Abstract—We evaluated the effectiveness of wooden artificial reefs (ARs) as fish habitat. Three types of ARs, made of cedar logs, broadleaf tree logs, and PVC pipes, respectively, were deployed in triplicate at 8-m depth off Maizuru, Kyoto Prefecture, Sea of Japan, in May 2004. Fish assemblages associated with each of the nine ARs were observed by using SCUBA twice a month for four years. Fish assemblages in the adjacent habitat were also monitored for two years before and four years after reef deployment. In the surveyed areas (ca. 10 m^2) associated with each of the cedar, broadleaf, and PVC ARs, the average number of fish species was 4.14, 3.49, and 3.00, and the average number of individuals was 40.7, 27.9, and 20.3, respectively. The estimated biomass was also more greater when associated with the cedar ARs than with other ARs. Visual censuses of the habitat adjacent to the ARs revealed that the number of fish species and the density of individuals were not affected by the deployment of the ARs. Our results support the superiority of cedar as an AR material and indicate that deployment of wooden ARs causes no reduction of fish abundance in adjacent natural reefs.

Fish assemblages associated with three types of artificial reefs: density of assemblages and possible impacts on adjacent fish abundance

Reiji Masuda (contact author)[1]

Masami Shiba[2]

Yoh Yamashita[1]

Masahiro Ueno[1]

Yoshiaki Kai[1]

Asami Nakanishi[1]

Masaru Torikoshi[1]

Masaru Tanaka[3]

Email address for contact author: reiji@kais.kyoto-u.ac.jp

[1] Maizuru Fisheries Research Station
Kyoto University
Nagahama, Maizuru
Kyoto 625-0086, Japan

[2] Ashiu Forest Research Station
Kyoto University
Miyama, Nantan
Kyoto 601-0703, Japan

[3] University of Malaysia Sabah
Locked Bag No. 2073
88999, Kota Kinabalu
Sabah, Malaysia

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Habitat complexity plays a major role in the survival of young demersal fishes by providing a refuge from predation (Ferreira et al., 2001; Scharf et al., 2006; Hamilton and Konar, 2007). Fish species richness is highly dependent on the rugosity and variety of growth forms in the habitat, whereas the height of vertical structures is an important predictor of total fish abundance (Gratwicke and Speight, 2005). In this respect, artificial reefs (ARs) are often deployed to improve the quality of habitat (Gorham and Alevizon, 1989). In addition to their role as refuges, ARs host encrusting invertebrates that can be consumed as prey by fishes (Seaman and Jensen, 2000). Fish are often more abundant at ARs than at natural reefs, probably because the vertical structures potentially allow more varied refuges for fish settlement and recruitment than the usual more moderately sloped bottoms of natural reefs (Rilov and Benayahu, 2000; Reed et al., 2006).

Although the deployment of structures functioning as ARs may well have started long ago by fishermen in various localities around the globe, research on this subject is relatively recent (Seaman and Sprague, 1991). Two countries, United States and Japan, have relatively long histories of nationwide projects on ARs. In the case of the United States, the main goal of deploying ARs has been to improve catch for recreational fishermen. Common materials used for these ARs have been waste products, such as automobiles, tires, and oil and gas platforms. The use of such products has caused environmental concerns, resulting in a shift toward the construction of ARs with concrete (Collins et al., 2002). In contrast, the purpose of Japanese deployments of ARs have primarily been to improve commercial fishery production, and governmental agencies have invested heavily in the construction of large ARs made of concrete and steel to be deployed in coastal areas.

The recent trend for ARs in Japan has shifted from concrete to wooden construction. This has been partly due to funding shortages, but also because fishermen have found that wooden ARs attract fish more rapidly than those made of concrete or steel. Indeed, most coastal prefectures in Japan deploy wooden ARs with or without governmental subsidies under the supervision of local fishermen's cooperatives. The materials and shape of wooden ARs differ depending on each fishery cooperative. As much as 70% of the land area in Japan is forested, half of which is plantation forests of conifers, such as Japanese cedar (*Cryptomeria japonica*) and hinoki cypress (*Chamaecyparis obtusa*). Although these forests require occasional thinning, many of them lack such maintenance because of the decline in the market price of timber. Therefore, the construction of wooden ARs also has the socioeconomic potential to stimulate the demand for forestry materials.

The primary goal of the present study was to confirm the efficacy of wooden ARs, especially those made of cedar tree logs as fish habitat. For this purpose, fish assemblages associated with ARs made from cedar trees were compared to those made from broadleaf trees and those made with polyvinyl chloride (PVC) pipes. There is a debate whether ARs merely attract fishes from adjacent areas or whether they do improve fishery productivity (Grossman et al., 1997; Pickering and Whitmarsh, 1997). We therefore tested the possibility that ARs attract fishes from adjacent areas and thus concentrate fish abundance at the ARs, rather than fish abundance is spread over the fishing ground as a whole. A visual census had been conducted twice a month for more than two years before the deployment of these ARs in adjacent areas; hence the fish fauna was compared in the area before and after the deployment of ARs.

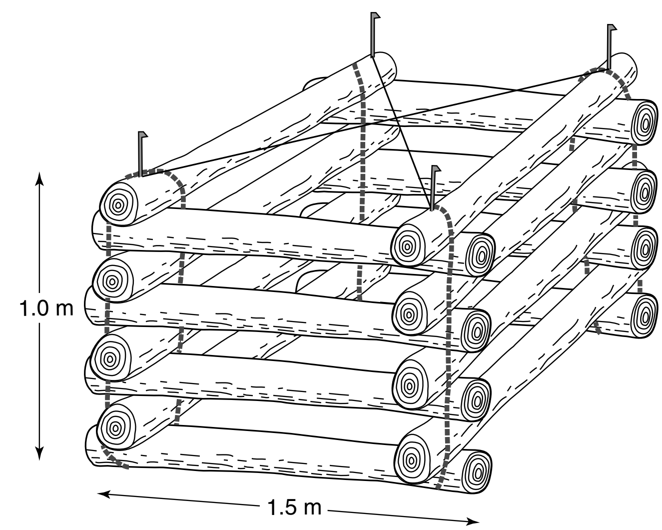

Figure 1

Shape and dimensions of the artificial reefs installed off Maizuru, Kyoto, in 2004 to evaluate the effectiveness of cedar, broadleaf, and PVC artificial reefs.

