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IMPACTS OF ARTIFICIAL REEFS ON FISHERY PRODUCTION IN SHIMAMAKI, JAPAN

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ABSTRACT

The role of artificial reefs as a tool for increasing fishery production rather than just aggregating fish is addressed for two fisheries, octopus, *Octopus dofleini*, and flatfish, (Pleuronectidae), near Shimamaki, Japan. The time series of catch and effort data examined covers periods before and after two adjacent fishing grounds received 8,645 and 40,766 m^3 of artificial reef. Octopus catches were increased by 4% per 1,000 m^3 of artificial reef or by an average of 1.8 kg/m^3 of artificial reef. Artificial reefs aggregated flatfishes but did not increase catches in the regions. A survey of fishermen in the two regions revealed that the reefs generally are considered beneficial.

Artificial reefs are widely advocated as a tool to enhance fishing. The U.S. Congress established a national policy to promote the use of artificial reefs (Stone, 1985). Japan has a long history of artificial reef usage, and its government currently spends about US$10 million annually on the construction and deployment of artificial reefs in its coastal waters. The Japanese Government has justified this program with reports of annual combined pelagic and demersal catches at the reefs of up to 16–20 kg/m^3 of artificial reef (Sato, 1985). However, these catch rates do not measure the extent that artificial reefs increase fishery production in a region because, if the reefs were not present, many of these fishes might have been caught at the surrounding natural habitat instead. Evaluating the extent that artificial reefs can produce a sustainable increase in fishery production in a region, rather than just aggregate fish already present, is an important ecological question as well as a high priority research topic with important consequences for fisheries management (Bohnsack and Sutherland, 1985; Sato, 1985).

This study compares annual catches and catch per unit of effort (CPUE) between two adjacent fishing grounds. Examining two regions rather than just one separates the effects of artificial reefs on catches from the effects of year-class strength, changes in fishing power, and market factors. Any changes in relative catch and CPUE, corresponding to differences in the magnitude of artificial reefs between the two regions, are likely due to the artificial reefs. This study is believed to be the first to quantify the extent that artificial reefs produce a sustainable increase in fishery production.

METHODS

The two fishing grounds are located off the rural village of Shimamaki on the southwest side of the island of Hokkaido, Japan. The region's primary industry is fishing, and the fishing grounds, which lie offshore of a 27-km stretch of coastline, are divided into a 15-km stretch of coastline fished exclusively by the West Shimamaki Fishery Association, while the remainder is fished exclusively by the East Shimamaki Fishery Association. The two cooperatives are composed primarily of small (< 10-ton) vessels fishing a variety of gear including hook and line, gill nets, and longlines. No large trawlers fish the area.

Commonly caught at, or near, the artificial reefs are the Pacific giant octopus, *Octopus dofleini* or mizudako, and a number of flatfishes (Pleuronectidae). For these two resources in East and West Shimamaki, a relatively long time series of catch data, and a shorter time series of CPUE data, are available.

The octopus has a rapid growth, attaining a weight of 15 kg in 3 years and reaching a maximum of 30 kg. Females become sexually mature after 3 years and, when spawning, deposit their eggs in

