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Review

Artificial Seaweed Reefs That Support the Establishment of Submerged Aquatic Vegetation Beds and Facilitate Ocean Macroalgal Afforestation: A Review

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Abstract: Macroalgae are invaluable constituents of marine forest environments and important sources of material for human needs. However, they are currently at risk of severe decline due to global warming and negative anthropogenic factors. Restoration efforts focus on beds where macroalgae previously existed, as well as the creation of new marine forests. Some artificial seaweed reefs (ASRs) have succeeded but others have failed; the contributions of ASRs to marine forest formation have been not fully determined. Here, we review ASRs, the benefits of macroalgal forests, threats to macroalgae, restoration, and marine forest formation to explore the current status of ASRs. The published literature indicates that ASRs have played critical roles in marine forest formation; notably, they support the establishment of submerged aquatic vegetation beds that allow ocean macroalgal afforestation. ASRs have evolved in terms of complexity and the materials used; they can sustainably mitigate marine deforestation. However, continuous reviews of ASR performance are essential, and performance improvements are always possible.

Keywords: artificial seaweed reefs; macroalgae; marine forest formation; ocean macroalgal afforestation; submerged aquatic vegetation beds

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1. Introduction

Most marine primary production is generated by algae and cyanobacteria, which also produce half of the world's oxygen [1]. These producers support almost all marine animal life by generating the majority of required oxygen and food. Primary production is limited by distinct factors in oceans and on land. The spatial and temporal distributions of oceanic net primary production (NPP) are restricted by light, nutrients, and temperature; water restrictions are also present on land [2]. Temperature variation is smaller in oceans than on land because the heat capacity of seawater buffers temperature changes; sea ice insulates water at lower temperatures. The availability of light and mineral nutrients plays an important role in ocean primary production [3].

Models suggest that ongoing oceanic biogeochemical changes could trigger a 3–10% reduction in oceanic NPP, depending on the chosen emissions scenario [4]. Thus, ocean afforestation is important because it increases primary productivity. "Marine forests" generally refer to macroalgal habitats, as well as vegetated coastal habitats (e.g., seagrasses, tidal marshes, and mangroves). However, in certain contexts, a marine forest can be defined as a three-dimensional benthic seascape created by macroalgae [5–7]. Most modern researchers believe that afforestation involves ocean macroalgal afforestation (e.g., [8,9]). Macroalgae (or seaweeds) are macroscopic, eukaryotic, multicellular, autotrophic organisms that can reach lengths of several meters [10,11]. These major producers lie at the base of the marine food chain and support many communities of herbivores that seek refuge from predators. To prevent overfeeding by such herbivores, many macroalgae have evolved defense strategies, such as calcification and the production of secondary metabolites that inhibit herbivore uptake [12]. Macroalgae are found in coastal areas, as well as open pelagic regions of the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea [5]. Pelagic macroalgae from Lagrangian ecosystems sometimes drift with winds and currents. Macroalgal distributions are often limited by tidal height [13], water clarity [14], wave exposure [15], and the extent of herbivory (for example, by sea urchins) [16]. Macroalgal forests are common in temperate and polar latitudes; laminarian kelp forests occur near the equator at depths >30 m in clear, nutrient-rich water below the thermocline [17]. Extensive *Sargassum* forests are common in many shallow tropical and subtropical environments [18]. Despite the wide distribution of such forests, unlike seagrasses and terrestrial plants, macroalgal forests require hard substrata (e.g., rock reefs) because the organisms lack roots that could anchor them to soft substrates such as mud or sand.

Many researchers have studied macroalgal distributions and their potential for reducing atmospheric carbon dioxide concentrations. Macroalgal forests dominate ≥25% of the world's coastlines [19,20] and will cover approximately 9% of all ocean surfaces by 2070 [8]. A recent meta-analysis estimated a global C burial rate of 6.2 Tg C year^{-1} for macroalgae growing on soft sediments [21], corresponding to ~0.4% of macroalgal NPP; this is close to the lower limit of estimates for tidal marshes [22]. Several studies have shown that macroalgae serve as C donors; detached macroalgae are transported by ocean currents and deposited in C sinks beyond the macroalgal habitats [21,23–26]. Unfortunately, however, coastal ecosystems have been in continuous decline worldwide for generations because of climate change and negative anthropogenic factors; this decline has resulted in 35–85% reductions in the areas of salt marshes, mangroves, seagrasses, oyster reefs, kelps, and coral reefs [27–31]. A recent estimate suggested that global kelp abundance is declining by 2% per year [20]. Accordingly, deforestation (also known as desertification) has rapidly spread to marine habitats and coastal fishing grounds, which then rapidly deteriorate. However, marine forests are literally hidden underwater, are not systematically studied in many regions, and are often overlooked; terrestrial forests receive most attention in regards to deforestation [32]. Thus, the United Nations has declared 2021–2030 to be the "Decade of Restoration" for 350 million hectares of degraded ecosystems; large-scale projects on land and at sea have been announced [31,33]. However, international support for the restoration of coastal ecosystems, which provide considerable benefits to humans, has been slow [33]. There is a need to review the cost-effectiveness of current restoration tools for macroalgal beds, mangrove wetlands, salt marshes, shellfish reefs, tidal freshwater wetlands, and coral reefs [33,34]. Artificial seaweed reefs (ASRs) (also known as artificial seaweed beds or marine forest artificial reefs) have been placed in generally shallow seawaters to provide light and firm (stable) substrates for seaweeds [7,35–39]; man-made reefs have often been used for restoration and/or the enhancement of ocean afforestation in recent years. For example, ASRs have been employed to restore kelp under the Korean Fish Stock Enhancement Program; this increased the annual income of fishermen by 95% and thus secured livelihoods that were at risk [31]. However, the current status of ASRs is poorly known in terms of their contributions to ocean afforestation by macroalgae or seaweeds. Here, we review the current status of ASRs that support the establishment of submerged aquatic vegetation beds, thereby allowing ocean afforestation. We describe why ASRs should be established (i.e., their benefits to seaweeds), threats to seaweeds, restoration of seaweeds, ASRs themselves, and Korean involvement in marine forest formation projects. We also discuss the histories of ASRs in Japan, Korea, and the United States (USA), changes over time in ASR shape and form (from initial concrete blocks to the present sophisticated structures), and current challenges in the use of ASRs for marine forest formation. The research questions and scope of this study are summarized in Figure 1.

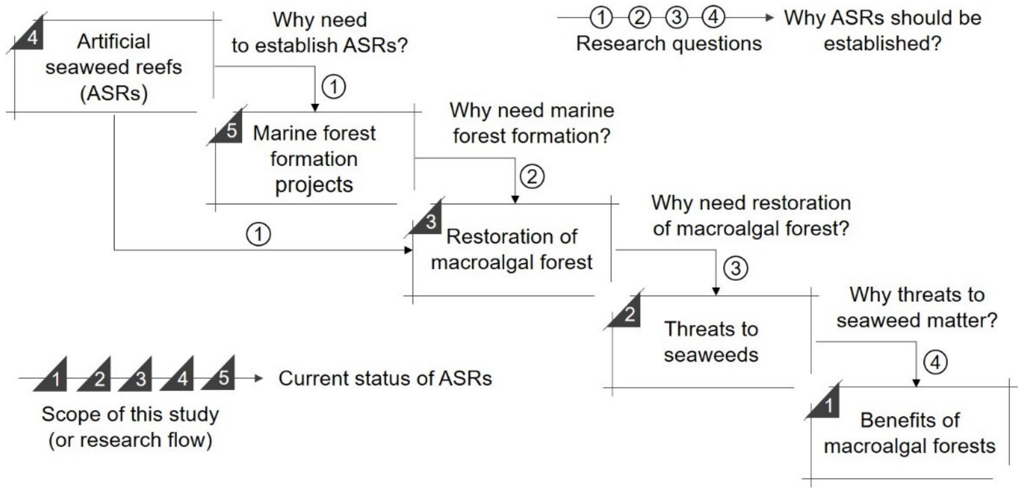

Figure 1. Research questions and scope of this study.

2. Materials and Methods

We searched relevant databases in the scientific literature, which is mostly represented by peer-reviewed journals. An initial scoping of the literature, including previous related reviews, identified the keywords to use when constructing search strings, as shown in Table 1. The Google engine was used for the majority of searches and included titles and/or abstracts containing at least one of the search terms from all four themes by linking the strings in Table 1 with the Boolean operator (AND). If a search for "macroalgae" did not yield many results, we searched for "seaweed" or "kelp" instead; this generally yielded additional results. To find papers written in Korean, searches were conducted using keywords that had been translated into Korean. We also searched the unpublished gray literature (e.g., technical reports) concerning marine forest projects in South Korea using the inventory of the Research Center for Ocean Industrial Development, Pukyong National University. In these ways, the literature addressing the themes was identified.

Table 1. Search strings.

Theme	Search String
Marine afforestation	(marine afforestation OR marine forest* OR macroalgal forest* OR formation* OR creation* OR aquatic vegetation bed* OR macroalgae OR seaweed OR kelp OR ecosystem* OR enhancement* OR function* OR restoration* OR benefit* OR threat* OR project*)
Benefits	(macroalgae OR seaweed OR kelp OR CO2 reduction OR marine habitats OR human well-being OR food* OR material* OR bioenergy)
Threats	(macroalgae OR seaweed OR kelp OR ocean warming OR marine heatwave* OR El Niño OR grazing OR harvesting OR sediment OR pollution OR storm* OR swell*)
Artificial seaweed reefs	(artificial OR man-made OR macroalgae OR seaweed OR kelp OR reef* OR marine forest OR bed*)

An initial screening of titles and abstracts, informed by the inclusion and exclusion criteria in Table 2, led to the retention of literature relevant to the research questions and four themes. Additional articles were sourced from the authors' prior reading, cross-referencing, and snowballing from database-sourced articles. We initially searched the relevant literature published from 2000 to 2022 and, if there was insufficient literature, the search was subsequently extended to the 1990s, 1980s, 1970s, and 1960s. In total, 365 publications were selected, including 307 for 2000–2022, 36 in the 1990s, 16 in the 1980s, 5 in the 1970s, and 1 in 1969.