Materials and methods

Deployment and visual census of artificial reefs

Three types of ARs were prepared. The design of the ARs was modified from that designed by the Atake Forestry Association, Yamaguchi, Japan (http://www.geocities.jp/abu_kikori/katsudou/gyosyou/gyosyou2.html, accessed on December 2003; also see Fig. 1). The first type of AR (cedar AR) was constructed of 16 log sections (1.5 m long, 6.9–18.4 cm diameter) of Japanese cedar (*Cryptomeria japonica*) arranged in a parallel cross formation. Each corner was tied with rope and fixed with a stainless steel rod. Diagonal wires helped maintain the rectangular shape. The second type of AR (broadleaf AR) was constructed from six species of broadleaf trees harvested from the Ashiu Forest Research Station, Kyoto University, and assembled with the same dimensions as those used for the cedar AR. The broadleaf tree species used were Japanese cherry birch (*Betula grossa*), hornbeam (*Carpinus laxiflora*), Japanese beech (*Fagus crenata*), Chinese chestnut (*Castanea crenata*), redvein maple (*Acer rufinerve*), and macropoda holly (*Ilex macropoda*). The diameter of broadleaf and cedar logs ranged from 7.5 to 19.2 cm. The third type of AR (PVC AR) was made of hollow PVC pipes (11.8 cm diameter, 3 mm thickness) and was assembled in the same manner as that used for the other two types of ARs.

These three types of ARs were constructed in triplicate and deployed at a depth of 8 m off the Maizuru Fisheries Research Station (MFRS), Nagahama, Maizuru, Kyoto (35°29′N lat. and 135°22′E long.) on 21 May 2004 (Fig. 2). The shore in this area is a concrete bank and its subtidal zone consists of natural rocks, concrete blocks, both partly covered by live oyster (*Crassostrea gigas*) and their dead shells, and sandy silt with some macroalgal vegetation. The substrate in the research area consisted of muddy silt with no macroalgae vegetation. Each AR was sunk with 240 kg of sand bags (60 kg attached to each corner of the AR). ARs were set 15 m apart.

Twice monthly visual censuses of fish assemblages associated with each AR were conducted for four consecutive years after AR deployment. All census observations were made by the first author with SCUBA equipment. The area in and around each AR was observed for about three minutes and the species, size, and number of fish were recorded. A census commenced from one of the lateral sides of an AR and extended out to about 1 m from each side. The observer then swam around and above the AR, and the fish inside the AR were

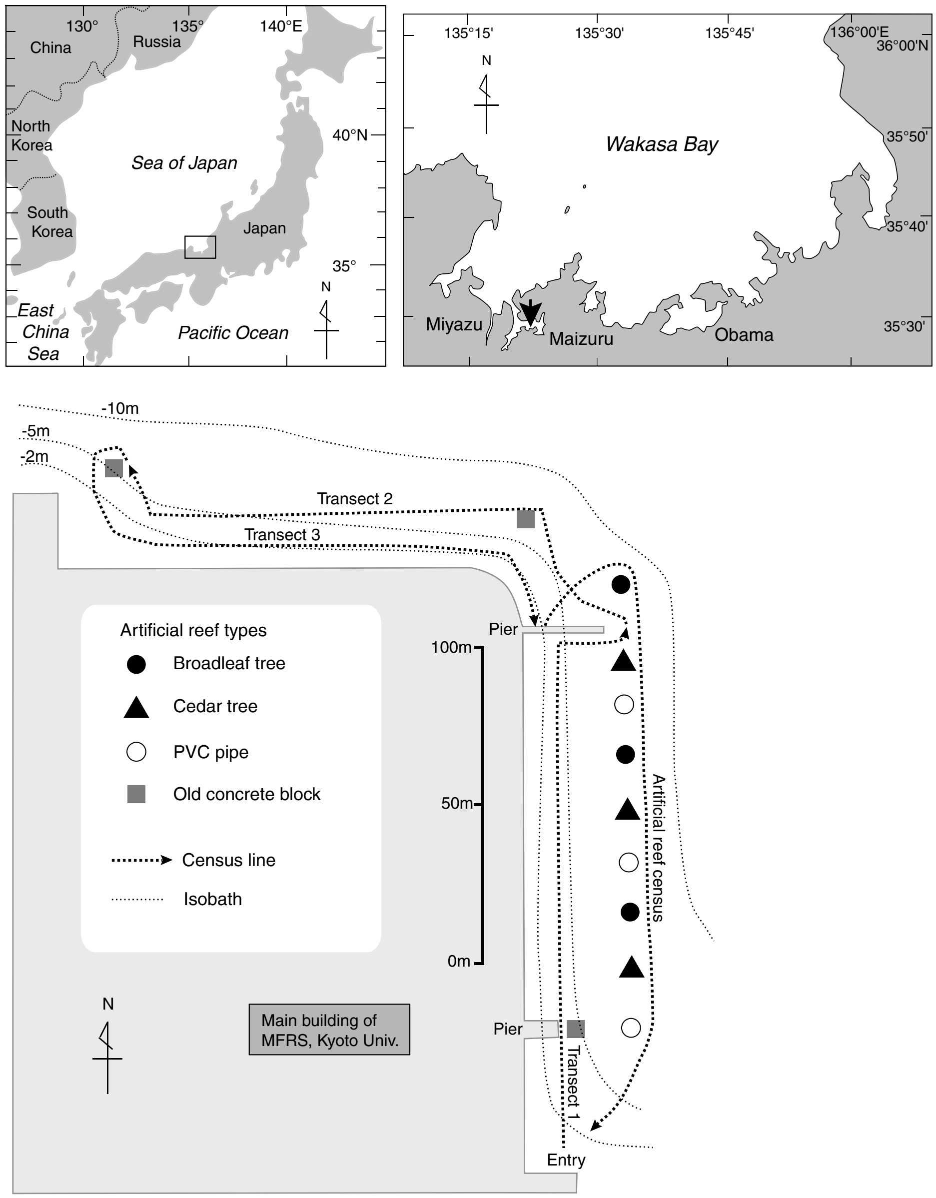

Figure 2

Map of study area for artificial reef deployment off Maizuru, Kyoto, in 2004. Upper-left map shows location of Wakasa Bay (in box) along the Sea of Japan. The arrow in the upper-right map represents the location of the research area in Maizuru Bay. Lower map shows the research area off the Maizuru Fisheries Research Station (MFRS), Kyoto University, with the nine artificial reefs (three types×three replicates) deployed in a line. Observations were conducted after the visual census of the adjacent habitat (transects 1–3). Census lines are expressed by thick dotted lines, and -2 m, -5 m, and -10 m isobaths are expressed by thin dotted lines.

recorded. Fish were considered as associating with an AR if they were swimming or dwelling within 1 m of the AR (Sherman et al., 2002), and thus fish in an area of about 10 m^2 were counted for each AR. Fish standard length (SL) was estimated with the help of a scale marked on a clipboard and was recorded. Length estimates were occasionally calibrated by capturing and measuring fish. These calibrations revealed that visual SL estimates were within 10% error of the actual measured SL. Water temperature and visibility during observations ranged from 10.1° to 28.8°C and from 1 to 5 m, respectively. Biomass calculation for each AR was conducted according to the method of Santos et al. (2005) and Friedlander et al. (2007). The estimated average length of each species for each sample was converted to mass by using the length-mass relationship

$$M=a\mathrm{SL}^b,$$

where a and b = constants for allometric growth;
SL = standard length; and
M = mass.