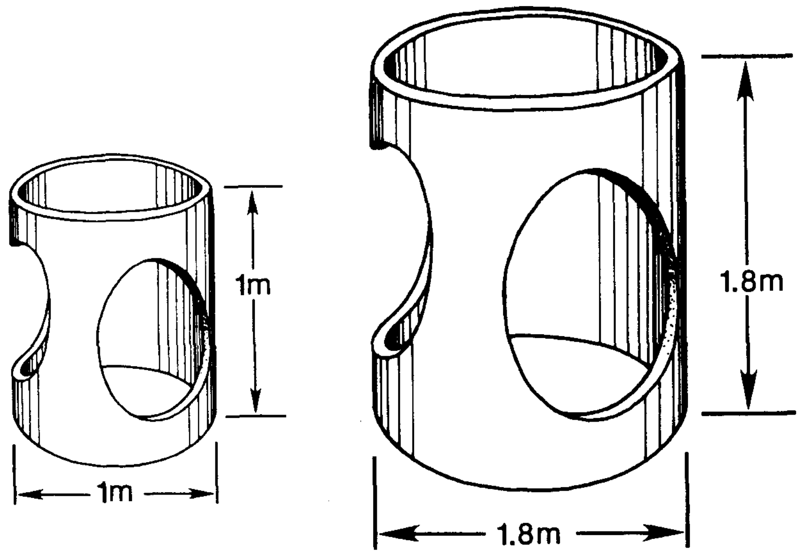


Figure 1. Small and large reef modules deployed in East and West Shimamaki.

rocky areas and guard them until hatching occurs. The larval state of this species apparently is short, after which the animals settle on benthic substrate. This species shows cryptic and solitary behavior, hiding in holes with one octopus per hole (Hartwick et al., 1978). The immature animals are fished at 40 to 60 m depths with octopus boxes or pots, which attract by offering shelter, whereas older animals are often caught with unbaited longlines. The fishery around Hokkaido has been stable since at least 1955 (Osako and Murata, 1983).

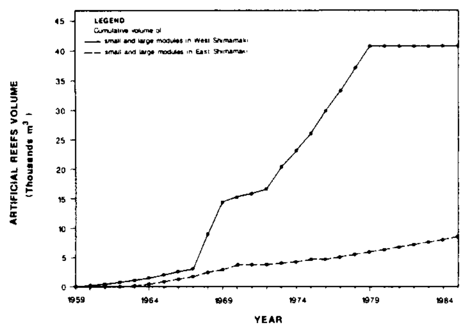
Of the flatfishes caught in the Shimamaki region, the most highly valued is the hirame or bastard halibut, *Paralichthys olivaceus*. Other flatfishes include the pointhead flounder, *Cleisthenes pinetorum herzenstein*; the smallmouth sole, *Limanda herzensteini*; and the flathead flounder, *Hippoglossoides dubius*. These fishes often are found on flat bottom areas; however, tracking studies with sonic tags show that, in areas with artificial reefs, the fish frequently move in and around the reefs perhaps to forage (Kakimoto, 1984). Flatfishes are fished with gill nets in the shallow (30–60 m) inshore waters of Shimamaki. The resource is heavily fished, and there is concern that growth overfishing is occurring.

The artificial reefs were composed of small (0.785 m^3 enclosed volume) or large (4.58 m^3 enclosed volume) cylindrical concrete modules with several large holes in the wall (Fig. 1). In West Shimamaki in 1960–1976, a total of 33,446 small modules were deployed in five locations 1–3 km offshore at depths of 30–40 m on either sand or gravel bottoms. The largest group had 5,000 modules, and the smallest, 555 modules. In 1976–1979, a total of 3,168 large modules were deployed over the same five locations, and at two new locations 1.5–3 km offshore at depths of 30–40 m on sand and gravel bottoms. West Shimamaki has a total of 36,614 artificial reef modules with an enclosed volume of 40,766 m^3 (Fig. 2).

In East Shimamaki in 1963–1975, 5,943 small modules were deployed at a single location 2.6 km offshore on a sandy bottom at a depth of 40 m. In 1977–1985 in the same location, 869 large modules were deployed. East Shimamaki has a total of 6,812 artificial reef modules with an enclosed volume of 8,645 m^3 (Fig. 2).

Aggregation and Enhancement Models.—The small area of the East and West Shimamaki fishing grounds makes it likely that recruitment for octopus and flatfishes comes from outside the region; hence, a linear relationship is assumed to exist between catch and fishing mortality in this area.