Table 2. Inclusion and exclusion criteria.

Criterion	Inclusion	Exclusion
Study type	Empirical and theoretical/conceptual studies. Peer-reviewed; technical books/conference articles/technical reports included if high quality; current practices and web data included if valuable	Current practices proposed, but no evidence in use
Language	English; Korean if necessary	Any other language
Date	2000 to 2022; subsequently extended to the 1990s, 1980s, 1970s, and 1960s if necessary	Any study published before 1960
Relevance	(i) Marine afforestation, marine forest; (ii) benefits/functions of macroalgae (or seaweed or kelp); (iii) threats to macroalgae (or seaweed or kelp); (iv) restoration/ enhancement of macroalgae (or seaweed or kelp), relevant techniques and methods; (v) artificial seaweed reefs (Japan, Korea, and USA); (vi) Korean involvement in marine forest formation projects	(i) Not directly relevant to the research question; (ii) artificial reefs not oriented to marine forest formation; (iii) seaweed aquaculture oriented techniques/methods; (iv) level of analysis: not firm-level practices and processes

All data and content were cross-checked at least twice by multiple authors from July 2021 to May 2022. During the analysis, we identified multiple factors that trigger macroalgal deforestation; therefore, the relevant content was also included. To explore macroalgal restoration methods/techniques, we focused on spore transplantation, vegetative transplantation, and green gravel. Among ASRs worldwide, we focused on ASRs in the USA, Japan, and Korea because these countries either have a long history of ASRs or are currently operating relevant projects. To illustrate Korean ASRs, detailed three-dimensional models were generated using ANSYS software; these were based on two-dimensional drawings provided by the Korea Fisheries Resources Agency (hereafter referred to as FIRA).

3. Benefits of Macroalgal Forests

Several quantitative analyses have revealed five major benefits/functions of macroalgal forests: two regarding the forests themselves and three regarding their yield (i.e., seaweeds) [40] (Table 3). The benefits include CO_2 reduction, creation of marine habitats, the provision of materials that enhance human well-being and nutrition, and the production of other useful materials and pure bioenergy. However, existing analyses have not or have only partly incorporated detailed scientific clues about these benefits; therefore, we describe the detail below, not only to emphasize the benefits of macroalgal forests, but also to imply the benefits of ASRs to macroalgal forests.

3.1. CO_2 Reduction

Climate change results from excessive anthropogenic production of atmospheric CO_2 (a major greenhouse gas). We term greenhouse gases "brown carbon" and particles caused by incomplete combustion (e.g., soot and dust) "black carbon" [41]. "Green carbon" refers to terrestrial carbon stored in plant biomass and soils in forests, plantations, agricultural land, and pastures; "blue carbon" refers to organic carbon captured and stored by the oceans and coastal ecosystems (particularly seagrass meadows, tidal marshes, and mangrove forests) [22,42]. Of the total carbon captured by photosynthetic activity, marine organisms contribute approximately 55% [43–46]. This is surprising because plant biomass in oceans is only 0.05% of plant biomass on land [47,48]. Sequestered ocean carbon remains stored for millennia (rather than decades or centuries, such as in rainforests). The potential for macroalgae to mitigate climate change by sequestering CO_2 has not yet been fully integrated into the blue carbon concept [23,41,49,50] because most macroalgae grow on rocky shores that lack sediment [49]. It was thus presumed that macroalgae decomposed in oceans and could not serve as CO_2 sinks [51]. However, this view has recently been challenged [21,24,25,52–54]; new evidence suggests that macroalgae are globally relevant contributors to blue carbon [55]. A significant fraction of macroalgal production is exported [56,57] to shelf sediments in angiosperm-dominated habitats [58–60] and the deep oceans, where it is stored for substantial lengths of time [21]. Indeed, macroalgae contribute to carbon sequestration, but largely in depositional areas beyond their habitats; this differs from angiosperm-dominated ecosystems such as mangroves, salt marshes, and seagrasses. Figure 2 compares the carbon sequestrations by macroalgae and angiosperm-dominated ecosystems such as mangroves, salt marshes, and seagrasses.

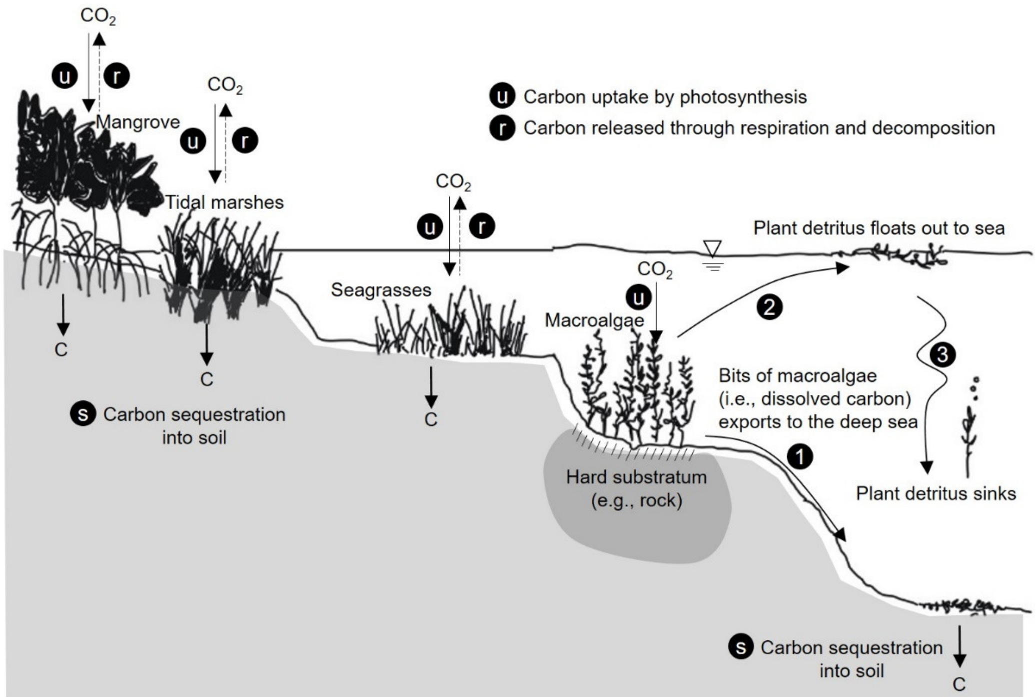

Figure 2. Carbon sequestration process by macroalgae and angiosperm-dominated ecosystems (e.g., mangroves, saltmarshes, and seagrasses). The angiosperm-dominated ecosystems uptake carbon by photosynthesis, release carbon through respiration and decomposition in the shore (often disturbed by natural and anthropogenic factors, e.g., runoff, human activity, and storms), and sequester the rest of the carbon into soil [21,23]. In contrast, macroalgae grow in a hard substratum (e.g., rock) where plant materials cannot be buried and where there is less disturbance by natural and anthropogenic factors; thus, they have less chance of releasing carbon to the atmosphere and sequestering carbon into the substratum. Instead, the carbon sequestered in macroalgae is sent to the deep sea either of the following ways [21]. First, bits of macroalgae in rocky and eroding conditions get exported to the deep sea, where the carbon can be sequestered. Second, using gas-filled bladders, macroalgae float towards the surface where they receive more sunlight for photosynthesis. Once the air bladders burst, the plant detritus sinks down towards the deep sea, where the carbon is likely to be sequestered away from the atmosphere for centuries and possibly up to millions of years [49].

Wild macroalgae and seaweed aquacultures significantly contribute to CO_2 removal; globally, autotrophic algal communities sequester 173 Tg C year^{-1} (range 61–268 Tg C year^{-1}) of macroalgal carbon in sediments and deep waters (numbers represent net values) [21]. This is comparable to sequestration by all other blue carbon habitats combined [50]. The global dissolved organic carbon exports from macroalgal beds have been estimated at net values of 0.14 $\pm$ 0.08 Pg C year^{-1} [61], 0.061 Pg C year^{-1} [62], and 0.34 Pg C year^{-1} [63]. These estimates are substantially greater than the values for seagrass meadows (0.016 $\pm$ 0.004 to 0.033 $\pm$ 0.008 Pg C year^{-1} [61] and 0.019 Pg C year^{-1} [62]). Australian kelp forests sequester 1.3–2.8 Tg C year^{-1}, which comprises >30% of all blue carbon sequestered on the continent and ~3% of global blue carbon [55]. Krause-Jensen et al. [49] identified key research questions in this area. There is a need for documenting macroalgal carbon sequestered outside blue carbon habitats, tracing this back to the source habitats, and showing that good habitat management increases remote sequestration. Although more research is needed, it is clear that macroalgae contribute to blue carbon and absorb atmospheric CO_2.

Table 3. Major benefits (or functions) of macroalgal forests [40].