Length-mass parameters were obtained from FishBase (www.fishbase.org, accessed on July 2008) and calibration was based on our own samples.

The number of fish species (species richness), total number of fish individuals (abundance), total fish biomass, and number of individuals of each fish species associated with each type of AR were compared among the three types of ARs by repeated measures ANOVA followed by Tukey's HSD test. Data for the number of fish individuals and their biomass were log (x+1) transformed to obtain homoscedasticity.

Estimation of the impact of AR deployment on fish abundance in the adjacent area

Fish assemblages in the area surrounding the ARs were compared before and after AR deployment. Data from the twice monthly visual censuses in each area were used for this purpose (Masuda, 2008; Fig. 2). The number and size of fish of each species found along three 400-m^2 belt transects have been recorded twice a month since 1 January 2002. One transect was close to the location of the ARs that we deployed in the present study (transect 1), and the other two were relatively distant (transects 2 and 3). Therefore, species richness and fish abundance in transect 1 would decline after AR deployment if fish were simply attracted from the adjacent natural reef to these ARs. Each of the three transects included areas of rocky reef, live oysters and their dead shells, a sandy or muddy silt bottom, and an artificial vertical structure made of concrete blocks that had been deployed more than 20 years earlier. The size (length × width × height) of the concrete structures along transects 1, 2, and 3 were 0.5×3×2.4 m, 1.8×3×1 m, and 2.5×2.5×2 m, respectively. Data from 23 May 2002 to 15 May 2004, and those from 29 May 2004 to 8 May 2008 were used to compare the fish assemblages before and after deployment of the ARs. Analyses of covariance (ANCOVA) was used to compare species richness and fish abundance in each transect before and after deploying the wooden or PVC ARs, and bottom water temperature was used as a covariant because fish species richness and abundance increase almost linearly with the increase of bottom water temperature in this habitat (Masuda, 2008). The number of individuals of each species was also compared by ANCOVA before and after deployment of the ARs. All statistical analyses were conducted with the software JMP (vers. 5.0.1J, SAS Institute, Inc., Cary, NC) with an alpha level of 0.01.

Table 1

The mean (±standard error) number of species, individuals, and estimated biomass of fish attracted to the cedar, broadleaf, and PVC artificial reefs over the entire observation period (2004–08) and for each of the four years (n=3 ARs per type). Different letters represent significant differences among AR types (P<0.01, Tukey's HSD test).

	Cedar ARs	Broadleaf ARs	PVC ARs
No. of species			
Whole period	4.14 ±0.138^a	3.49 ±0.107^b	3.00 ±0.113^c
1st year	5.14 ±0.332^a	3.44 ±0.245^b	2.51 ±0.201^c
2nd year	4.10±0.289^a	3.49 ±0.244^b	2.83 ±0.232^c
3rd year	3.93 ±0.226^a	3.63±0.225^{ab}	3.28 ±0.217^b
4th year	3.38 ±0.196	3.40 ±0.193	3.38 ±0.195
No. of individuals			
Whole period	40.7 ±4.43^a	27.9 ±2.88^b	20.3 ±2.18^c
1st year	84.5 ±12.9^a	36.8 ±5.86^b	29.6 ±6.23^c
2nd year	24.1 ±5.00^a	28.0 ±5.88^a	10.9 ±2.25^b
3rd year	32.1 ±8.31^a	24.7 ±6.80^b	19.0 ±4.00^b
4th year	22.0 ±4.59	22.1 ±4.15	21.9 ±3.82
Fish biomass (grams)			
Whole period	284 ±34.7^a	143 ±19.1^b	157 ±40.7^b
1st year	498 ±89.8^a	113 ±24.4^b	243 ±157^b
2nd year	222 ±51.6	134 ±38.7	89.1±19.3
3rd year	310 ±82.0	179 ±44.8	141 ±28.4
4th year	108 ±29.9^b	148 ±41.8^b	155 ±28.2^a

Results

Fish assemblages associated with the ARs

Both species richness and fish abundance were highest associated with the cedar ARs, intermediate with the broadleaf ARs, and lowest with the PVC ARs when compared over the entire sampling period (Table 1). These differences were significant among the three AR types in both of these measurements (repeated measures ANOVA followed by Tukey's HSD test: P<0.01). The greater effectiveness of the cedar ARs was prominent in the first year after deployment but decreased with time and became nonsignificant in the fourth year (Table 1; Fig. 3). Fish biomass was greatest in the cedar and PVC ARs in the first and fourth year, respectively, but did not differ significantly in the second and third years.

A total of 62 fish species were observed in 96 dives on these nine ARs, among which six species were found most frequently in the cedar ARs, two in the broadleaf ARs, and two in the PVC ARs (Table 2). Five most commonly observed fish species in the ARs were black rockfish (*Sebastes inermis*), jack mackerel (*Trachurus japonicus*), bambooleaf wrasse (*Pseudolabrus sieboldi*), chameleon goby (*Tridentiger trigonocephalus*) and whitespotted pigmy filefish (*Rudarius ercodes*) (Fig. 4); the former three species are targeted in commercial fisheries, whereas the latter two are prey species of other commercial species. Jack mackerel is pelagic and migratory, and the other four species are demersal and relatively sedentary. The typical fishes showing high preference for the cedar ARs were black rockfish, sunrise sculpin (*Pseudoblennius cottoides*), black sea bream (*Acanthopagrus schlegelii*), whitespotted pigmy filefish, thread-sail filefish (*Stephanolepis cirrhifer*), and finepatterned puffer (*Takifugu poecilonotus*). Two species of goby (*Istigobius hoshinonis* and *T. trigonocephalus*) were most abundant in the broadleaf ARs (Fig. 4). Redspotted grouper (*Epinephelus akaara*) and barface cardinalfish (*Apogon semilineatus*) were most abundant in the PVC ARs. Jack mackerel and bambooleaf wrasse were the most abundant species during the entire census period (Table 2), but they did not show any clear preference for a particular type of AR.

