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A study on Marine Algal Succession and Community in Pyramid-shaped Artificial Reef

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We propose a marine ecosystem restoration means to build marine ecosystems and restore marine forests by introducing ecological engineering concepts to oceans that have lost habitats and include dysfunctional marine ecosystems using pyramid-shaped artificial reefs during 2016 to 2017 at Mundong, Busan, Korea. The marine algal succession in the artificial reefs was as follows: in January of 2016, two months after the reef installment, only *Ulva* spp. and non-geniculated coralline algae were found. Ten months after installment, non-geniculated coralline algae were dominant; however, perennial *Ecklonia cava* continued to grow robustly. During the 2 years of monitoring, *Ecklonia cava* and *Grateloupia elliptica* were the dominant species growing on the artificial reefs. During the earlier stages post-installment, short-lived annual marine algae attached and grew on the reefs; however, as time progressed, the algal succession pattern changed to perennial marine algal dominance. In this study with artificial reefs, from the early stages post reef installment, various marine algal succession were observed in stages, and after normal structured communities were formed, a large perennial brown algae colony attached to the reef and formed a stable community. When installing artificial reef in new regions for ecological restoration, higher success rates will be observed if the surrounding vegetation is considered and the installation timed to when the large marine algae release their spores. Therefore, the timing of artificial reef installment should be carefully considered.

Key words: Ecosystem restoration, Marine forest, Ecological engineering, Succession

INTRODUCTION

Generally, marine forests are locations in the ocean where marine algae and eelgrass are abundant in large areas, similar to the forests on land. However, during the high economic growth period after the 1960's, land was reclaimed from coastal waters, concrete buildings were built near the coast line, and industrial water waste coming from the coastal industry caused water pollution; these factors collectively increased environmental pollution, which rapidly decreased the naturally formed marine forests. As a result, the total marine forest area has decreased by about 40% in the three decades since the 1980's (Serisawa *et al.* 1998; Cho *et al.* 2007).

Recently, barren ground formation in many areas has been reported to reduce marine forests. Research on the effects of barren ground formation was initiated on Jeju Island, and more research is continuing on the east coast and south coastal waters of Korea, while barren grounds are gradually expanding in the eastern coastal waters (MOMAF, 2002; Choi *et al.* 2006b; Sohn *et al.* 2007). Therefore, to restore the marine ecosystem and marine resources, artificial marine forests are necessary, and various studies on marine forest formation are being conducted by phycologists and fishery scientists (Serisawa and Ohno, 1995a, b; Choi *et al.* 2006a). The

installation of artificial reef is one method of artificial marine forest formation, and research on the marine algal succession process from the point of artificial reef placement to marine forest formation is very important (Serisawa and Ohno, 1995b; Choi, 2001). The usage of artificial reef in coastal waters for artificial marine forest formation, increase in marine resources, expansion of habitats, microorganism growth area formation, etc., has developed into an extremely important and generalized method for marine ecosystem restoration. Marine ecosystem formation using artificial reefs increases the number of marine products and marine resource organisms, and thereby naturally increases the amount of resources and yield (Choi *et al.* 2002, 2006a).

Researches of marine forest expansion and of increasing marine resource utilizing artificial reefs in Korea started from 1971 in all coastal areas of the country to create coastal resources, improve the environment for low-production fisheries, and to create marine ecosystems. However the materials and shapes of the artificial reefs have been limited and the majority of the installations have been concrete reefs. Recently, materials such as steel or ceramic has been used for artificial reefs to target diverse organisms such as fish, benthos, marine algae, etc.; however, diversity in the usage and materials of the artificial reef needs to be further developed (Cho *et al.* 2007; Choi, 2001).

The substrate is an important aspect of benthos distribution, and which substrate the organisms adjust to determines how each physiologically adjusts to the changes in habitat (Nybakken, 1982). However in a natural environment, there are many limitations and difficulties in determining the characteristics of the sub-

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strate-based distribution pattern of the benthos, because it is difficult for the researcher to control the date of substrate formation, location, gradient, direction, environmental factors, etc. Therefore, algal succession and distribution analysis with artificial substrates offers diverse usefulness on the ecological study of benthos (Osman, 1982; Kim, 1987).