No.	Benefits (or Functions)
1	It reduces greenhouse gas by absorbing CO_2 from the water and air. It has excellent efficiency in reducing CO_2, compared to temperate forests and tropical rain forests. It purifies the marine environment by providing dissolved oxygen and eliminating water pollutants.
2	The forest provides a habitat for marine life. It acts as a spawning ground and growing area for reproduction of marine life, provides food for algae-eating marine creatures, and enhances the basic productive capacity of coastal areas as the primary producer in the ocean.
3	It is food that contributes to well-being, highlighted by high-protein levels while being a low-calorie diet food. It contains many useful elements for the human body including vitamins and minerals (e.g., iodine and magnesium).
4	It provides useful/functional materials for medicine, food, and industrial goods (e.g., fucoidan, seanol, alginic acid, and sun block). It absorbs and supplies rare industrial metals (e.g., uranium and lithium) from the sea.
5	It is a source of pure bio energy as bioethanol, superior to biomass from grains and wood (3rd-generation biomass).

Oceans are rapidly acidifying because they absorb half of all human-related CO_2 emissions [64]. Indeed, ocean acidification and warming progress together [65]. If acidification continues, the oceans will become uninhabitable for many life forms that depend on calcification, including corals, marine mollusks, and coralline algae [66]. Ocean afforestation reduces atmospheric and dissolved CO_2 concentrations in macroalgal forests in a manner similar to the mechanism by which atmospheric CO_2 levels decrease in terrestrial agricultural regions [67]; ocean afforestation creates sanctuaries with regionally higher pH values [8]. A recent study found that kelps modified the chemical environments on their surface to create a micro-zone, known as the diffusive boundary layer, through metabolic processes controlled by light intensity [68]. Such microenvironments may serve as refuges from ocean acidification because their pH values are higher than the values in bulk seawater; they may also increase the resilience of coastal ecosystems in the context of global change.

3.2. Creation of Marine Habitats

Water exerts strong drag forces on aquatic organisms [69], allowing them to seek refuge in water flows. Many aquatic organisms have acquired morphological and behavioral adaptations to life in a fluid that is more viscous and denser than air. The physical structures of aquatic habitats directly influence how effectively aquatic organisms can protect themselves from predators, who exhibit excellent mobility in the high-drag environment [70], and from physical forces exerted by water. The environment is both risky and energetically expensive; three-dimensional aquatic ecosystems enhance species diversity and co-existence [71–76] by providing protected habitats for many organisms [77]. Macroalgae are the major submerged aquatic vegetated ecosystems worldwide; they are among the most productive habitats on land and in water, and they provide critical habitats for numerous animals [31]. The forests exhibit complex three-dimensional geometries, in contrast to the generally unstructured (i.e., flat) two-dimensional habitats of sand and mud [78]. Macroalgae thus serve as ecosystem engineers [79]. For example, kelp forests create canopy and understory habitats that support distinct communities of animals, fish, and other fauna [80]. Kelps are the most prolific primary producers on the planet; their productivity per unit area is comparable to the productivities of intensively cultivated agricultural fields and tropical rainforests [81]. Many studies have found that macroalgae create marine habitats that protect the ecological statuses of marine coastal systems [82,83]. For example, a recent study identified more than 627 fish species in tropical macroalgal meadows, of which 218 exhibited greater local abundance within this habitat (compared to other habitats) during at least one stage of the life cycle [84]. Tropical East African seaweed beds exhibited greater abundance of mobile epifauna than did seagrass meadows; they also exhibited greater invertebrate biomass and taxonomic richness, although macrophyte biomass was lower than in seagrass [85]. However, kelp deforestation has occurred in many places in recent decades [5,6,86]. The loss of forest-forming kelps and the benthic communities they support can dramatically affect nearshore ecosystems, especially if the loss is widespread [87]. Although kelp restoration projects are increasing, most are short-term and small-scale [88]. Upscaling is imperative, but current restoration tools often rely on scuba divers or require labor-intensive and expensive techniques.

3.3. Products That Aid Human Well-Being and Serve as Functional Foods

Macroalgae contain chlorophyll [89,90] and are divided into green algae (Chlorophyta), brown algae (Ochrophyta, Phaeophyceae), and red algae (Rhodophyta) according to the chemical nature of the photosynthetic storage products, as well as pigmentation, morphological appearance, and the organization and components of photosynthetic membranes [90,91]. Chlorophyll content affects color; for example, green algae contain equal amounts of chlorophyll a and b (as do higher plants). Xanthophyll and fucoxanthin pigments are predominant in brown algae, where they mask the effects of chlorophylls and other xanthophylls while imparting the brown color; phycoerythrin and phycocyanin are dominant in red algae, where they mask the effects of other pigments and impart the red color [92,93]. These pigments have found applications in food and beverage industries, animal feeds, cosmetics, and pharmaceutical products; the materials impart bioactive and sensorial properties [93,94]. Macroalgal phycocolloids (polysaccharides) have industrial applications [95]. The three major phycocolloids are alginates, agars, and carrageenans. Alginates are primarily extracted from brown seaweeds, while agar and carrageenans are primarily extracted from red seaweeds [96]. Most phycocolloids can be safely consumed by humans and animals; many phycocolloids are used in ready-mixed cakes, instant puddings, pie fillings, and artificial dairy toppings. Moreover, seaweeds are rich sources of natural bioactive compounds (e.g., antioxidants, flavonoids, phenolic compounds, and alkaloids) that serve as alternative foods and drugs [97–102]; the food industry employs such health-promoting ingredients [91,103,104]. Seaweeds often contain high amounts of vitamins A, D, E, C, B, and K [105–109] (but see [110]) and minerals, including calcium, potassium, magnesium, and iron [111,112]. However, the levels considerably vary according to morphological features, environmental conditions, and geographical locations [113,114]. Carrageenan, agar, and other polysaccharides serve as sources of fiber and prebiotics that may be beneficial for bacteria in the large intestine [91,115,116]. Brown macroalgae are attracting particular attention because of their high levels of complex polysaccharides, phlorotannins, fucoxanthin, and iodine [100,117,118]. Such algae and their extracts have been extensively studied in efforts to develop products that exhibit improved nutritional value and/or shelf-life [118–121]. Macroalgae are generally unexplored sources of biologically active compounds, serve as healthy functional foods or nutraceuticals, and have higher market values than indicated by their biomass alone [122].

3.4. Other Useful Materials

Macroalgae contain antimicrobial and antioxidant compounds, as well as materials used in healthcare, cosmetics, and other manufacturing industries. Macroalgae serve as biofertilizers and feed for monogastric animals [90,123–129]. The first three of these applications have been thoroughly reviewed [127]; we thus focus on the other applications. Macroalgae may serve as natural fertilizers and biostimulants [123,128,130–133], minimizing the need for chemical fertilizers. "Biostimulants" constitute materials other than fertilizers that promote plant growth when applied in low quantities via root drenching, foliar spray, or a combination of the two [134,135]. The effects of seaweed extracts on plant and soil systems include plant phenotype improvements, enhanced tolerance, microbial restructuring, metabolic pathway modulation, and enhanced quality and nutrient acquisition [132]. For example, a mixture of green and red macroalgae from the Black Sea coast served as a useful fertilizer; macroalgae do not accumulate inorganic compounds or grow in polluted regions [123]. As mentioned above, macroalgal thickening and gelling agents include agar, alginate, and carrageenan. In addition, macroalgae have been used for food packaging [129,136–138] and as fillers in thermoplastic composites [125,139]. For example, conventional plastic packaging manufactured from crude oil can be replaced by seaweed-derived bioplastics. Thus, macroalgae are abundant and contain many potentially useful compounds [137]. Macroalgae are a valuable source of bioplastics considering their high biomass, rapid reproduction, ease of management in all environments, and cost-effectiveness [140]. Moreover, seaweeds contain biodegradable antimicrobials (phenols, fatty acids, carbohydrates, proteins, and trace compounds) [137]. However, current methods of hydrocolloid extraction are expensive in terms of time, energy, and water [136,137]. New methods include green extraction and automated processing techniques [141].

Both microalgae [142,143] and macroalgae have been used as sources of protein and bioactive compounds for monogastric animals [90,144–147]. Some seaweeds contain rather high levels of proteins with balanced amino acid compositions; these may serve as food for both humans and animals [148–150]. Thus far, however, nutritional research concerning seaweeds has involved only chemical analyses and a few in vitro studies; there is a need for in vivo studies to show that the nutrients are available to monogastric animals [147]. Some in vivo studies found that the addition of seaweeds to the diets of monogastric animals did not increase weight; the protein and energy levels may have been insufficient and the seaweeds were indigestible [90]. The protein levels of *Saccharina latissima* and *Palmaria palmata* were low; only a *Palmaria* protein concentrate might serve as a useful protein source [147]. Thus far, the effects cannot be generalized; more studies are needed concerning macroalgal feeds for monogastric animals.