Maximum, minimum, and average body length in two highly abundant and commercially important species, black rockfish and jack mackerel, are plotted for each type of artificial reef in Figure 5. Black rockfish generally had a wide range (1.5–16 cm) of body length, whereas jack mackerel had a smaller body size range (4–12 cm). This was prominent in cedar ARs, especially shortly after the deployment of the AR (Fig. 5A).

A bryozoan community was established within two to three months of deploying the cedar ARs. Other encrusting epibenthic assemblages, such as Porifera, Cnidaria, Mollusca, and Annelida, gradually formed on the broadleaf and PVC ARs after one year. The upper sections of the ARs attracted these encrusting organisms more rapidly than the lower sections. In the fourth year, some of the upper sections of the cedar and broadleaf ARs began to decay because of fouling by encrusting organisms, particularly wood boring piddock (*Martesia striata*). Crabs (*Charybdis japonica*) and sea cucumbers (*Stichopus japonicus*) were common in all types of ARs. At least four fish species, black sea bream, Temminck's surfperch (*Ditrema temmincki*), whitespotted pigmy filefish, and thread-sail filefish, were observed feeding on the encrusting organisms on and around the cedar ARs. Conger eel (*Conger myriaster*), two species of groupers, and large individuals of bambooleaf wrasse resided inside the PVC pipes. Some fish, such as thread-sail filefish and redfin velvetfish (*Paracentropogon rubripinnis*), overwintered, showing minimal movement in the cedar ARs through the winter.

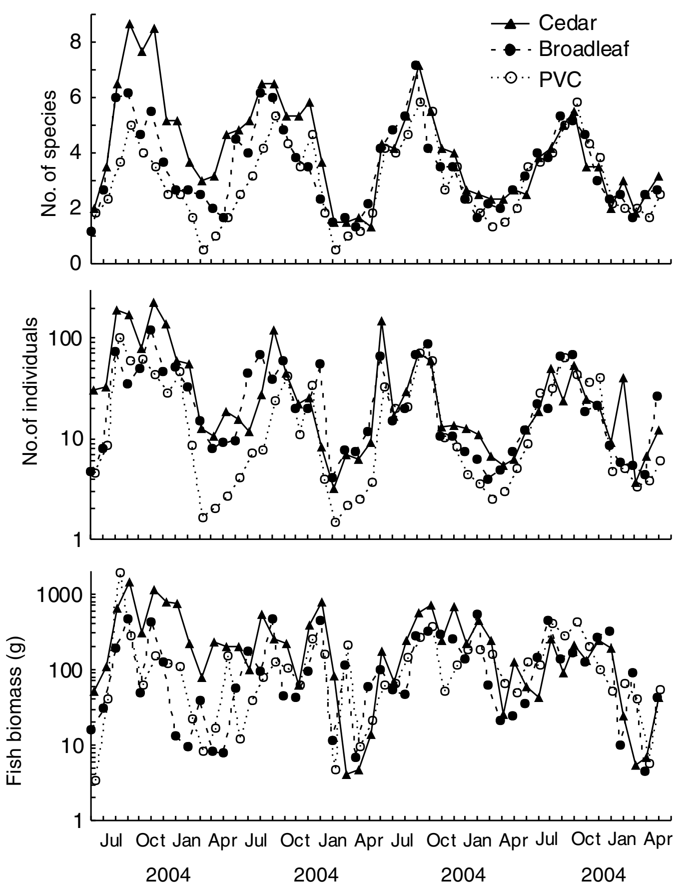

Figure 3

Species richness, fish abundance, and fish biomass associated with each type of artificial reef on each observation day between May 2004 and April 2008. Plotted data are averages of the two monthly observations carried out at each triplicate artificial reef. Note log scale for individuals and biomass plots.

Fish assemblages in the adjacent habitat

Visual censuses of the areas adjacent to the ARs revealed that both fish species richness and abundance showed clear seasonal changes corresponding to variations in sea bottom water temperature (Fig. 6). A total of 73,922 fish individuals from 90 species were recorded from 23 May 2002 to 8 May 2008 in transects 1–3. There was no significant change in fish species richness or abundance along any of the three transects after the deployment of ARs (P>0.5, ANCOVA; Table 3). Species-to-species analysis revealed that although there were several cases of increases or decreases in abundance after deployment, there was no evidence of a systematic decrease in species richness along transect 1, in which one species decreased and four species increased after the deployment (see far-right column in Table 2). The average (±SE) number of individuals in the entire census area of the adjacent habitat was 171 ±12.6 per 400 m^2.

Table 2

Families and species of fish found on the three types of artificial reefs, as well as the mean body length, size range, frequency of occurrence (no. of sightings from the 3 replicates × 96 bimonthly observations) and mean number of specimens observed. Different letters represent significant differences among artificial reef types ($P<0.01$, Tukey's HSD test). An increase or decrease in the number of individuals in the adjacent habitat is noted under the heading "Transects"; for example, "–2" represents a significant decrease in the transect 2 ($P<0.01$, ANCOVA). Only species which were observed three times or more are included in the table.