In this study, we propose a marine ecosystem restoration means to build marine ecosystems and restore marine forests, etc., by introducing ecological engineering concepts to oceans that have lost habitats and include dysfunctional marine ecosystems due to various causes, such as the formation of barren grounds, increase in water temperatures, and marine pollution. Considering its potential for future applications in ecosystem restoration, a pyramid-shaped artificial reef was used, since the structure seemed more habitable for marine algae and benthos. This study was conducted to elucidate the characteristics related to marine algae attachment, stage-based pattern of succession, and the possibility to create marine forests.

MATERIALS AND METHODS

Marine environment

An artificial reef was installed at Mundong-ri, Gijang-gun, Busan in November 2015. To determine the marine environment characteristics, eight quarterly investigations were carried out during 2016 and 2017. Water temperature, salinity, DO, pH, transparency were measured at the top of the artificial reef with YSI-6600V2 and Secchi disc (ϕ 30 cm).

Diving investigation

Following placement of the pyramid-shaped artificial reef, eight quarterly SCUBA diving investigations were performed in 2016 and 2017 to determine which organisms were living attached to the surface of the reef. Quantitative analysis was performed with samples collected from 25×25 cm or 50×50 cm quadrats on the reef, and all attached organisms were collected after underwater photographing. Separately, organisms not found in the sampling quadrats were photographed and sampled, and were included in the species list for the qualitative analysis of organisms living on or near the

reef.

Analysis of attached organisms

The collected marine algae samples were thoroughly washed with fresh water to remove contaminants, and they were categorized based on the taxonomic group and species classification; species identity was determined either by eye, dissection microscope (Nikon SMZ745T), or optical microscope (Olympus BX41). We referred to recent publications for the observed marine algae species list and scientific names (Kang, 1968; Kim *et al.* 2013; Lee and Kang, 2002). The biomass of each sample was obtained by measuring the dry weight after species separation and dehydration in a dryer set to 105°C for 24–48 h and was converted to biomass per unit area (g/m^2).

To measure the ecological index of the algal community in the study sites, the richness index, evenness index, and diversity index were calculated based on the species formation and biomass data, and cluster analysis was performed with PRIMER version 5.0.

RESULTS AND DISCUSSION

The marine environment data measured during the research period is shown in Table 1. The water temperature was $7.31\text{--}24.93^\circ\text{C}$ at the surface and $7.09\text{--}24.56^\circ\text{C}$ at the bottom, and seasonal temperatures were observed; the temperature was highest during the summer season and lowest in the winter season. Salinity was $31.16\text{--}35.41$ PSU at the surface and $32.07\text{--}35.40$ PSU at the bottom; DO was $1.77\text{--}6.77$ mg/L at the surface and $1.54\text{--}6.84$ mg/L at the bottom. pH was $6.99\text{--}8.38$ at the surface and $7.10\text{--}8.37$ at the bottom, and transparency was in the range of 1.7–5.0 m.

The marine algal succession in the pyramid-shaped artificial reefs was as follows: in January of 2016, two months after the reef installment, only *Ulva* spp. and non-geniculated coralline algae were found. In March, the attachment and growth of *Ulva* spp., *Papenfussiella kuromo*, and the blade of *Ecklonia cava* on the reef were growth. *Ecklonia cava* was the dominant species, and the average dry weight was 3.32 g/m². Eight months after reef installment, not only *Ulva australis* and *Ecklonia cava*, but also various red algae such as

Table 1. Marine environment around pyramid-shaped artificial reef

	Item	1 st	2 nd	3 rd	4 th	5 th	6 th	7 th	8 th
Temp. ($^\circ\text{C}$)	Surface	8.52	7.31	15.38	13.71	9.15	13.42	17.25	24.93
	Bottom	8.02	7.09	12.43	13.63	8.12	13.98	15.68	24.56
Salinity (PSU)	Surface	33.80	33.03	32.36	34.06	35.41	31.16	34.37	32.16
	Bottom	33.80	33.10	33.26	34.16	35.40	32.07	35.23	32.30
DO (mg/L)	Surface	6.77	6.70	1.77	3.50	4.79	4.53	5.48	4.79
	Bottom	6.84	6.70	1.54	3.96	5.69	4.65	5.65	4.53
pH	Surface	7.49	7.07	7.97	7.60	6.99	8.18	7.92	8.38
	Bottom	7.53	7.10	8.04	7.84	7.19	8.25	8.17	8.37
Transparency (m)		3.5	3.5	5.0	1.7	3.0	2.0	2.5	2.5