3.5. Sources of Pure Bioenergy

There is considerable interest in the potential of micro- and macroalgae serving as sources of renewable energy. First, agricultural land is not required for cultivation; moreover, many species grow in brackish water or saltwater, thus avoiding competition with the freshwater required for food production [151,152]. Second, the potential yield of algae per unit area is also often higher than the potential yield of terrestrial plants [153,154]. For example, brown seaweeds cultured for 7 months yielded 13.1 kg dry weight m^{-2} $year^{-1}$, compared to 6.1–9.5 kg fresh weight m^{-2} $year^{-1}$ from sugar cane [155]. Third, algal biomass requires no fertilizer; ocean currents and water exchange provide a continuous flow of nitrates and phosphates. Indeed, large cultures can mitigate excessive nitrogen levels in coastal waters [154,155]. Fourth, large-scale macroalgae farming is ongoing in Asia [156–158], and there is extensive harvesting of natural populations [159,160]. Recent studies have shown the potential for large-scale culturing of macroalgae in the Americas [161,162] and Europe [163–167]. Fifth, although macroalgae exhibit lower growth rate and energy productivity, compared with microalgae, macroalgae are more cost-effective [168]. These observations have led to interest in the use of macroalgae as biofuels; today, macroalgae serve as a feedstock for clean (i.e., third-generation) biofuels [169,170]. More cost-effective methods are needed for the growth, harvesting, transport, and processing of large quantities of macroalgae. For example, the multi-disciplinary project MacroBioCrude seeks to establish an integrated supply/processing pipeline for the sustainable production of liquid hydrocarbon fuels from macroalgae [170]. The project is examining methods to overcome seasonal supply issues and the high moisture content of seaweeds; it is also exploring modifications to existing fossil fuel technologies (e.g., gasification and the Fischer–Tropsch process) that enable the use of seaweeds as a feedstock, thus reducing fuel consumed in transportation. In general, algae-derived fuel production involves cultivation (including seedling production), harvesting, cleaning, size reduction, preservation, and storage, and energy extraction. Future success will require optimization of all of these areas [170].

4. Threats to Macroalgae

Many marine habitat-forming species, such as seagrasses, corals, and oysters, have experienced global declines [29,171–173]. The loss of such foundation species often directly damages ecosystems, the health of which influences both human well-being [174–176] and the localized survival of taxa ("service providers") [177,178]. The kelps found along 25% of the world's coastlines [6,21,81,179,180] have been intensively studied worldwide because they are globally important foundation species that inhabit 43% of the marine ecoregions of the coastlines of all continents except Antarctica [86]. There is a need to evaluate the current status of kelps, their threats, and possible marine re-afforestation. A comprehensive analysis of changes in kelp forests over the past 50 years revealed substantial variations in geographical extent, with respect to both magnitude and direction [19,86]. Such spatial variabilities reflect regional differences in the drivers of change, uncertainties in some regions because of poor spatial and/or temporal data coverage, and the dynamic nature of kelp populations. A recent estimate suggested that global kelp abundance could be decreasing by 2% per year [6], with negative impacts on many species that depend on kelps for food and habitat. Many natural influences and human activities affect kelp forests. Factors that compromise forest stability include: (i) ocean warming and heatwaves; (ii) other climate-driven stressors (e.g., El Niño events); (iii) grazing by fish, sea urchins, and crustaceans; (iv) kelp harvesting; (v) sedimentation; (vi) pollution and eutrophication; (vii) high-energy storms; and (viii) combinations of these factors [6,181]. We describe the threats to macroalgae in detail below, not only to emphasize the current status of macroalgal forests, but also to underscore the need for restoration/enhancement of macroalgal forests.

4.1. Ocean Warming and Marine Heatwaves

Ocean warming and marine heatwaves are anomalous events that substantially affect marine ecosystems. A "marine heatwave" is defined as a daily temperature above the 90% threshold of a 30-year historical baseline period that persists for at least 5 days [182]. Marine heatwaves have multiple drivers, including air–sea heat fluxes, ocean heat advection, and large-scale climate variability [183]. From 1925 to 2016, the mean global frequency and duration of marine heatwaves increased by 34% and 17%, respectively, resulting in a 54% increase in annual marine heatwave days (from 26 to 40 days). The principal driver was an increase in mean ocean temperatures; thus, further increases in such days can be expected to result from global warming [184,185]. The impacts on marine species and habitats may be devastating [186]. Kelps can be physiologically stressed at high temperatures, especially if nutrient availability is low [30,187–192]. Large-scale declines in kelp, potentially attributable to ocean warming, have been observed on the coasts of northern California [193,194], Japan [195], southern Norway [196], Portugal [19], and eastern Tasmania [197]. Most kelps have been replaced by turf-forming non-kelp macroalgae. For example, in northern California, a marine heatwave caused a rapid catastrophic migration of kelps in 2014, resulting in widespread urchin barrens and the reduction of more than 90% of the bulk kelp canopy along >350 km of coastline [193]. Similarly, Australian kelps have been replaced by turf algae [55,198] or urchin barrens [199,200]. Turf algae (i.e., algal turfs) are dense, multi-species assemblages of filamentous benthic algae, including small macroalgae and cyanobacteria with heights typically <1 cm [201].

4.2. El Niño Events

Kelp deforestation caused by El Niño events is regarded as a climate-driven stressor because strong El Niño events stop coastal upwelling and ensure that the surface waters remain warm [202–204]. In southern California, El Niño events caused patchy deforestation but recovery was rapid [203,205,206]. In the Philippines, El Niño events affected macroalgal survival in many coastal farms [207]. For example, a disease known as "ice-ice" occurred during dry months when kelp was exposed to high heat and salinity [208]. Affected seaweeds produced a moist substance that attracted bacteria and caused branches to whiten and harden. Such physiological stressors are more likely to affect kelps in lower latitudes [19]. After the El Niño event of 1982–1983, the northern limits of three brown algae of northern Chile shifted toward the southern high latitudes [209]. Such physiological stressors may also render kelps more susceptible to disease. Low-latitude kelps in northern New Zealand exhibited a disease that was potentially induced by physiological stress [210,211].

4.3. Grazing

Grazing by sea urchins, fish, and crustaceans can damage kelps [212–214], turning complex ecosystems into barren seascapes (e.g., encrusted coralline algae and bare rock) [215]. Sea urchins play important roles in subtidal communities via direct or indirect interactions [216,217], which has led to the term "urchin barrens." The urchins disappear when large-scale deforestation affects temperate, subtropical, and tropical coastal regions [82,218–220]. A typical grazing event occurred in coastal areas of the Aleutian Archipelago. Overgrazing by herbivorous sea urchins began in the 1990s; it resulted in widespread deforestation of regional kelp forests, lower macroalgal abundance, and higher benthic irradiance [87,199]. When high numbers of sea urchins are not extensively preyed upon, they can destroy vast, subtidal seaweed communities [220–223], creating barrens that remain for generations [224,225]. Such destruction reduces primary production, as well as the number and abundance of species that inhabit kelp beds [216,226,227]. The shift from a macroalgal forest to barrens can be divided into four chronological stages over a 3–4-year cycle of irreversible changes, and a 10–15-year cycle affected by predator removal, behavioral interactions, and extraneous events [228]. For example, fishery exploitation is a major driver of transitions in urchin population density, which then affect the distributions of canopy algae [215]. Furthermore, kelp forest fish (e.g., opaleye or halfmoon) and crustaceans (e.g., kelp crab) can damage the forests [214,229–231]. The seaweed resources of Japan have been greatly affected by herbivorous fish (rabbitfish and parrotfish), resulting in seaweed bed reduction or extinction, particularly off the southwestern coast [195]. As is true of all dynamic ecosystems, even this complex environment can attain a balance when predatory species (e.g., sea otters) limit the numbers of sea urchins or grazing fish; however, this balance is disrupted when predatory populations decline or phase shifts occur, as observed along the coastlines of Alaska, California, Nova Scotia, and Tasmania [199,223,228].

4.4. Commercial Kelp Harvesting

Commercial kelp harvesting potentially threatens long-term kelp stability because of environmental changes that facilitate disease development, alter population genetics, and affect the local physiochemical environment [167]. The many consequences of macroalgal cultivation include crop-to-wild gene flow caused by the release of reproductive material [232,233]; habitat changes that facilitate disease, parasites, and the introduction of non-native species [232,234–236]; effects on planktonic, epifauna, and megafauna species [167,237]; and benthic impacts via the release of dissolved and particulate matter by seaweed biomass [238,239]. However, the demand for kelp is increasing because kelp has supported many industries for a century. Kelp is a traditional daily food in Asia [92,240] and abalone feed in some Asian countries; algin extracts are widely used in cosmetics, pharmaceuticals, and foods [241,242], as well as efforts to mitigate eutrophication [243,244]. Kelp farming has been well-established in Asia for decades [156,158], especially on the temperate coastlines of China, Japan, and Korea [157]; interest in macroalgal farming is growing in the Americas [161,162] and Europe [167]. Global kelp production increased at an annual rate of 7.6% between 2014 and 2015 (to an estimated 28.1 million tonnes [245]) and at an annual rate of 6.8% in 2016 (to an estimated 30 million tonnes [246]). It is thus essential to remove any uncertainty in kelp farming; large-scale projects require a complete understanding of scale-dependent changes. There is a need to balance the potential benefits and corresponding environmental risks with the goal of remaining within the carrying capacity of the environment and ensuring conservation.

4.5. Increased Sediment Load

Increased sediment load affects macroalgal degradation, distribution, abundance, and composition [247]; it also affects such factors in coral reefs [248], seagrass meadows [249,250], and invertebrate communities [251,252]. Sediments can be released into the water column via terrestrial runoff [253,254], natural resuspension [255], and anthropogenic activities in coastal areas [256,257]. Sediments can either be deposited or remain in the water column depending on the concentration, size, density, and buoyancy of the particles, as well as the hydrodynamics of the water column [258]. Excessive sedimentation negatively affects the structure and function of macroalgae and corals; it alters reproduction, metabolism, recruitment, growth, coverage, and density [259]. Notably, the effects of excessive sedimentation vary among macroalgal species [247,260,261]. For example, an increased sediment load may decrease macroalgal depth distributions [262,263], reduce the rate of zoospore adhesion and the rates of gametophyte survival and growth [264,265], alter local species distributions and abundances [261,266], and affect the composition and assemblage of sublittoral, rocky-shore macroalgal communities [261,267]. However, grazing rates are also significantly reduced at high sediment loads, which may reduce the grazing populations of macroinvertebrates [268–270].