		Body length (cm)		Frequency			No. of individuals, mean ±SE			
Family	Species name	Mean	Range	Cedar	Broadleaf	PVC	Cedar	Broadleaf	PVC	Transects
Engraulidae	*Engraulis japonicus*	6.0	3–7	2	2	0	2.4 ±1.4	1.7±1.2		
Plotosidae	*Plotosus lineatus*	7.2	4–20	4	6	3	3.1 ±1.6	3.5±1.5	2.3 ±1.4	
Scorpaenidae	*Sebastiscus marmoratus*	11.8	5–18	8	3	5	0.031 ±0.010	0.010 ±0.006	0.017 ±0.0077	
	Sebastes joyneri	3.6	3–7	2	5	0	0.014 ±0.11	0.066 ±0.044		
	Sebastes thompsoni	3.4	2–8	8	12	10	0.35 ±0.22	0.20 ±0.077	0.48 ±0.26	
	Sebastes inermis	5.2	1.5–16	167	104	104	6.8 ±0.99^{a}	3.7 ±0.48^{b}	2.2 ±0.33^{b}	
Synanceiidae	*Paracentropogon rubripinnis*	4.8	3–7	21	29	14	0.087 ±0.019	0.14 ±0.028	0.063 ±0.015	2–
Hexagrammidae	*Hexagrammos agrammus*	11.5	9–14	4	0	0	0.017 ±0.0092			
	Hexagrammos otakii	12.8	12–16	2	5	1	0.0069 ±0.0049	0.017 ±0.0077	0.0035 ±0.0035	
Cottidae	*Furcina ishikawae*	3.7	3–4	2	1	0	0.0069 ±0.0049	0.0035 ±0.0035		
	Pseudoblennius cottoidae	6.3	3–12	62	46	35	0.31 ±0.042^{a}	0.19 ±0.028^{ab}	0.16 ±0.028^{b}	
Serranidae	*Epinephelus akaara*	14.1	10–19	4	2	12	0.014 ±0.0069^{b}	0.0069 ±0.0049^{b}	0.045 ±0.013^{a}	
	Epinephelus awoara	9.1	4–15	6	2	11	0.021 ±0.0084	0.0069 ±0.0049	0.038 ±0.011	
Apogonidae	*Apogon semilineatus*	4.3	2–6	4	3	20	0.049 ±0.036^{b}	0.017 ±0.010^{b}	1.5 ±0.38^{a}	
Carangidae	*Trachurus japonicus*	6.7	4–12	38	38	41	9.4 ±2.3	5.4 ±1.5	6.3 ±1.2	2–
Lutjanidae	*Lutjanus russellii*	6.0	5–8	1	3	1	0.0035 ±0.0035	0.10 ±0.0060	0.0035 ±0.0035	
	Lutjanus ophuysenii	4.7	3–7	8	11	7	0.069 ±0.038	0.27 ±0.12	0.10 ±0.047	
Haemulidae	*Parapristipoma trilineatum*	3.9	3–5	2	4	7	0.021 ±0.018	0.17 ±0.11	0.087 ±0.035	
Sparidae	*Acanthopagrus schlegelii*	28.6	6–40	36	26	14	0.19 ±0.037^{a}	0.16 ±0.032^{ab}	0.059 ±0.037^{b}	
	Pagrus major	6.5	2–14	18	15	4	0.080 ±0.019	0.080 ±0.025	0.014 ±0.0069	1+ 2+
Pentacerotidae	*Evistias acutirostris*	35.0		2	0	1	0.0069 ±0.0049		0.0035 ±0.0035	
Cheilodactylidae	*Goniistius quadricornis*	6.3	3–12	6	2	2	0.024 ±0.010	0.0069 ±0.0049	0.0069 ±0.0049	
Embiotocidae	*Ditrema temmincki*	7.5	3–16	37	18	20	0.15 ±0.024	0.080 ±0.019	0.094 ±0.022	
Pomacentridae	*Chromis notata*	3.7	3–4	2	1	0	0.0069 ±0.0049	0.0035 ±0.0035		
Oplegnathidae	*Oplegnathus fasciatus*	5.9	3–8	4	2	2	0.23 ±0.21	0.0069 ±0.0049	0.11 ±0.10	
Girellidae	*Girella punctata*	9.8	6–15	4	1	4	0.080 ±0.070	0.010 ±0.010	0.045 ±0.026	
Labridae	*Choerodon azurio*	18.4	16–22	2	1	2	0.0069 ±0.0049	0.0035 ±0.0035	0.0069 ±0.0049	
	Pseudolabrus sieboldi	9.7	1–25	135	110	141	0.99 ±0.089^{a}	0.62 ±0.089^{b}	0.94 ±0.060^{a}	
	Halichoeres poecilopterus	13.7	8–20	11	6	2	0.049 ±0.016	0.024 ±0.010	0.0069 ±0.0049	3–
	Halichoeres tenuispinnis	11.6	5–15	5	3	1	0.024 ±0.011	0.014 ±0.0085	0.0035 ±0.0035	
Stichaeidae	*Dictyosoma burgeri*	16.0	14–18	0	3	0		0.010 ±0.0060		
Blenniidae	*Parablennius yatabei*	3.9	2–6	4	6	0	0.024 ±0.010	0.024 ±0.010		
	Petroscirtes breviceps	5.3	1–8	16	16	12	0.080 ±0.022	0.076 ±0.028	0.066 ±0.023	

Continued

Table 2 (continued)

Family	Species name	Body length (cm)		Frequency			No. of individuals, mean ±SE			Transects
		Mean	Range	Cedar	Broadleaf	PVC	Cedar	Broadleaf	PVC	
Gobiidae	*Chaenogobius gulosus*	3.3	2–4	2	1	1	1.5 ±1.4	0.010 ±0.010	0.0069 ±0.0049	
	Pterogobius zonoleucus	3.8	3–5	4	4	0	1.3 ±1.1	0.53 ±0.39		
	Istigobius hoshinonis	5.8	6–9	2	10	2	0.0069 ±0.0049[b]	0.038 ±0.012[a]	0.0069 ±0.0049[b]	
	Istigobius campbelli	5.4	2–7	3	3	3	0.010 ±0.0060	0.010 ±0.0060	0.014 ±0.0085	
	Acentrogobius pflaumii	3.0	1–5	2	4	3	0.010 ±0.0060	0.014 ±0.0069	0.010 ±0.0060	1–
	Tridentiger trigonocephalus	2.8	1–5	151	175	105	2.9 ±0.35[b]	5.1 ±0.51[a]	2.1 ±0.29[b]	1+ 2+
Sphyraenidae	*Sphyraena pinguis*	13.9	10–18	4	0	4	0.80 ±0.54		0.45±0.25	
Monacanthidae	*Rudarius ercodes*	2.4	1–5	183	157	124	8.6 ±10.98[a]	5.1±0.76[b]	2.8 ±0.53[b]	1+2+
	Thamnaconus modestus	6.2	5–11	5	6	2	0.017 ±0.0077	0.056 ±0.028	0.014 ±0.011	
	Stephanolepis cirrhifer	5.7	2–18	30	25	20	0.27 ±0.063[a]	0.19 ±0.044[ab]	0.090 ±0.021[b]	
Tetradontidae	*Takifugu poecilonotus*	9.7	6–20	56	32	24	0.26 ±0.035[a]	0.15 ±0.025[ab]	0.12 ±0.023[b]	1+ 3+
	Takifugu niphobles	6.3	3–8	17	6	8	0.16 ±0.11	0.039 ±0.016	0.049 ±0.021	

Discussion

The greater effectiveness of cedar ARs

We found that ARs made from logs of cedar trees had a higher fish species richness and abundance than those made of broadleaf trees or PVC pipes. The greater effectiveness of the cedar ARs can be attributed to the direct or indirect effects of cedar wood as an AR material. Qualitative observations support the latter because we observed some fish feeding on encrusting organisms on the cedar ARs. Cedar emits volatile compounds that repel terrestrial invertebrates to protect the living tree (Morisawa et al., 2002), but such chemicals might not be effective as repellants in seawater, making it a suitable habitat for fouling marine organisms. The rapid growth of cedar trees results in relatively soft tissues that can further make the wood a suitable substrate for fouling organisms. A comparison of the abundance of epibenthic assemblages between cedar and broadleaf logs will be required to confirm this hypothesis.

