functional Groups" [57] that may efficiently enhance coral-reef recovery.

4.4. Ecosystem Engineering

Considering the interactive and synergistic bearings of global change with other local/regional stressors on reef organisms [58], the acclimation and adaptation mechanisms of the impacted corals, as efficient as they may be, may not be sufficient or fast enough to cope with the projected sum impacts, resulting in a critical ecological state that necessitates active human intervention [23]. Following this rationale, the "gardening" tenet, equipped with the tools developed for coral farming and transplantation, may serve as a unique platform for employing novel environmental engineering tactics, in addition to the abilities reef corals display as key allogenic (intensively generating and transforming inorganic and organic materials) and autogenic (changing the biogeochemical services of associated habitats through colonial astogeny) reef ecosystem engineers [38].

Two such ecological engineering approaches will be outlined in the following discussion. The first approach focuses on the use of coral nurseries as hubs for coral larvae production, with the aim of enhancing larval seeding and recruitment in impacted reefs or reefs that suffer from reduced recruitment (Figure 2a; [59]). Small fragments of the model branching coral *Stylophora pistillata* were cultured in a mid-water floating nursery situated in Eilat, in the Red Sea. Results revealed that after two years in the nursery, these fragments developed into gravid colonies the size of five-year old naturally growing colonies, with circa 35% more oocytes/polyp than in colonies from the reef, and that they released amounts of planula larvae equal to (or even larger than) corresponding natal colonies. Moreover, nursery-born planulae possessed more zooxanthellae, contained more chlorophyll per larva and developed larger young colonies. The research appraisal [59] was that a coral nursery could generate tens of millions of planula larvae during the reproductive season. When towed upstream to impacted reefs, such a nursery, upon releasing these larvae, could be regarded as a "larval dispersion hub" to be used as a novel management tool for enhanced natural seeding of coral larvae [59]. Another practice related to the engineering of coral reef larval supply [33] was developed based on coral transplants (the second phase of the "gardening" approach). Results ([33] and unpublished) showed that nursery grown transplant colonies displayed better reproductive capacities than the natal colonies for at least 8 years post-transplantation. This was reflected by the higher percentages of gravid transplants that shed more planulae/colony, yielding significantly augmented numbers of total planulae compared to naturally grown/natal colonies. These results further illuminated the unexpected novel engineered larval dispersal instrument developed for reef rehabilitation with nursery-farmed coral colonies, which further enhances reef resilience by a multi-year supply of planulae ([33] and unpublished 8 years post transplantation results in the Red Sea). Moreover, by combining the two practices described above, one can transplant nursery-reared colonies precisely at the onset of the reproductive season, so that larvae shed at transplantation sites still benefit during their various growth stages from the advantageous conditions at the nursery, augmented by larvae released by transplants in the following reproductive seasons, altogether subsidizing/intensifying local reefs' recruitment rates.