4.6. Pollution

Non-point- and point-source pollution, including sewage and industrial disposals, can contribute to the degradation of kelp forests [271,272]. Kelp may exhibit reduced growth rates and reduced reproductive success in highly toxic waters and sediments [273]. Studies of the microscopic stages of kelp development have shown that kelp serves as a bioindicator species; it is sensitive to sewage, industrial waste, and other causes of poor water and sediment quality [274–277]. For example, fertilizers carried to the sea by rivers mix with various pollutants from the land and sea, triggering light-extinguishing algal blooms that cloud coastal oceans and deprive organisms in the deep sea of their main source of energy (sunlight). Such "coastal darkening" is not well-understood [278,279]. This darkening alters the relative abundances of various phytoplankton populations [280], delays phytoplankton blooms (thus affecting organisms that rely on such blooms) [281], changes the chemical composition of water [282], limits the contributions of kelp to coastal carbon cycles [279,283], and severely hinders kelp growth. Such declines in kelp productivity affect fish and other organisms that use kelp for food or shelter; they also limit the ability of kelp to sequester carbon. Moreover, marine pollution by micro- and macroplastic debris has become a widely recognized environmental problem [284]; such pollution also affects macroalgal growth [285]. Although some microplastics can be washed away by water swirling around macroalgae, microplastics can be absorbed onto macroalgal surfaces or incorporated into macroalgal structures [286,287]. Approximately 20% of marine plastic debris originates from ocean-based sources (principally commercial fishing) [288]; accordingly, nylon fishing lines are commonly found in macroalgal forests and seaweed farms [289,290].

4.7. High-Energy Storms or Swells

High-energy storms or swells can uproot entire kelp forests and break the fronds [291,292]. El Niño events, characterized by severe storms and warm water, often devastate kelp forests [293]. Although El Niño events are generally low-latitude phenomena, they affect ocean and atmospheric conditions by transferring energy to mid- and high-latitude regions [294,295]. The extension of El Niño-related conditions to high latitudes has caused habitat expansion, habitat redistribution, and widespread mortality involving many seaweeds and other organisms across much of the eastern Pacific [296–298]. The unusually large waves and nutrient-poor water associated with the 1982–1983 and 1997–1998 El Niño events led to severe mortality among giant kelp (*Macrocystis pyrifera*) populations in many areas along the coasts of Southern California and Baja California; however, the impacts considerably varied, even within adjacent populations [297,299–302]. For example, the 1997–1998 El Niño event had the strongest impact on the giant kelp population along western North America on a regional spatial scale [298]; it caused almost 100% mortality along the Baja California coast south of Punta Banda, approximately 80–90% mortality in southern California between Punta Banda and Point Conception, and <10% mortality north of Point Conception [293]. These geographical differences were driven by regional-scale patterns of seawater temperature and storm-induced wave energy [298]. The rates of recovery in these regions also varied; however, a lack of data prevented a definitive investigation of the aftermath [303].

4.8. Multiple Factors

Multiple factors can cause macroalgal deforestation. For example, declines in Australia have been caused by eutrophication, overgrazing, warming, and marine heatwaves [30,274,304–307]; declines in the inner basin of the Salish Sea have been caused by elevated temperature, lower nutrient concentrations, and generally low current velocities [308]. In the time since the first bleaching event was observed off the coast of Jeju Island, South Korea, many macroalgal forests have been reduced by the seawalls constructed to protect reclaimed land, coastal pollutants accumulated during recent decades, and warm low-nutrient water from the Kuroshio Extension [7,309]. A "bleaching event" comprises the domination of coastal ecosystems by white, crustose coralline algae, which prevent the attachment of marine algal spores [7]. Such bleaching has propagated to the east, west, and south coasts of South Korea [35,310–312]; a recent survey using hyperspectral aerial imagery found that 44.9% of the surveyed area (18,759 of 40,868 ha) was affected by ongoing or severely intensified bleaching [312]. Similarly, some seaweeds in Japan have declined in certain regions because of ocean warming [195]. Between 1978 and 1992, reclamation, eutrophication, and low-transparency water caused the loss of approximately 6400 ha of seaweed off the coast of Japan [313].

5. Restoration of Macroalgae

"Restoration" implies that an ecosystem is returned to the condition it was in before any disturbance, while "enhancement" suggests that an original ecosystem is replaced by a different ecosystem [314,315]. Accordingly, ecosystem restoration is costly and labor intensive; recent studies shown that macroalgal forest recovery requires extensive measures, and the viability of large-scale restoration activities is compromised by continued human pressures [316]. In this regard, we need a well-designed road map for macroalgal restoration. For example, Cebrian et al. [316] proposed a roadmap for Mediterranean macroalgal restoration to assist researchers and stakeholders in decision making by subdividing the planning process into five steps and considering the most effective methods in terms of cost and cost-effectiveness. In general, restoration of macroalgae focuses on beds where they previously existed, whereas enhancement focuses on marine afforestation of new habitats [317]. However, the dividing line is not always clear; some overlap is apparent. For example, one recent study classified restoration methods into transplantation, seeding, grazer control, and ASRs [31,317]; however, ASRs can be used for both restoration and enhancement. Thus, we first consider spore (or seeding) and vegetative transplantation because these have been used to restore natural, submerged macroalgal beds for several decades [35,309,318,319]; we then discuss a newer technique: "green gravel" [320].

5.1. Spore Transplantation

Spore transplantation employs spore dispersal, spore-bag, and rope-seeding techniques [321–323]. For example, spores can be delivered by attaching mesh bags of fertile sporophylls to the bottom [206]; additionally, microscopic stages can be grown in the laboratory and dispersed over the bottom. The success of the laboratory approach requires benthic conditions suitable for attachment, reproduction, and/or development of the stage used [324]. A spore dispersal technique was developed to grow mass cultures of *Macrocystis* plants from liberated zoospores through gametophytes to embryonic sporophytes [321]. The zoospores settle on various substrates and are then placed in flowing seawater under constant light. Gametophytes require 10–20 days to reach sexual maturity and another 5–20 days to develop into embryonic sporophytes. The cultures are then dispersed near the bottom of a coastal area suitable for kelp growth. The embryonic plants can re-attach at this stage if the site is fairly calm. In one study, the dispersal of 10^5 embryos was required to produce a single, attached, identifiable *Macrocystis* juvenile approximately 15 cm in height [325]. Thus, mortality was extreme; several billion embryos were dispersed [326]. The success rate may be affected by environmental conditions at the time of dispersal, as well as embryo age; the results may not be known for 4–18 months. The advantage of this approach is that large numbers of kelp embryos that are genetically adapted to specific environmental conditions may be released into selected locations without handling large amounts of plant material.

The spore-bag technique typically utilizes bags packed with fertile, adult plants suspended over rocky substrata or ASRs during the reproductive season. The spores are naturally released from the adult plants and eventually settle on the hard surface. This approach was successfully used to create brown seaweed beds [35]. Spore bags packed with fertile *Sargassum* spp. and *Ecklonia cava* were installed on an artificial iron reef and a natural rock substratum at three different sites around Shikoku in southern Japan [322]. Seaweed growth was observed monthly or bimonthly by scuba divers with digital video cameras. The rope-seeding technique involves growing macroalgal seedlings on ropes in the laboratory, winding the ropes around frames constructed with pipes, and transporting the frames to a site [321,327]. This is cost-effective; thallus planting on ropes is rapid, the required hatchery space is small, and the process is mechanized [328,329].

5.2. Vegetative Transplantation

Vegetative transplantation uses either young or old plants and either threads, gravel bags, or concrete blocks [321–323]. Vegetative transplantation is used to grow small sporophytes (<1 cm in height) on artificial substrata in the laboratory; the substrata are then placed in the field [330] or used to transplant much larger juvenile and adult sporophytes that are less sensitive to bottom conditions. Vegetative transplantation is very labor-intensive; many plants are harvested, transported, and individually attached to the bottom. Since the late 1950s, transplantations of adult, sub-adult, and juvenile *Macrocystis* plants from existing healthy beds have been extensively used by kelp restoration workers across southern California [326]. This method requires large amounts of plants to be processed; additionally, it is difficult to anchor the plants. Typical transplantation with sub-adult or juvenile plants can be summarized as follows [326]. First, a kelp bed is identified with sufficient size to tolerate periodic removal of some plants. Such plants are typically 2–6 m long with at least four to six fronds minimally damaged by fish, as well as new hapteral growth and some sporophyll blades. Second, prior to removal from the substrate, old or deteriorated fronds are removed to facilitate handling and reduce drag. Third, the holdfast is pried from the substrate using a diver's knife and trimmed. Efforts are made to avoid damaging new haptera. Fourth, transplantation is conducted via plant re-attachment in a suitable habitat with rubber bands or rings. Plants have been successfully secured to anchored floats using several such methods.

The adult plant transplantation technique involves the use of concrete blocks, threads, and gravel bags. Concrete blocks are used to attach one or two adult plants via strong rubber bands or ropes. To increase the surface area, plastic coils are often used to cover the concrete surface. The plants are then covered with plastic sheets or placed in large cages to protect against fish grazing; finally, they are installed in the seabed. Holdfasts of *Ecklonia* are attached to the blocks 1 month after installation [321]. The threading technique involves the use of a needle to thread the holdfasts of macroalgae onto a nylon line at specific intervals. Plants thus connected are moved to the transplantation site by a boat; the plants are moored using anchors and buoys until they gain a permanent hold on the substratum [321]. The gravel-bag technique uses a nylon mesh bag filled with coarse gravel, typically 3 cm in diameter and 50 kg in dry weight; the rim of the mesh bag is pulled around the top of the holdfast. After transplantation, stability is increased by gradual sediment accumulation in the bag; the plant hapteron grows in the bag and then extends to the seabed. Several plant bags can be anchored using chains and ropes to optimize stocking density [321,331]. Holdfast fragments are valuable in terms of transplantation; the holdfast of one adult can be cut into $\geq$8 fragments and fixed to new substrata, where new individuals form [332].