Any increase in catches and CPUE in the West, relative to the East, may be due to a net enhancement of the resources, or to movement between the two regions as a result of the greater reef volume in the West. To distinguish between these two possibilities, an enhancement model and an aggregation model are considered. The enhancement model hypothesizes that artificial reefs increase catches over those produced by the natural habitat in both regions, by an amount proportional to the artificial reef volume in each region. The aggregation model assumes that the combined catch from both regions does not



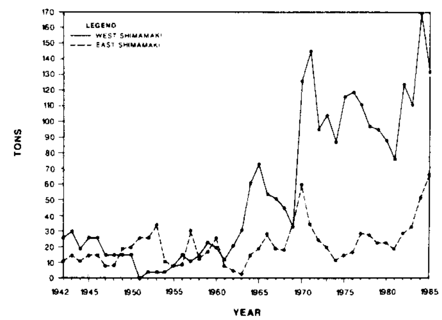


Figure 2. (Left) Cumulative volume of combined small and large module artificial reef volume for East and West Shimamaki.

Figure 3. (Right) Catches of octopus from East and West Shimamaki Fishery Associations from 1942 to 1985.

increase because of the artificial reef volume, and that a fraction of the combined catch moves from one region to the other in proportion to the difference in artificial reef volume between the two regions. The volume of artificial reefs typically has been used as a measure of their potential effectiveness, and it probably is a reasonably good index for the octopus found within the reef structure.

Specifically, let Cw(t) and Ce(t) denote the catches for a specific resource group in West and East Shimamaki, respectively, in year t. Let Fw(t) and Fe(t) denote fishing mortality, and Nw(t) and Ne(t) denote the fishable biomass associated with the natural habitat in the two regions, in year t. Let Rw(t) and Re(t) denote the cumulative artificial reef volume deployed up to and including year t in West and East Shimamaki, respectively.

For the enhancement model, we have

$$Cw(t) = Fw(t) \cdot Nw(t)(1 + B \cdot Rw(t)) \tag{1}$$

and

$$Ce(t) = Fe(t) \cdot Ne(t)(1 + B \cdot Re(t)), \tag{2}$$

where B is a constant such that 1 m^3 of artificial reef volume increases the catch by 1 + B. From Equations (1) and (2), the ratio of catches and the ratio of the CPUE of West to East, by year, can be expressed as

$$Cw(t)/Ce(t) = (Fw(t) \cdot Nw(t))/(Fe(t) \cdot Ne(t))(1 + B \cdot Rw(t))/(1 + B \cdot Re(t)) \tag{3}$$

and

$$CPUEw(t)/CPUEe(t) = (qw \cdot Nw(t)/qe \cdot Ne(t))(1 + B \cdot Rw(t))/(1 + B \cdot Re(t)), \tag{4}$$

where qw and qe are the catchability coefficients in West and East Shimamaki, respectively.

Although there may be annual changes in fishing mortality, biomass, and catchability coefficients that are due to variation in year-class strength, changes in fishing effort, gear, and power and economic factors, the similarity between the two regions' environment and fishing fleets suggests that the ratios qw•Nw(t)/qe•Ne(t) and Fw(t)•Nw(t)/Fe(t)•Ne(t) will remain relatively constant over time. Under this assumption, the coefficient B can be estimated from Equation (3) or (4) with a nonlinear regression of Cw(t)/Ce(t) or CPUEw(t)/CPUEe(t) on Rw(t) and Re(t).

The aggregation model assumes that the reefs do not increase the abundance of the resource, but rather, move the resource between the two regions in proportion to the difference in the artificial reef volume:

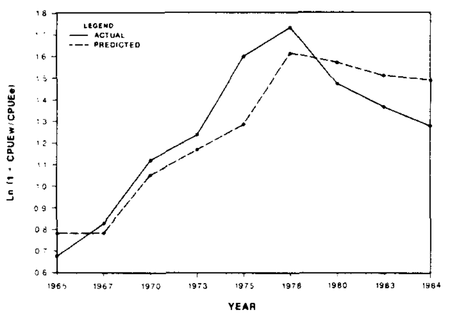
$$CPUEw(t) = qw \cdot Nw(t)(1 + B \cdot (Rw(t) - Re(t))), \tag{5}$$

$$CPUEe(t) = qe \cdot Ne(t)(1 - B \cdot (Rw(t) - Re(t))), \tag{6}$$

and

$$CPUEw(t)/CPUEe(t) = (qw \cdot Nw(t)/qe \cdot Ne(t))(1 + B \cdot (Rw(t) - Re(t))/(1 - B \cdot (Rw(t) - Re(t))). \tag{7}$$