Pachymeniopsis elliptica, *Chondrus ocellatus*, *Lomentaria catenata*, *Chondracanthus intermedius*, and *Gelidium elegans* were growing on the reef. Ten months after installment, non-geniculated coralline algae were dominant; however, perennial *Ecklonia cava* continued to grow robustly, with an average dry weight of 8.42 g/m², 77.6% of the total marine algae. At 14 months post-installment, *Ecklonia cava* was the dominant species, and red algae such as *Chondrus ocellatus* and *Plocamium telfairiae* coexisted; in subsequent investigations, red algae such as *Pachymeniopsis elliptica*, *Corallina pilulifera*, and *Lomentaria catenata* were dominant. The *Ecklonia cava* length was approximately 30–50 cm, showing continuous development compared to earlier stages of growth. During the 2 years of monitoring, *Ecklonia cava* and *Pachymeniopsis elliptica* were the dominant species growing on the artificial reefs, and marine algae such as *Chondrus ocellatus*, *Chondracanthus tenellus*, *Pterocladia capillacea*, *Rhodymenia intricata*, and *Corallina pilulifera* were frequently observed. During the earlier stages post-installment, short-lived annual marine algae attached and grew on the reefs; however, as time progressed, the algal succession pattern changed to perennial marine algal dominance (Table 2).

It is known that during the initial stages of marine algal succession on artificial reef shortly after installment, short-lived pioneer species are dominant; consistent with this, our research showed *Ulva* spp. as the early settler on the reef surface 2 months after reef installment (Serisawa *et al.* 1998). Kim (1987) reported that pioneer algae (the first algae that adheres to the new artificial surface) mostly consisted of spherical blue-green algae, diatom, filamentous green algae, or crustose coralline algae. Our results were consistent with these findings.

Thereafter, during the monitoring at 8 months after installment, the species that appeared changed from pioneer algae to *Ecklonia cava*, *Pachymeniopsis elliptica*, *Gelidium elegans*, etc. These marine algae were stably maintained without significant changes even after 2 years, showing a stable succession pattern of the dominating perennial brown algae *Ecklonia cava*. *Corallina pilulifera*, geniculated coralline algae, and non-geniculated coralline algae also consistently grew on the reef

surface.

Choi *et al.* (2006a) separated the succession process into three stages (early stage, second stage, and climax stage), and reported that marine algal flora gradually changes from the short-lived *Ulva intestinalis* and *Colpomenia sinuosa* dominating early succession stage. They reported that the artificial reef showed stable succession patterns with perennial large brown algae dominance 24 months after entering the second stage; in our research, we observed the same pattern of initial growth of short-lived marine algae, later leading to perennial algae succession. Niell (1979) reported into three phases the process of marine algae community formation after attaching to temperate seas substrates: colonization phase, channeling succession phase, and normal structured communities, and the marine algal succession pattern we observed two years after reef installation was in the normal structured communities phase.

So far, research elucidating the marine algae ecological characteristics on the artificial reefs installed in our seas, such as determining the marine algal community succession pattern and community structures, has been insufficient (Kim and Park, 1997). However, since artificial reef is frequently installed to protect marine resources, increase the number of fishes caught, and build artificial marine forests, the results obtained from these studies have great importance as useful data for diverse fields. Therefore, when artificial reef is installed and related studies are conducted in various seas, studies of the marine algal succession pattern and community analysis should also be conducted.

The marine algae that appeared in the artificial reefs during our study comprised a total of 83 species; 9 Chlorophyta, 4 Phaeophyta, and 70 Rhodophyta were observed, and red algae comprised 84.3% of the total species observed. The average dry weight of the investigational area was 140.10 g/m²; green algae was 0.48 g/m², brown algae was 88.97 g/m², and red algae was 50.66 g/m². Brown algae had the highest percentage, accounting for 63.5% of the total dry weight (Table 3, Figs. 1, 2).