Young plants are much easier to transplant than adults and can be attached to the stumps (i.e., holdfasts plus short sections of stipes) of understory kelps after the upper portions have been removed [206]. Juvenile kelps were transplanted in California during the 1970s and 1980s, and recruitment was successful near the southern limit in Baja California after the mass kelp disappearance during the El Niño event of 1997–1998 [301,330]. Similar approaches have been used in Mexico [206], Japan [333], and Chile [330]. It is important to consider kelp reproduction when a kelp canopy develops; the canopy influences the light regime within the forest and reduces radiation to the seafloor, thus hindering the growth of young plants and the recruitment of other algal species [334–336].

5.3. Green Gravel

Conventional spore and vegetation transplantation techniques are associated with difficulties that involve working underwater, the use of species with complex multi-phasic life histories, and large losses [337]. Donor plants mush be maintained in dynamic wave-exposed habitats for a period that allows reproduction. Complex structures must be attached to the seabed or natural reefs; these are often vulnerable to storms and waves [277]. The deployment of such structures is labor- and skill-intensive; it typically involves scuba diving under harsh conditions associated with strict health and safety requirements [320]. Recently, a new approach, green gravel, has been tested [320]. Kelp seeds were sown in small rocks and grown to 2–3 cm in the laboratory, then sown in the field. Even when the planted kelp was dropped from the water surface, the survival and growth rates remained high for >9 months. This technique is inexpensive and simple, does not require scuba diving or highly trained workers, is scalable to large areas, and allows the introduction of genes from very resilient kelp populations to vulnerable reefs [320]. The method appears to be very promising.

6. Artificial Seaweed Reefs

The first ASRs were simply stones thrown into the sea to extend natural seabed substrata and thus increase seaweed production [338]; ASRs have since evolved. Many ASR projects have been launched in the USA, Japan, and Korea; the ASRs have various shapes and sizes, and they are constructed from different materials [7,338,339]. We discuss some of these projects in detail.

6.1. The Pendleton Artificial Reef in Southern California

The California Department of Fish and Wildlife has been involved in ASR construction since the 1950s; the California Artificial Reef Program of 1985 was created by statute to address declines in various Californian marine species. ASRs placed on a sandy bottom have been used to create new kelp forests. Early ASRs resembled piles of trash rather than custom-built environments. Old tramcars and tires were dumped to enhance fishing; some of these small reefs were colonized by giant kelp [340]. Since the early 1980s, at least in

California, there has been a need to mitigate anthropogenic impacts along the coastline by providing new habitat. In particular, power plants draw large volumes of seawater through heat exchangers and send warm water back to the ocean; the main sources of such heated seawater have been the San Onofre Nuclear Generating Station (near San Clemente in southern California) and the Diablo Canyon Power Plant (near Avila Beach in central California). Although various forms of mitigation have been implemented or proposed, ASRs have been extensively used to provide new kelp forest habitat [339,341–343]. The results have been mixed because of differences in ASR sizes, installation depths, and configurations. Current reef designs are much more effective than the original designs; they are custom-built to support giant kelp forests and the associated communities.

The first of these ASRs was the Pendleton Artificial Reef, constructed in 1980; 1.4 ha of quarry rock (eight modules) was deposited on a sand bottom approximately 11 m deep and 5–6 km from the nearest kelp forest [344]. Giant kelp and abalone were transplanted to rapidly establish a kelp forest. Unfortunately, herbivorous fishes (halfmoon and opaleye) were attracted to the modules and ate the kelp. The abalone did not survive, possibly because of a lack of food or consumption by predators [341]. Since that time, giant kelp has occasionally colonized the Pendleton Artificial Reef; however, the modules failed to develop a giant kelp community similar to the communities on nearby natural reefs. The failure was attributed to the isolation of the modules from other reefs, their placement in an area where light did not always favor kelp growth, and the high relief of the modules [339,341]. Low-relief modules with moderate sand cover would have been better [340].

6.2. Artificial Seaweed Reefs in Japan

In Japan, many researchers have studied seaweed succession in the intertidal and subtidal zones, either by placing artificial substrata on the sea bottom or by removing seaweeds from their natural substrata [345–350]. Most studies installed ASRs and observed the succession of seaweeds. In total, 209 artificial reef units (presumably fishery resources) were installed on sandy, boulder, and rocky bottoms at 3–10 m depth in Ashizuri, Tosa Bay, Japan [345,346]. Each reef unit was a concrete trapezoid block $2 \times 1.2 \times 1$ m^3 in volume, weighing 3.3 tonnes. Plastic mats (similar to Tartan Turf) were placed on the sloped sides as substrata for both seaweed and attaching animals. Seaweeds (including mature thalli of *Sargassum* and *Gelidium*) were transported in mesh bags from other coastal areas, and slow-eluting fertilizers were placed among the blocks to support growth. At 2 years after placement, the total number of species was 22–35 per site, and the fertilizers increased seaweed growth; *Sargassum* became the dominant population on all types of bottoms after 6 years. After 1 year, the seaweed biomasses on ASRs in the sandy, boulder, and rocky areas were 9998, 441, and 229 g m^{-2} wet weight, respectively [345]. After 6 years, these biomasses were 5137, 2666, and 2848 g m^{-2}, respectively; sea urchins were the most active grazers, especially in the rocky area [346]. The *Sargassum* communities expanded from the reefs to adjacent rocky areas over time.

Concrete ASRs were installed on a gravel bottom 7 m deep (where few seaweeds were growing) [347] and 300 m off the Tei coast of Tosa Bay, Japan [348]. In total, 25 concrete plates $25 \times 22 \times 1.2$ cm^3 in volume were attached (by scuba divers using glue) to the ASRs at 2-month intervals from April 1993 to February 1994. Species succession was affected by the season of substrata placement [348]. For example, within 3 months of placement, species of *Melobesioideae* were dominant (~80%) on plates placed in April, June, and August; the coverage of plates placed in October, December, and February was ~30%. In 1999, an artificial iron reef with 12 different substrata fixed onto the roof was installed on a sandy bottom at a depth of 8 m in Muronohana, Ikata, Japan, to grow various seaweeds [349]. Within 1 month of placement, diatoms were dominant (~100%). Two seaweeds, *Enteromorpha intestinalis* and *Colpomenia sinuosa*, were dominant within 3 months but coverage differed among substrata (plate-like iron bars, concrete plates, plates with fixed pebbles, wood accumulations, and steel plates). The differences were possibly caused by variations in surface roughness, which influenced zoospore settlement and thus gametophyte development.

To create fishery resources, ASRs were placed on sandy substrates at depths of 8, 10, and 13 m in Muronohana, Ikata, Japan [350]. The reef types included an M-type ($2.5 \times 1.5 \times 1.25$ m^3) and an RF-type ($2 \times 2 \times 1.2$ m^3). From March 1999 to June 2001, the succession and growth of marine algae were observed monthly or bimonthly by scuba divers with digital cameras. In total, 38 seaweed species were found; kelp settlement was promoted by reduced sand cover (attributed to turbulence). The results suggested that large-scale surface roughness was important for community maintenance after initial establishment.

Breakwaters can also serve as artificial substrata for seaweed beds; many breakwaters (of armored blocks) have been built to protect ports and coastal structures. Vegetation and the standing crops of seaweeds on armored blocks have been explored [351]. After 7 years, the crops were nearly identical to the natural state. Variations in surface roughness did not affect the growth of *Sargassum* spp., but many *Ecklonia stolonifera* plants were observed on such surfaces. Seawall construction has been improved in Japan. For example, the vertical seawalls that border Kansai International Airport have gentle slopes to facilitate seaweed growth, as well as the restoration of habitats for fish and other animals [313]. Moreover, steel slag has been tested as a fertilizer, while artificial slag stone has been tested as a seaweed substratum; seaweeds grew on the slag stone surface [352].

6.3. Artificial Seaweed Reefs of South Korea

Korea has high seaweed biodiversity and a long history of seaweed use. The abundance and composition of seaweed has been altered over the past few decades because of climate change and anthropogenic influences. Some species have significantly expanded their distribution to the north, while others have declined; some areas have become barren grounds [353]. Consequently, in addition to the development of sustainable seaweed aquaculture, the Korean government has launched a marine forest project for (principally) seaweeds that will cover 35,000 ha (35×10^7 m^2) by 2030 [354]. The strategy includes expansion of marine forests via de novo formation, as well as improvements to the efficiency of existing techniques. The core techniques include installation of marine forest plant facilities, submerged mooring ropes, spore pockets, and transplant panels, as well as seagrass transplantation [355]. Both simple concrete blocks and complex ASRs have been used for the marine forests and transplant panels.

The FIRA classifies artificial reefs according to the material used: reinforced concrete (41 types), concrete (3), steel (20), and "complex" (25 types) (89 types in total; Table 4) [356]. A "general artificial reef" is a reef approved by the Central Artificial Reef Committee of the Ministry of Oceans and Fisheries, installed by the central government or a local government, and maintained by the FIRA [309,357]. Artificial reefs can be also classified according to their intended purpose (target species): fish, fish/shellfish, shellfish/seaweeds, marine forest, and sea cucumber (Table 4). Artificial reefs for shellfish/seaweed, marine forest, and sea cucumber have been used for seaweed restoration and enhancement (42 ASRs). Representative ASRs are shown in Figure 3; the most common type is hemispherical (R02).