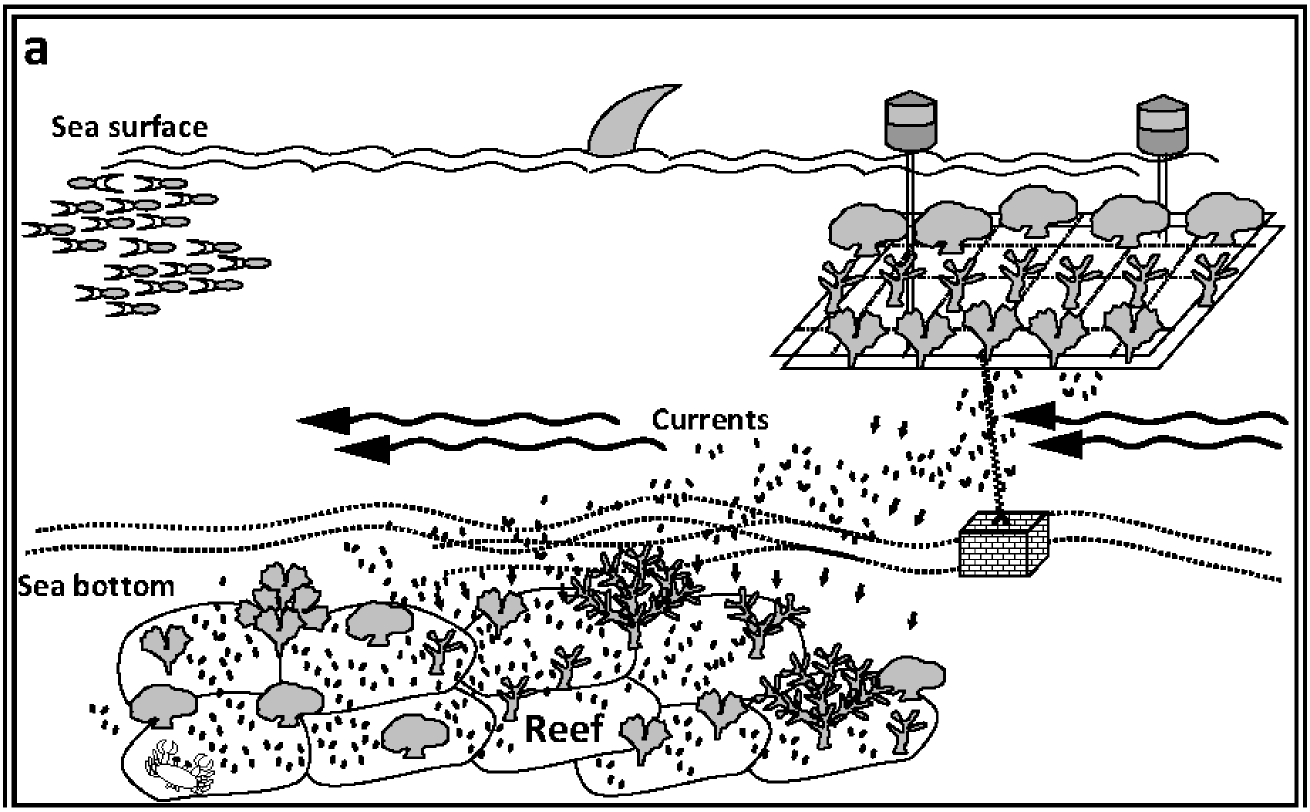

Figure 2. *Cont.*

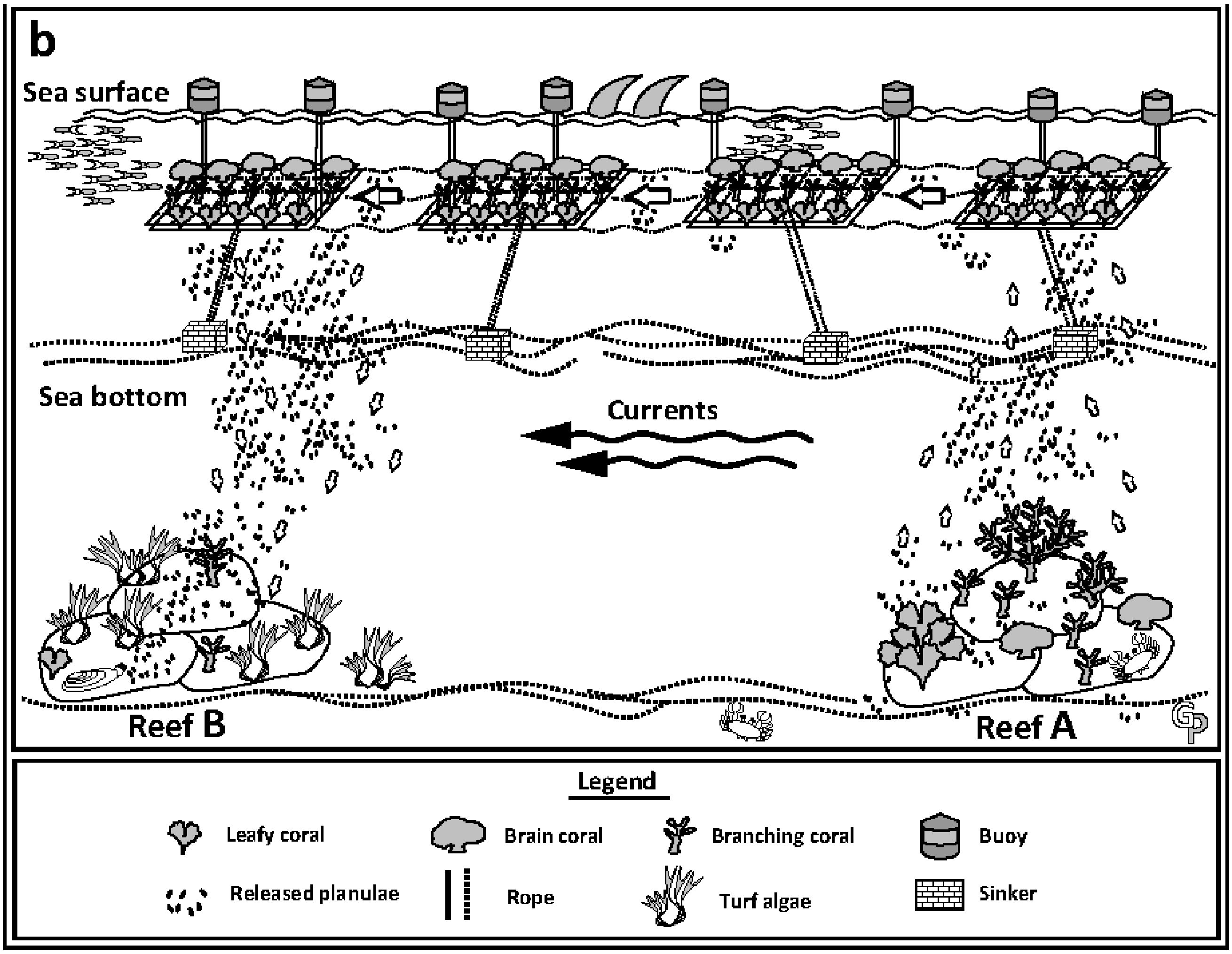

Figure 2. Schematic illustrations of two ecological engineering approaches to reef restoration, using the "gardening" tenet. (**a**) Employing coral nurseries as sexual reproduction hubs for the creation of masses of coral larvae, with the aim of enhancing larval seeding and recruitment in degrading reefs or in reefs that suffer from reduced recruitment (the reef at the left); (**b**) The establishment of new biological connectivity routes for coral reefs' larvae. As a result of either reef degradation or changes in the current directionality, caused by global change/anthropogenic activities, the two reefs (right and left in the scheme) are no longer connected to each other via propagules. The establishment of stepping stones between both reefs, using floating mid-water nurseries, enables the reconstruction of biological connectivity between these two separated reef zones. Current literature provides additional ecological engineering approaches using sexual recruits, such as the tactic called "coral plug-ins" [60], where *ex situ* settled and raised spats are designed in a way that simplify their transplantation to degraded reef areas.

The second ecological engineering approach focuses on the restoration of damaged biological connectivity routes for coral reefs' larvae or on the establishment of new such routes (Figure 2b). It is conceivable that climate change would notably alter biological connectivity routes in coral reef ecosystems, through temperature-associated accelerated larval development, for example, thus reducing competent dispersal scales and the reproductive activities of gravid colonies, as well as other demographic traits, and increasing larval mortality rates [61]. Furthermore, other clusters of global change impacts, for instance conversions in ocean chemistry and currents alternations, may jointly lead to shifts in the size, structure, type and spatial range of reef populations. As these changes accelerate, connectivity, dispersal and replenishment by larvae would be further lessened by the increased fragmentation of reef habitats due to global reef degradation [6–8]. Series of mid-water coral nurseries, arranged to create novel biological corridors through stepping stones mechanisms, may promote dispersal among fragmented reef populations and thus dramatically rehabilitate degraded reef habitats. Mid-water nurseries attract commensals and coral-inhabiting, reef-dwelling species (fish and invertebrates alike), arriving from the plankton, that contribute to the establishment of the entire coral infaunal biodiversity, transforming the nurseries into small floating reef ecosystems, oases in blue waters [54], a novel dispersal apparatus for patchy reef ecosystems. As conceptual documentation for the applicability of this notion one can look at the offshore oil and gas platforms in the northern Gulf of Mexico, which are recognized accordingly as stepping stones for the expansion of coral communities [62], closing connectivity gaps between distance reefs.