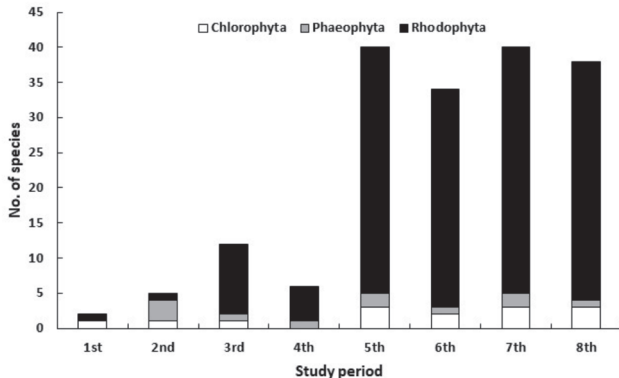
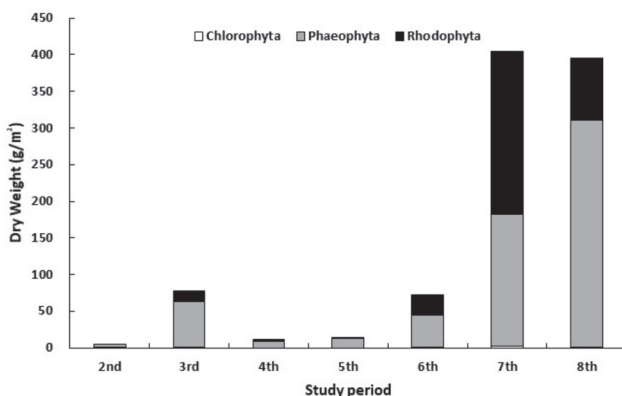
The number of observed species per investigation period is as follows; 3 Chlorophyta, 2 Phaeophyta, and 34 Rhodophyta (a total of 39 species) were observed in January to May of 2017, which was the highest number

Table 2. Percentage (%) of dry weight of dominant marine algal species during study period

Species	2 nd	3 rd	4 th	5 th	6 th	7 th	8 th
<i>Ulva</i> spp.	15.9						
<i>Ecklonia cava</i>	62.1	79.7	77.6	85.7	61.4	44.5	78.7
<i>Papenfussiella kuromo</i>	21.3						
<i>Pachymeniopsis elliptica</i>		18.1	22.2		15.5	17.5	5.2
<i>Grateloupia cornea</i>			0.2				
<i>Grateloupia</i> spp.				4.5			
<i>Chondrus ocellatus</i>		1.0					3.5
<i>Chondrus</i> spp.				3.8			
<i>Corallina pilulifera</i>					6.2	11.8	

Table 3. Number of marine algal species and dry weight in pyramid-shaped artificial reef

Division	No. species	Ratio (%)	Mean DW (g/m ²)	Ratio (%)
Chlorophyta	9	10.8	0.48	0.3
Phaeophyta	4	4.8	88.97	63.5
Rhodophyta	70	84.3	50.66	36.2
Total	83	100.0	140.10	100.0

**Fig. 1.** Number of marine algal species in pyramid-shaped artificial reef.**Fig. 2.** Dry weight of marine algal species in pyramid-shaped artificial reef.

of species observed during the investigational period. During the early stages after reef installment, in March of 2016, the least number of species was observed, which consisted of 1 Chlorophyta, 3 Phaeophyta, and 1 Rhodophyta. The dry weight of the marine algae attached to the reef was highest in the May 2017 investigation, reaching an average of 404.87 g/m², and lowest in March of 2016, which was also when the lowest number of species was observed, with an average of 5.35 g/m².

The dominant species that was observed on the artificial reef, determined by the dry weight, was the brown algae *Ecklonia cava*, which had an average dry weight of 88.80 g/m², comprising 63.4% of the total dry weight. Red algae *Pachymeniopsis elliptica* and *Corallina pilulifera* were also dominant, with average dry weights of 17.00 g/m² (12.1%) and 9.20 g/m² (6.6%), respectively.