ASR construction and management is controlled by the Regulations for Artificial Reefs outlined by the Ministry of Oceans and Fisheries [358]. A representative ASR covers 2 ha or 20,000 m^2; flat ASR modules have areas of $\geq$500 m^2. An example is shown in Figure 4. Other ASRs vary in terms of their survey details, planning, design, and management. To facilitate the use of ASRs in coastal waters for marine forest formation, several ecological and physical issues have been considered. For example, residence time is critical in terms of algal spore (or germ cell) adhesion; it is primarily affected by water motion. Such motion near the substratum affects the transportation of algal spores and larvae from the water column to a benthic habitat; it also determines whether spores and larvae become established on the substratum. Several studies have explored water motion around a reef module to ensure efficient spore placement [7,39,309].

Table 4. Classification of artificial reefs used in South Korea [356]. The numbers have changed according to newly approved or de-approved artificial reefs.

Material	Total	Intended Purpose (Target Species)				
		Fish	Fish–Shellfish	Shellfish– Seaweed	Marine Forest	Sea Cucumber
RC §	41	10	5	18	7	1
Concrete	3	–	–	1	1	1
Steel	20	20	–	–	–	–
Complex	25	9	3	9	4	–
Total	89	39	8	28	12	2

§ Reinforced Concrete.

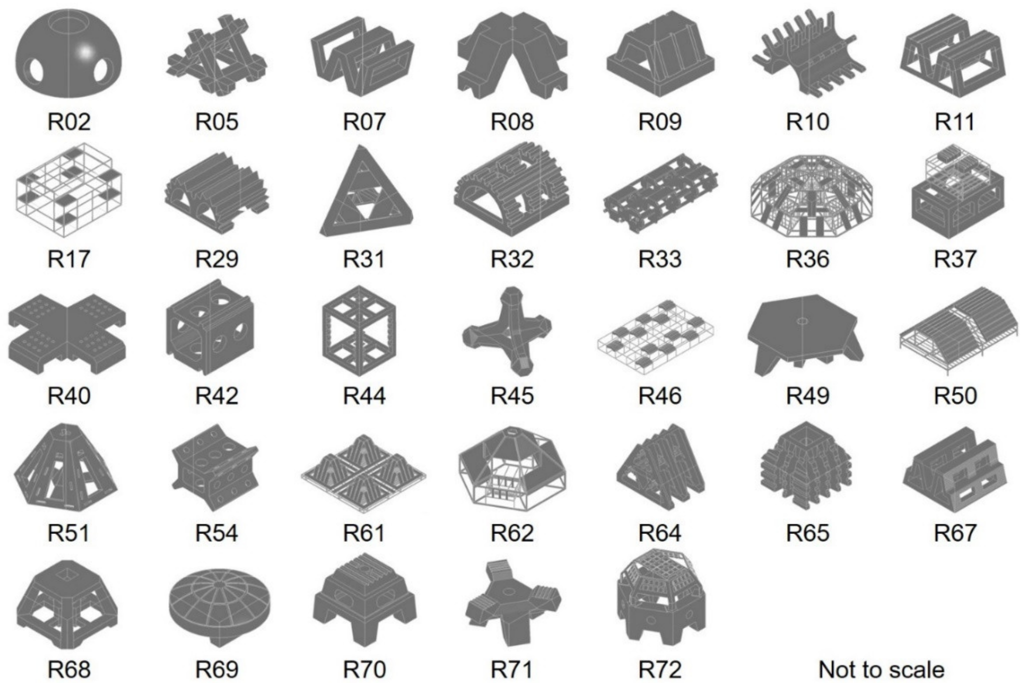

Figure 3. Representative ASR models used in South Korea. Numbering is in accordance with the artificial reef information book published by the FIRA [356].

Newer ASRs employ novel materials. For example, the ASR known as Triton is constructed using steel slag (a byproduct of steelmaking); 100 units were recently installed off the coast of Ulleungdo as a part of the marine forest formation project [359]. Both the local government and POSCO are monitoring the effects of steel slag (high in minerals such as calcium and iron) on seaweed growth, photosynthesis, and marine ecosystem restoration and diversification. Since 2020, oyster shells have been mixed with concrete substratum in the coastal area of Gijang-gun, Busan; algal coverage has been monitored [360]. Initially, the macroalgal coverage of the oyster–shell–concrete substratum was 10–80%; no macroalgae were attached to the concrete substratum alone. After 11 months, the macroalgal coverage was 49% greater on the oyster–shell–concrete substratum than on the original substratum.

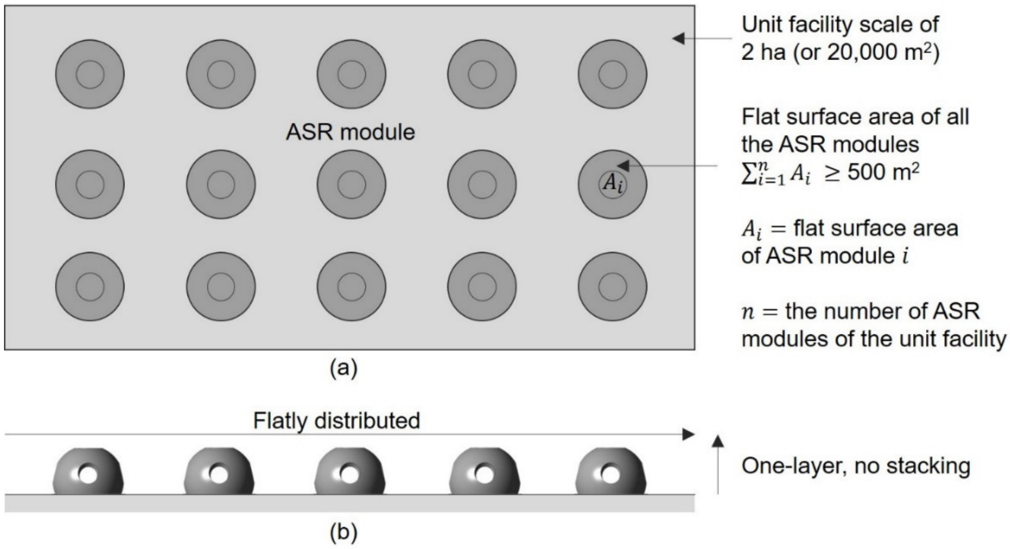

Figure 4. Representative practice of ASRs in South Korea: (**a**) plan view characterizing unit facility scale of 2 ha (or 20,000 m^2) and flat surface area of all the ASR modules (≥500 m^2) and (**b**) side view indicating the flatly distributed placement model.

7. Marine Forest Projects in South Korea

There are three types of marine forest projects in South Korea. First, the East Sea Fisheries Research Institute of the National Institute of Fisheries Science developed a marine forest formation program after a trial-and-error approach led to some failures in the establishment of seaweed forests in the East Sea. The research results have helped to achieve more efficient marine forest construction [361]. Second, the Ministry of Oceans and Fisheries recently developed a seed bank technique for seaweed forest restoration; this is a component of a marine industry development project [362]. Third, since 2013, an annual "Marine Gardening Day" has highlighted the importance of seaweeds [363]. We briefly introduce these projects below.

7.1. Marine Forest Formation

In regions where flat coralline development (communities of crustose, coralline, red alga-dominated communities) is absent, marine forest creation is less difficult than in other areas because natural seaweed spores attach to and grow on substrata, including ASRs and natural stones. However, when establishing a growth facility, the seafloor topography must be precisely mapped to ensure that the growth facility does not overlap with natural bedrocks on which seaweeds grow; the influence of wind and waves must also be minimized. If such facilities are installed in areas where coralline algae occur, green algae (e.g., green laver) will quickly grow in an epiphytic manner and then disappear. When red algae are epiphytic, crustose coralline algae will initially grow in an epiphytic manner and modify the shape of the bedrock. Thus, it is difficult to create a marine forest in an area of coralline flats; the construction methods are both challenging and artificial. Exhaustive testing has revealed that forest formation technology must be chosen after consideration of the nature and use of the water. We have convinced some local governments and self-managed fishing villages of the usefulness of our construction methods; we study the results (with these governments and villages) and modify our recommendations on an annual basis.

We assigned ourselves the following tasks: perennial seaweed seedling production and aquaculture, fabrication of ASRs for seedling transplantation, transplantation itself, utilization of floating rope methods, installation of spore bags, spraying of zoospores, periodic extermination of herbivorous animals, and very thorough follow-up [361]. In real-world project sites, it is difficult to apply all of these methods; some were omitted or neglected depending on specific circumstances. When creating a marine forest, the critical point is the selection of seaweeds. The following is a description of our findings thus far. First, the seaweed must be capable of mass production and artificial seedling culture. Marine forest creation is a large-scale effort; it is impossible if seedlings are not readily available. Second, the seaweed must be suitable for the local environment (i.e., the macroalga must be able to grow). Small-scale field tests in the target site are invaluable. Candidate seaweeds may be seaweeds already located at the project site or seaweeds that were previously located at that site. Third, the seaweeds should be large; such seaweeds are more economical and effective than small seaweeds when creating marine forests. If a marine forest is initiated using large seaweeds, spores of smaller seaweeds can subsequently be introduced to surrounding natural bedrocks to increase species variety. Fourth, perennial seaweeds are preferable because it is time-consuming and expensive to reconstruct ASRs. However, if the floating rope technique is used, fast-growing annual seaweeds are preferred because these often both feed herbivores and create marine forests. A floating rope facility can be reconstructed annually (at minimal effort and expense). The income of fishermen is optimized when floating ropes are used for annual delivery of food to coastal waters where seedlings of valuable aquatic animals (e.g., abalone) are released. *Eisenia bicyclis*, *Ecklonia cava*, *Ecklonia stolonifera*, and *Sargassum* tolerate seedling transplantation to ASRs; *Saccharina japonica*, *Undaria pinnatifida*, and *Costaria costata* tolerate seedling transplantation via floating ropes.