Redspotted grouper was significantly more abundant in PVC ARs than in the other two types of ARs. The body length of this species was an average of 14 cm and ranged from 10 to 19 cm (Table 2), and the inner diameter of the PVC pipes was 11 cm. ARs with holes are expected to host more fish (Kellison and Sedberry, 1998), especially large predators (Hixon and Beets, 1989). Indeed, PVC pipes, because of their size, provided a suitable shelter for redspotted groupers. Yellowspotted grouper (*E. awoara*), conger eel, and some large individuals of bambooleaf wrasse also used the cavities of the PVC pipes.

Two species of goby were more abundant in the broadleaf ARs than in the other two ARs. Most of these gobies ranged from 1 to 5 cm. Predation pressure by the abundant sunrise sculpin and black rockfish in the cedar ARs, and groupers in the PVC ARs, may have reduced the survival of gobies in these two types of ARs, resulting in the relatively higher abundance of gobies in the broadleaf ARs.

Black rockfish associated with cedar ARs ranged from 1.5 to 16 cm SL. Black rockfish is a viviparous fish and matures at 12 cm BL in 1–2 years after birth, and 1.5 cm and 16 cm SL individuals represent 1.5-month and 4–5 year-old individuals, respectively (Hisada et al., 2000). Whitespotted pigmy filefish associated with cedar ARs ranged from 1 to 5 cm SL. Whitespotted pigmy filefish mature at 3 cm SL (Ishida and Tanaka, 1983). Therefore these species use ARs as settlement sites, nurseries, and adult habitats. Jack mackerel associated with ARs ranged from 4 to 12 cm SL. Jack mackerel mature at 14 cm SL (Ochiai et al., 1983) and attain 4 cm in 2 months (Xie et al., 2005). Therefore they use ARs mainly as nursery habitat and are loosely associated with ARs. This finding is in agreement with that of Rooker et al. (1997) who reported that some midwater pelagic fishes, such as carangids and scombrids, were transient members of the AR fish assemblages. Considering that there are both pelagic predators, such

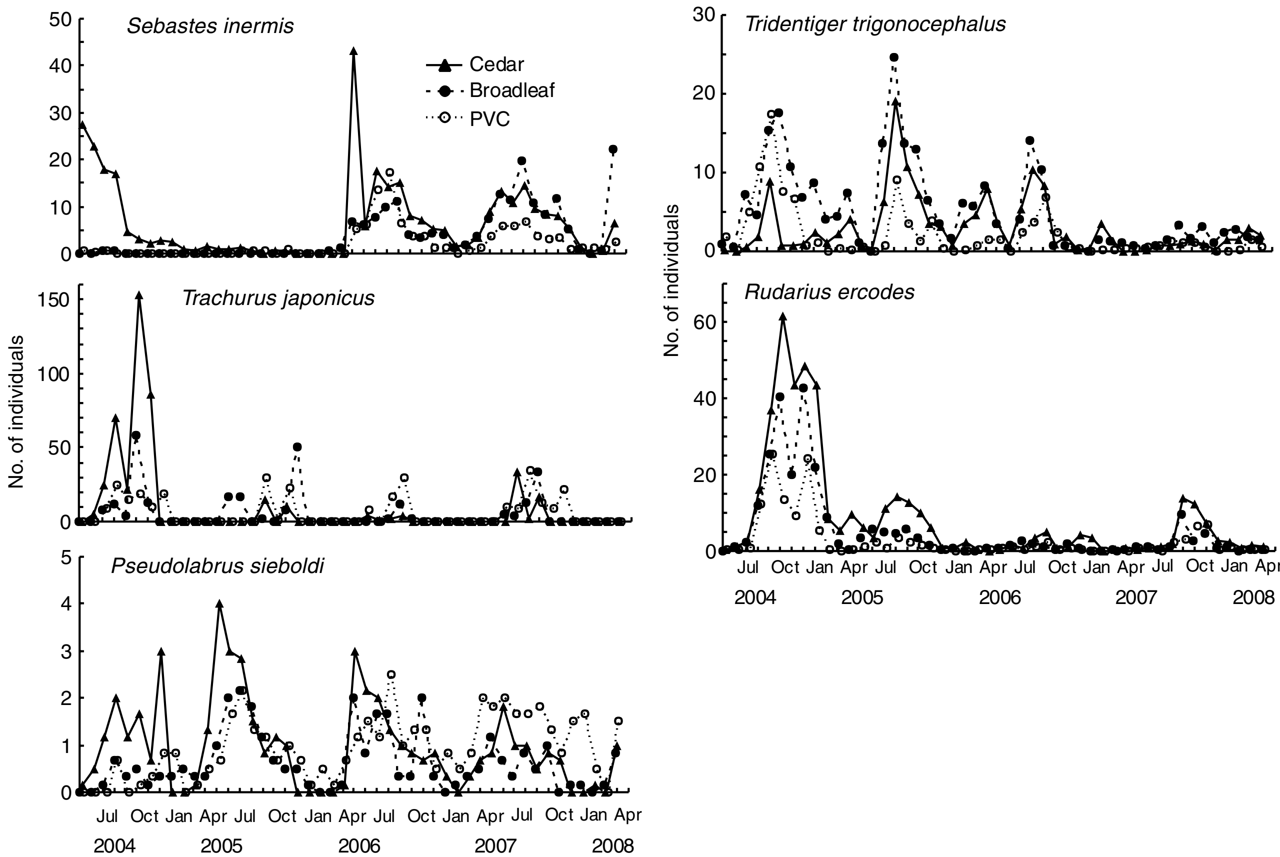

Figure 4

The monthly average of individuals of black rockfish (*Sebastes inermis*), jack mackerel (*Trachurus japonicus*), bambooleaf wrasse (*Pseudolabrus sieboldi*), chameleon goby (*Tridentiger trigonocephalus*), and whitespotted pigmy filefish (*Rudarius ercodes*) associated with each type of artificial reef installed off Maizuru, Kyoto, in 2004.

as Japanese seabass (*Lateolabrax japonicus*), and benthic predators, such as Japanese flounder (*Paralichthys olivaceus*), in this area (Masuda, 2008), these ARs may well be used as refuges from predators.