Ecklonia cava growing on the surface of the artificial reef is greatly affected by the ocean and tidal current, and the density of *Ecklonia cava* is highest where the tidal current forms a whirlpool on the reef surface (Cho *et al.* 2007). Depending on the artificial reef structure, the attached *Ecklonia cava* density can differ by up to 8-fold. Foster (1975) reported that the edge effect increases the settlement of marine algae spores, and Choi *et al.* (2002) stated that blade attachment is easier on the edge of the artificial reef where the whirlpool forms. The dominant growth of *Ecklonia cava* on the reef surface observed in our study suggests that either the edge effect or whirlpool effect had an influence on the growth of *Ecklonia cava*. Furthermore, the *Ecklonia cava* population attached to the artificial reef stably developed a community, and the annual and perennial population co-existed to form a community of mixed life-spans.

Kim and Park (1997) speculated that the community formed on artificial substrates in the intertidal zone near the one-year period forms a stable structure. However in our study, the *Ecklonia cava* attached to the artificial reef within 4 months of reef installment, and stably developed thereafter. The shortened time required for stable growth of the *Ecklonia cava* and the formation of an algal community suggests that the surrounding marine environment was optimal for marine algae attachment and growth.

Kang *et al.* (2008) reported that *Pachymeniopsis* spp., *Ulva australis*, *Ecklonia cava*, etc. are widely distributed in Ilgwang bay, which is near our research area, and that those species dominate in autumn and winter. The dominating species of our studies were similar, and we speculate that the new substrate in the artificial reef was suitable for marine algae development. The composition and biomass of the coastal marine species have been decreasing due to ocean pollution caused by recent increases in ocean temperatures, various marine pollution accidents, and increased usage of ocean space (Choi, 2007). The installation of artificial reefs that have wide applications as a new substrate can be offered as a solution to these problems.

The ecological indices at each peak period were as follows: richness index was 16.59, evenness was 0.34, and diversity was 1.49 (Table 4). During the investigational period, richness was highest in January of 2017 with a value of 14.34, and the lowest value (1.68) was reached in September of 2016. Evenness showed the highest value (0.59) in March of 2016, and the lowest was 0.18, in January of 2017. Diversity was highest (1.88) in May of 2017, and the lowest was 0.55, in September of 2016.

Table 4. Ecological index of marine algal species in pyramid-shaped artificial reef

	Richness	Evenness	Diversity
Pyramid-shaped artificial reef	16.59	0.34	1.49

Our ecological indices of the marine algae growing on the artificial reef surface were similar or slightly lower than the species diversity index of 1.2–3.0 calculated from the marine algal coverage in the nearby Ilgwang Bay (Kang *et al.* 2008). This difference is considered to be due to the environmental differences during the peak of each study. The severe changes in salinity and the soft bottom environment of the seas near Ilgwang Bay is thought to cause a greater deviation in the species diversity index, compared to the diversity index calculated from the artificial reef. Yoo (2003) suggested that to accurately determine the criteria for the maintenance of a stable community, substantial research on marine algae communities in different environments needs to be conducted, and that it is unreasonable to determine species diversity based on simple numerical values. Therefore, the diversity index calculated in this study, and the numbers calculated by prior studies conducted nearby, should only be compared to determine whether there was a significant difference.

In this study with artificial reefs, from the early stages post reef installment, various marine algal succession were observed in stages, and after normal structured communities were formed, a large perennial brown algae colony attached to the reef and formed a stable community. These results showed that, in the future, when artificial reef is installed in the sand substrate near bedrock, the possibility of expanding the artificial marine forest is very high. In addition, when installing artificial reef in new regions for ecological restoration, higher success rates will be observed if the surrounding vegetation is considered and the installation timed to when the large marine algae release their spores. Therefore, the timing of artificial reef installment should be carefully considered.

AUTHOR CONTRIBUTIONS

C. G. Choi, S. W. Jung, J. K. Ahn, and I. J. Kang designed this study and drafted the manuscript. C. G. Choi, and I. J. Kang conceived and designed the study, and also revised the manuscript. Y. Shimasaki supervised the work. All authors read and approved the final manuscript.

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