7.2. Seed Banks

Herbivores can devastate marine forests within a few days; urchins and other herbivores must be controlled. Seaweeds transplanted to barren grounds can create marine forests, sustain forest growth, and serve as seed banks that eventually restore healthy coastal ecosystems. Accordingly, before the restoration of a marine forest, certain organisms must be removed from the surface of natural bedrocks and ASRs; these organisms can trigger further bleaching or the development of urchin barrens. Unlike projects that focus on the installation of concrete structures, seed bank researchers seek to restore marine ecosystems using natural bedrock and existing ASRs. The main goal is the restoration of marine forests through improvements in the natural adhesive substrates of bedrocks and ASRs, which creates seed banks that prevent seaweed feeding while helping seaweed spores to settle and grow [362]. The workflow involves the following steps: (i) identification of key components; (ii) selection of a site; (iii) formation of a seed bank complex (hereafter referred to as SBC); (iv) use of a high-pressure pump to improve adhesion; (v) development of a system that encourages seaweed spore diffusion; (vi) monitoring of the SBC; and (vii) measurement of seaweed growth. This new approach uses natural bedrocks, along with existing ASRs, wires, and floating bodies. The key components (wire length adjusters and tension-holding devices) of the system prohibit changes in wire length and tension. A wire length adjuster regulates wire length while considering the difference between the initial environment of the transplant structure and the environment of the seabed where the structure is installed. The tension-holding devices prevent the loss of tension that might otherwise result from changes in the height of the floating body. All components are designed to tolerate underwater waves.

An SBC was evaluated in the coastal waters of Odori, Pohang City. The seabed was natural bedrock, sand, and gravel (sand proportion <5%). Mean bedrock depth was approximately 5 m and bleaching had already progressed to rank 3 (see Table 5). A preliminary survey indicated that an SBC was appropriate. At high tide, natural bedrock was drilled to 12–16 m in water depth; anchors were then fixed and eco-friendly (non-toxic) natural cement was placed. Eleven lower fixing devices were attached to each line; the SBC of 0.605 ha was finalized in 2017. A high-pressure pump was used to improve adhesion to substrata on which macroalgae had died or from which they had disappeared. Compared with conventional pumps, the high-pressure pump was less noisy, operated for longer, and was both smaller and lighter.

Table 5. Ranks, criteria, and causes of urchin barrens [362]. Of the causes, commercial resource utilization factors are excluded.

Ranks	Criteria	Causes
1	Coverage of crustose coralline algae: 40–60% (coverage of seaweed: 60–80%)	① Seaweed feeding by herbivores: 30 g m^{-2} day^{-1}; ② Number of herbivores: 5–10 m^{-2}; ③ Seaweed state: decrease in large brown algae and perennial seaweeds, increase in small red algae
2	Coverage of crustose coralline algae: 60–80% (coverage of seaweed: 20–40%)	① Seaweed feeding by herbivores: 40–60 g m^{-2} day^{-1}; ② Number of herbivores: 10–20 m^{-2}; ③ Seaweed state: signs of disappearance of large brown algae, colonies of small perennial red algae
3	Coverage of crustose coralline algae: ≥80% (coverage of seaweed: <20%)	① Seaweed feeding by herbivores: 70 g m^{-2} day^{-1}; ② Number of herbivores: ≥20 m^{-2}; ③ Seaweed state: disappearance of large brown algae, colonies of small perennial red algae

After formation of the SBC, a seaweed spore diffusion system was introduced. Adults were induced to release spores; falling spores became attached to a seedling frame. This system prevented spore diversion by currents and predation by herbivores (e.g., sea urchins). After 1 year, all parts were recovered. Tensile strength tests revealed that damage and corrosion were negligible. To analyze the growth rates of seaweeds attached to the parental lines, the sizes of 20 randomly selected individuals were averaged. Growth increased by 135.5%, from 26.5 to 62.4 cm. In total, 392 transplanted seaweeds grown from seed bank spores were identified 1 year after establishment. Thus, the seed bank technique is expected to restore once-dominant marine forests that have been bleached or have become urchin barrens. However, long-term monitoring is required. The seed bank technique may indeed mitigate declines in marine forests, but continuous evaluation and improvement are essential.

7.3. Marine Gardening Day

During Marine Gardening Day (May 10), seaweeds are planted in the ocean. The day was originally conceived by the FIRA, proposed to the National Assembly in 2011, legislated in 2012, and finally implemented through an amendment (Article 3-2) to the "Fisheries Resources Management Act" in 2013 [363]. The day seeks to raise awareness of the extent of ocean devastation and the importance of marine forests. The day focuses national and international attention on marine forest development, as well as the need to restore and enhance the marine ecosystems of calcified oceanic areas. For example, from 2 May 2022 to 13 May 2022, the public engaged in seaweed transplantation and waste collection in marine forests in the eastern, western, and southern coastal waters of South Korea. Educational programs were provided by the FIRA. Young children were encouraged to make sea forests, to view forest animations, and to turn these experiences into fairy tales told at daycare centers and kindergartens. In addition, regional educational offices created videos and other materials concerning marine ecosystem protection for use by elementary school students nationwide; the tools were age specific. All educational programs (except experimental teaching aids) are freely downloadable from the website of the Korea Fisheries Resources Service (www.fira.or.kr (accessed on 20 May 2022)). Annually, the FIRA recruits college students to support marine forest creation and marine resource enhancement. The FIRA is active on social media, develops online content, and supports both online and offline events (e.g., Marine Gardening Day). The benefits for supporters include certificates of completion, awards to outstanding performers, waiving of manuscript and team activity fees, and preference when applying for internships.

Similar days of emphasis have been implemented worldwide. In 2020, the United Nations Global Compact nominated June 4 as "Seaweed Day" and issued a "Seaweed Manifesto" that focused on the potential applications of these amazing sea vegetables. The manifesto, which was addressed to private companies, research institutions, United Nations agencies, and societies, explains how seaweed can literally save the world [364]. The Seaweed Manifesto was initiated by the Lloyd Register Foundation and has been supported by the Sustainable Ocean Business Action Platform and the United Nations Global Compact. Japan also has a "National Seaweed Day" (February 6), which was established in 1966 by the National Lionfish and Shellfish Cooperative Federation Association in accordance with a consensus of Japanese seaweed fishermen. This date marks the beginning of the nori season (early spring); nori (purple laver in English) is a dry edible seaweed used in Japanese cuisine (red algae of the genus *Pyropia* including *P. yezonesis* and *P. tenera*) [365].

8. Conclusions

Macroalgal forests enhance marine environments and human lives in many ways. Such forests reduce CO_2 levels, create marine habitats, yield products that enhance human well-being and serve as valuable foods, deliver other useful materials, and constitute sources of pure bioenergy. However, given the continuous degradation of global coastal ecosystems in recent decades (caused by both climate change and anthropogenic factors), global kelp levels may be declining by 2% annually, along with the levels of other coastal and marine ecosystems (e.g., salt marshes, mangroves, seagrasses, oyster reefs, and coral reefs). There are eight threats to macroalgae: ocean warming and marine heatwaves, El Niño events, grazing, commercial kelp harvesting, increased sediment loads, pollution, high-energy storms or swells, and combinations of these factors. For example, bleaching (possibly caused by ocean warming, grazing, and pollution) has spread to the east, west, and south coasts of South Korea; a recent survey showed that 44.9% of the study area was affected by ongoing or severely intensified bleaching.

Ocean macroalgal afforestation mitigates the declines in macroalgae and their forests while securing their benefits. There is worldwide implementation of microalgal restoration and enhancement via spore and vegetative transplantation techniques, as well as green gravel. ASRs are deployed in the USA, Japan, and Korea; early ASRs were simple concrete blocks, while current ASRs are more complex. ASR effectiveness depends on scale, materials used, structural composition, and surface complexity; success or failure remains a matter of trial and error. ASR complexity and materials have evolved to sustainably mitigate marine deforestation. Forty-two ASRs have been approved by the Korean government to enhance seaweed habitats. The numbers are increasing, the structures have become better, and current practices/guidelines even consider unit scale (2 ha or 20,000 m^2), flat surface area ($\geq$500 m^2), and placement (a flat distribution). Moreover, steel slag (Japan) and oyster-shell/concrete substrata (Korea) appear to be effective.

Ocean macroalgal forests are being created worldwide. The Korean projects focus on forest development and seed bank techniques, as well as Marine Gardening Day. ASRs support the establishment of the submerged aquatic vegetation beds necessary for oceanic macroalgal afforestation. For example, seedling transplantation to ASRs was possible for *Eisenia bicyclis*, *Ecklonia cava*, *Ecklonia stolonifera*, and *Sargassum*. The SBC identified 392 seaweeds 1 year after establishment; mean growth rate increased by 135.5% (from 26.5 to 62.4 cm). The application of seed bank techniques to existing ASRs may restore marine forests that were once widespread but were killed by bleaching or became urchin barrens. ASRs mitigate declines in marine forests. However, there is a need to continuously monitor progress and refine the ASRs. Successful outcomes depend on an understanding of marine forests that are literally hidden underwater, not systematically studied, and often overlooked; they also depend on the extent of desire for restoration of blue coastal ecosystems when international support is tepid.

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