The best way to distinguish between the aggregation and enhancement models is to examine CPUEw(t) − CPUEe(t). In the aggregation model, as the CPUE in one region increases, the CPUE in the other



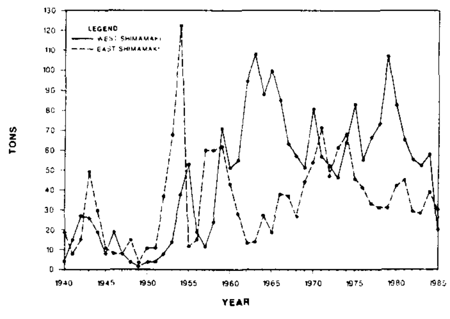


Figure 4. (Left) Actual and predicted values of Ln(1 + CPUEw/CPUEe) for octopus by year (predicted values from model y = 0.75(1 + 0.00004•RW)/(1 + 0.00004•RE)).

Figure 5. (Right) Catches of flatfishes in East and West Shimamaki Fishery Associations, 1940–1985.

region must decline; therefore, the difference increases faster as a function of reef volume than in either region alone. In the enhancement model, each region is affected independently of the other. Because the difference in CPUE's is affected by changes in year-class strength, the ratio of CPUEw(t) − CPUEe(t) divided by CPUEw(t) + CPUEe(t) regressed on Rw(t) − Re(t) is used to distinguish between the two models.

Results

Octopus. Octopus catch data from East and West Shimamaki were available from 1942 to 1985 (Fig. 3): Catches were similar from 1942 to about 1961, then began increasing in the West and, since about 1970, averaged about 5 times higher than in the East. Vessel tonnage of octopus fishing vessels in both regions had a similar constant rate of increase, roughly doubling in both associations. Estimates of vessel tonnage from 1965 to 1984 are used as a measure of annual fishing effort to compute a CPUE series, fit to the models developed in the previous section.

The ratios of the West to East CPUE's and catches were fit with nonlinear regression to the cumulative combined volume of large and small artificial reef cylinders (Equations (3) and (4)). The fit of the models was improved by using Ln(1 + CPUEw(t)/CPUEe(t)) and Ln(1 + Cw(t)/Ce(t)) as the dependent variable, instead of using simply the CPUE or catch ratios. Both regressions produced similar and statistically significant estimates of the parameter B, supporting the hypothesis that the artificial reefs increased the fishery production of octopus (Table 1, Fig. 4). The estimate of B (4.0×10^{-5}) from the CPUE regression is probably more accurate than from the catch regression (3.2×10^{-5}) because the CPUE regression, although based on a shorter time series, involves an effort measure. The estimates of the intercepts of Equations (3) and (4) (qw•Nw/qe•Ne and Fw•Nw/Fe•Ne) were not statistically different from 1.0 ($P > 0.10$). Further, the fit of these regressions was slightly better if the independent variable was the cumulative volume of only small modules rather than small and large combined, but the improvement was not significant ($P > 0.10$).

The ratio of CPUE's and difference of CPUE's divided by the sum of the CPUE's, under the assumptions of the enhancement and aggregation models (Equations (3), (4), (5), and (6)), were fit to the reef volume with the further assumption, previously tested, that qw•Nw/qe•Ne was 1.0 (Table 2). Under the aggregation model, when qw•Nw/qe•Ne is 1.0, the regression model is linear with the dependent variable (Rw(t) − (Re(t)) and, under the enhancement model, is

Table 1. Fit of enhancement model to catch and catch per unit effort (CPUE) data with estimates of parameter B for octopus and flatfishes