Because the size of ARs was 1.5×1.5 m and fish were counted within a distance of 1 m, the survey area represented about 10 m^2 for each AR. The density of fish associated with the AR was estimated as 4.07, 2.79, and 2.03 fish per m^2 in and around the cedar, broadleaf, and PVC ARs, respectively (Table 1). Santos et al. (2005) studied fish assemblages associated with ARs made of concrete blocks located at a similar latitude but deeper depth (17–22 m) in south Portugal (37°00′N lat., 7°45′ and 8°00′E long.), and estimated the mean fish density as 2.01 ±0.74 fish per m^2 and fish biomass as 123.6 ±77.4 g per m^2. Fish density on our cedar ARs was about twice as much but the biomass was much less than the value reported by Santos et al. This finding was probably the result of the cedar ARs hosting more recruited juveniles than adults.

Table 3

The number of species and number of individuals of fish recorded during observations along transects 1, 2, and 3 before and after the deployment of the artificial reefs, expressed as the mean ±standard error (*n*=48 and 96 observations for before and after deployment, respectively).

	Transect 1	Transect 2	Transect 3
No. of species			
Before deployment	9.69 ±0.61	9.67 ±0.60	8.88 ±0.62
After deployment	9.40 ±0.43	9.44 ±0.47	8.40 ±0.42
No. of individuals			
Before deployment	116.9 ±21.5	237.6 ±44.6	178.0 ±37.4
After deployment	165.7 ±22.7	225.9 ±34.8	171.1 ±28.9

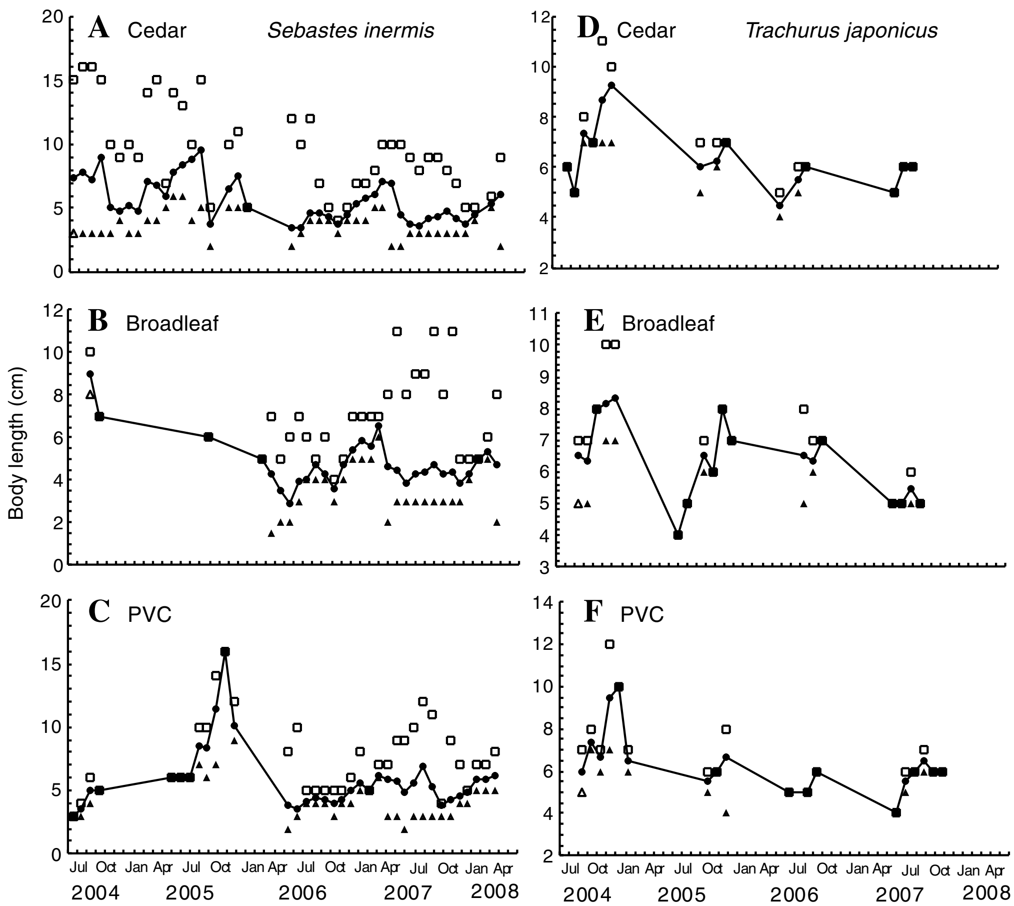

Figure 5

Monthly maximum (rectangles), minimum (triangles), and average (circles) body length of black rockfish (*Sebastes inermis*) found associated with (**A**) cedar, (**B**) broadleaf, and (**C**) PVC artificial reefs, and those of jack mackerel (*Trachurus japonicus*) found associated with (**D**) cedar, (**E**) broadleaf, and (**F**) PVC artificial reefs.

The cedar ARs hosted fish assemblages within the first two to three months of deployment. These recruits may have come from the adjacent coastal habitat or from offshore. Rapid colonization of ARs was also reported by Bohnsack et al. (1994) who observed that fish species, number of individuals, and biomass reached peak levels within two months of deploying concrete ARs in Florida.

There was only one species, *Acentrogobius pflaumii*, that decreased in abundance in transect 1 after the deployment of ARs. This goby is the fifth most frequently observed fish in the adjacent natural reef (Masuda, 2008), but relatively few were associated with ARs. Therefore it is unlikely that the attraction to ARs induced the decline in the population along transect 1. The relative stability of fish species and abundance observed among the three transects supports the concept of an inshore migration and is in agreement with data of Connell (1997) who found that the number of recruits did not differ between ARs located close to and far from a natural reef. Sánchez-Jerez and Ramos-Esplá (2000) also confirmed that antitrawling reefs deployed in a seagrass habitat had little effect on seagrass fish assemblages in the surrounding area. We therefore conclude that the three types of ARs deployed in this study provided additional habitat for young fish without any significant depletion of numbers in the existing fish community.

The average number of fish in the adjacent habitat was 171 individuals per 400 m^2, or 0.43 individuals per m^2. Fish density on the cedar reef was thus 10 times larger than that of the adjacent area. Bohnsack et al. (1991) reviewed experimental studies, where fish densities at natural reefs were compared with those at artificial reefs, and found that in some cases the latter can host densities of more than 10 times that of the former. Therefore, our results of fish density on cedar ARs are within the range of previously reported ARs.