5. Closing Remarks

Although the foremost objective of coral reef management should be the prevention of reef degradation, the unfortunate reality is that reef ecosystems worldwide are continuously degrading and that these degradation trends are not lessening [6–8,24], further reinforcing the apprehension that the "reefs of tomorrow" will not return to their historic conditions [4,22,23]. While this inevitable situation calls for the application of active reef restoration methodologies [22,23,26–29], this scientific discipline of restoration ecology is still evaluating the best adaptive and effective approaches to employ [63].

Clearly, the limited ability of coral reef organisms to adaptably respond to climate change will directly affect the persistence of reef biodiversity, including the provision of coral reefs services [5,10,13,40,44,47]. Active reef restoration practices, as discussed above, may radically improve the limited capacities of reef dwelling organisms to adapt to the anticipated climate change conditions. Most loikely, this will be achieved first by actively moving coral colonies/coral planulae between sites/populations within current species ranges to mitigate maladaptation, and then additional ecological engineering acts will be employed to enhance the effects. While the aforementioned practices (and others to be developed; e.g., [64]) may pose potential genetic risks, other practices, such as the development of reef repositories through mid-water coral nurseries, may alleviate any such presumed genetic risk, taking into consideration that the "reefs of tomorrow" would most probably not resemble the "reefs of today" [4,22,23]. The above-mentioned discussion does not consider other measures that are not associated with the "gardening" tenet [22,23,26–29], such as the "assisted colonization" approach [55], which considers the translocation of corals that were introduced and adapted to extreme environmental conditions as a rehabilitating tool, used to mitigate the impacts of similar future stress events.

Even under contemporary conditions, without considering the global change impacts, the successful recovery of degraded reefs is questionable [22,23,25]. Furthermore, the vast majority of current management actions are responses to threats generated by local drivers, usually associated with anthropogenic impacts such as resource extraction, pollution, fisheries, urbanization and tourism, without taking into account the global changes [5]. Since climate change represents highly complex trajectories and significant impacts on biota [18,39,58], it may be further stressed that traditional management measures cannot and will not mitigate or effectively respond to global change sways [22,23], necessitating the development of additional novel approaches. Thus, climate change creates new challenges for biodiversity conservation and reef rehabilitation [58]. In response to these needs, the potential application of four ecosystem engineering approaches under the auspice of the "gardening the reef" tenet [22,23,26,28,29] are evaluated here. The first, the take-home lessons approach, focuses on the critical evaluation of reef restoration outcomes (of the nursery and the coral transplantation stages). This approach does not only offer the benefits of gaining more insight on the results, but is also an applied modifier of the actual measures performed in the field, providing further suggestions on how to improve the activities in the field. The two other approaches, which consider the tool of genetics and the use of coral nurseries as repositories for coral and reef species, are somehow linked, though each carries a distinctive set of activities. Furthermore, the "genetic" approach not only takes into account the genetic repertoires presented by marine organisms (and the assisted gene flow between populations) but also the promising epigenetic outcomes (not detailed in in this overview). The last approach, employing novel environmental engineering tactics, is a platform that encourages nonconventional restoration acts, based on a wide range of ecological principles. In all cases, when employing these suggested measures, there is a need to weigh the outcomes, risks and expected changes to the local coral assemblages against the outcomes, risks and expected changes of maladaptation due to climate and other environmental/anthropogenic sources; though they may seem more independent than ever, they may nevertheless interact with each other synergistically to augment these effects [5].

The overarching issue is climate change and its associated uncertainties. Indeed, major uncertainty is associated with any human intervention at the coral reef ecosystem-level, including the application of the "gardening" tenet, as all biodiversity processes are a sequence of changes in biological and environmental properties. That further heralds the state of imbalance between the available methodologies and the methodologies required for the improvement of future reef restoration [23]. At least two of the approaches discussed here, the take-home lessons approach and the use of coral nurseries as repositories for coral and reef species, already consider the uncertainty and the gaps in knowledge, and they are further supported by the genetic approach and by the use of novel environmental engineering tactics as useful auxiliaries. Thus, employing simultaneously more than a single approach may improve considerably the success of reef restoration, minimizing the impacts of uncertainty and counteracting the lack of efficient tools for alleviating the inevitable influences of global change.

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Conflicts of Interest

The author declares no conflicts of interest.

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