Dependent variable	Species	B	SE	R^2
Ln[1 + (CPUEw/CPUEe)]	Octopus	4.0×10^{-5}	1.9×10^{-5}	0.73
Ln[1 + (Cw/Ce)]	Octopus	3.2×10^{-5}	1.1×10^{-5}	0.30
Ln[1 + (CPUEw/CPUEe)]	Flatfishes	1.4×10^{-5}	1.6×10^{-5}	0.22
Ln[1 + (Cw/Ce)]	Flatfishes	8.6×10^{-6}	8.4×10^{-6}	0.02

nonlinear with the reef volume appearing in the numerator and denominator. A comparison reveals that the enhancement model fits slightly better than the aggregation model when the dependent variable is the Ln(1 + CPUEw(t)/CPUEe(t)) and significantly better when the dependent variable is (CPUEw(t) − CPUEe(t))/(CPUEw(t) + CPUEe(t)) ($P < 0.10$; Table 2). Thus, the increase in catch and CPUE in West Shimamaki was not at the expense of East Shimamaki.

The estimate of B (4×10^{-5}) means that 1,000 m^3 of artificial reef increases the catches by 4%. The average biomass contribution of the reef cylinders can be estimated by fitting Equation (1) to the combined East and West catch and CPUE data. This fitted equation estimates that 1 m^3 of artificial reef added an additional biomass to the catches (in kilograms) amounting to the product of 0.018 and fishing effort (in vessel tons). Taking the average level of octopus fishing effort for 1965–1984 as 100 vessel-tons, the increased catch due to the reefs is estimated at 1.8 kg/m^3. Studies of the ecology of *Octopus dofleini* support this finding; the animals are almost always associated with dens, with a single individual per den (Hartwick et al., 1978; Osako and Murata, 1983).

The decline in the values of Ln(1 + CPUEw/CPUEe) relative to the values predicted by the enhancement model in the years 1980, 1983, and 1984 (Fig. 4) may be due to dynamics that are not incorporated in the enhancement model. For example, if the contribution of the artificial reef in increasing the catches is not strictly a linear function of reef volume, especially for a large volume, then the enhancement model will overestimate CPUE in the West in the more recent period when the reef volume was greatest. The same pattern could result from an interaction between fishing effort and the contribution of the artificial reefs. At high levels of fishing pressure (the more recent period), the contribution of the artificial reefs (per unit volume) was less than at lower levels of fishing effort when the standing stock was greater. Several modifications of the enhancement model based on these hypotheses were tested, but their improved fit was not statistically significant, perhaps because of the short CPUE time series. Further, the enhance-

Table 2. Fit of enhancement and aggregation model (E = enhancement; A = aggregation) to octopus catch per unit of effort (CPUE) data

Dependent variable	Model	B	SE	S^2	R^2
Ln[1 + (CPUEw/CPUEe)]	E	4.0×10^{-5}	1.9×10^{-5}	0.036	0.73
Ln[1 + (CPUEw/CPUEe)]	A	7.7×10^{-6}	2.0×10^{-6}	0.050	0.63
$\frac{CPUEw - CPUEe}{CPUEw + CPUEe}$	E	1.6×10^{-4}	3.1×10^{-5}	0.005	0.89
$\frac{CPUEw - CPUEe}{CPUEw + CPUEe}$	A	1.4×10^{-5}	3.2×10^{-6}	0.0147	0.73