Deployment of wooden ARs as a tool for ecosystem-based fishery management

The major anthropogenic impacts on coastal ecosystems include overfishing, loss of physical complexity induced by construction or trawling, and eutrophication induced by water discharge. ARs made of cedar and other materials have the potential to attenuate at least some of these problems. ARs are useful in that they preclude trawling, protect juveniles in nursery grounds, and provide fishing sites for artisanal fishermen (Polovina, 1991). Our study site had also been a trawl fishing ground for bivalves and sea cucumbers, but fishermen could not trawl at our ARs. The prevention of trawling resulted in the accumulation of relatively large individuals of sea cucumber in our ARs (R. Masuda, unpubl. data). Habitat complexity, such as vertical relief and holes, can be a positive factor for the survival of juvenile fish. For instance, Gorham and Alevizon (1989) showed that the attachment of polypropylene rope to ARs significantly increases the abundance of juvenile fish. Wooden ARs not only provide vertical relief but also provide a porous substrate for boring and attachment by encrusting organisms, such as boring sponges, oysters, and wood boring piddock. Some demersal fishes, such as black rockfish, wrasses, and gobies might well use these encrusting organisms for both refuge and as prey.

Most of the encrusting organisms on ARs are plankton feeders that can use a wide size range of phytoplankton and zooplankton. For example, a single oyster filters several liters of sea water per day and produces pseudofeces that contain about half of the organic content of that trapped on the gills (Deslous-Paoli et al., 1992). Most juvenile and young demersal fish feed on benthic organisms in addition to relatively large zooplankton. Therefore, encrusting organisms on ARs can transform phytoplankton and microzooplankton to a usable energy source for fishes. Fabi et al. (2006) demonstrated that ARs provide the main food source (e.g., encrusted organisms and crustaceans) for the three major fish species (*Sciaena umbra*, *Diplodus annularis*, and *Lithognathus mormyrus*) they studied. Furthermore, improved water clarity due to the filtering function of the encrusting organisms is likely to result in the better growth of primary producers, such as macroalgae. The use of fish reefs as biofilters for nutrient removal has also been proposed by Seaman and Jensen (2000).

The efficacy of wooden ARs is of a short duration (up to 3–5 years) compared to those made of concrete, which can last decades (Yabe, 1995). However, fishermen have observed that wooden ARs attract fish sooner than other types of AR. Although wooden ARs biodegrade sooner than concrete ARs, from an ecological point of view of providing immediate refuge, habitat, and a source of food, they have long-term effects on the marine environment. Simple wooden ARs that combine logs and concrete blocks sink easily in a muddy substrate, and their life as an effective AR can be as short as one year (R. Masuda, personal observ.). The shape of wooden ARs presented in this article, with a double-cross formation (Fig. 1), provides an open and stable vertical relief that can attract more fish recruits. This formation can also act as a stable substrate for encrusting organisms that can function as powerful biofilters, and has a longer durability than other wooden constructs.

The recruitment of reef fishes is often limited by the availability of suitable nearshore nursery habitats, which tend to be vulnerable to anthropogenic impacts. The decrease of reef fish populations is therefore partly attributable to the loss of nursery habitats, such as natural rocky reefs and seagrass beds. The deployment of wooden ARs may provide an opportunity to mitigate this trend of decline in nursery quality and because they are highly biodegradable, the risks of unexpect-

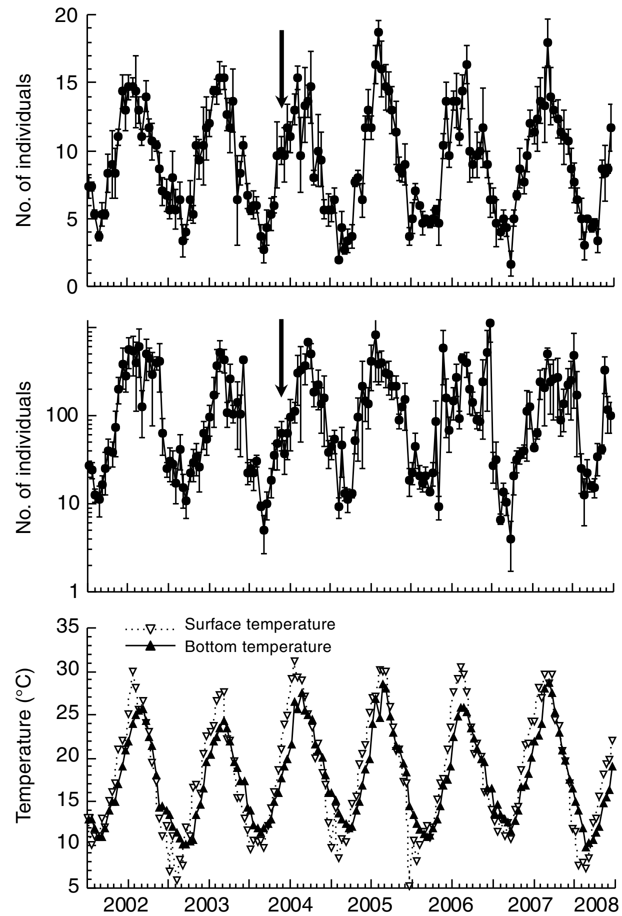

Figure 6

Seasonal changes in the mean (±standard error) number of fish species and individuals per transect in the area immediately adjacent to the artificial reefs, and the surface and bottom water temperatures measured in those areas during the surveys from January 2002 to June 2008, at Nagahama, Maizuru, Japan. Vertical arrows represent the date (21 May 2004) of artificial reef deployment.

ed negative impacts on the environment are minimal. Stock enhancement, defined as the release of cultured juveniles into wild populations to augment harvest, has been used as a strategy to reconstruct depleted fisheries resources (Bell et al., 2008). We suggest that the release of reef-associating fish juveniles, such as black rockfish, combined with the deployment of wooden ARs would be an efficient approach for the recovery of depleted coastal fisheries.

A major problem of deploying ARs is that they attract fishermen as well as fishes. There is always the possibility that fishermen will catch more fish than the increase of production because fish attracted to ARs are generally more easily exploitable than those spread over natural reefs (Powers et al., 2003). Indeed, we often observed local anglers fishing at our experimental reefs. Therefore, a management strategy is critically important in controlling the harvesting pressure at AR sites (Pickering and Whitmarsh, 1997). As our long-term goal is to improve the productivity of local inshore fishing grounds, we would suggest that part of the areas to be enhanced should have ARs distributed within them and be managed as marine protected areas.

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