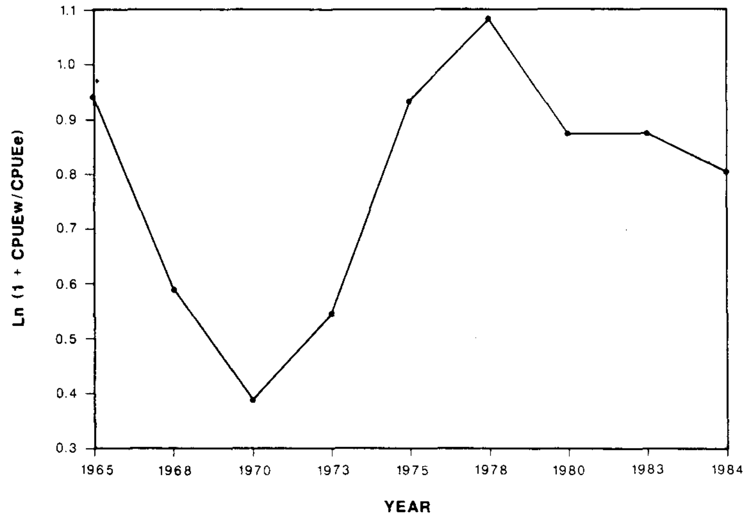


Figure 6. Ln(1 + CPUEw/CPUEe) by year for flatfish.

ment model with only the volume of the small or large reef modules, or with separate parameters for small and large reef modules, did not significantly improve the fit.

FLATFISHES. The catches of flatfishes show considerable annual variation. Although similar in both regions from 1942 to 1959, catches after the beginning of the artificial reef period in 1959 have declined in West Shimamaki and, in the East, have declined, increased, and more recently declined (Fig. 5). Nine vessel censuses in 1965–1984 report the number of gill-net vessels in East and West Shimamaki, and this series is used as the measure of fishing effort for the flatfish resource. The number of gill-net vessels in both regions showed very little change over most of 1965–1984.

The nonlinear regressions of the ratios of catches and CPUE's between West and East Shimamaki fit to the cumulative artificial reef volume (Equations (3) and (4)) for flatfishes give estimates of B that are positive (Table 1, Fig. 6) but not statistically significant ($P > 0.10$). A series of research surveys conducting standardized gill-net fishing at the artificial reef sites in 1977, 1980, and 1981 indicate that flatfishes constitute 30% of the gill-net catches at the artificial reefs (Anonymous, 1985). Thus, the artificial reefs are aggregating the resource but not increasing production for the region. It is possible, however, that the annual variations in catches and CPUE mask the effect of reefs or that the effort measure used was not sufficiently precise.

DISCUSSION

Both flatfishes and octopus are caught at and near the artificial reefs, suggesting that the reefs may be beneficial for these resources. A March 1986 questionnaire completed by 30 and 31 members of the East and West Shimamaki Fishery Associations, respectively, revealed that the reefs are considered beneficial. Generally, the fishermen from the two regions responded similarly to the survey questions. For the two regions combined, 52.5% of the respondents reported using the artificial reefs regularly, 11.5% use them only when fishing elsewhere is poor, and 36% do not use the artificial reefs at all. The gear types most frequently used were gill-net, longline, and octopus fishing gear in the vicinity of the artificial reefs, and pole-and-line gear above the artificial reefs. Flatfishes, scorpionfish (Scorpaenidae), Atka mackerel (*Pleurogrammus monopterygius*), and octopus were commonly caught above and in the vicinity of the reefs. Thirty-three percent of the respondents thought the artificial reefs had expanded the amount of productive habitat, while 38% thought they had not, and 30% could not make a determination.

Unfortunately, the survey did not collect responses for specific resources, but our analysis suggests that the octopus fishermen would be among those who believed the artificial reefs expanded the amount of productive habitat, while the flatfish fishermen would be among those who did not. Our analysis suggests that the octopus are habitat limited, whereas the flatfishes are not but still find the reefs useful perhaps as sites for foraging or orientation.

Although our model expresses catch as a linear function of artificial reef volume and fishing effort, it is likely that this relationship is nonlinear. For example, since increases in fishing effort reduce the standing stock, the need for artificial reefs or the benefits derived from them may vary inversely with the level of fishing effort. Also, the benefits of 1 m^3 of artificial reef volume are likely to be greater if only a few reefs have been deployed than if a large volume of reefs is already in place. The decline below that predicted by our simple linear model of the ratio of the octopus catches in the West to the East since 1978 is possibly due to such nonlinear relationships. Thus the artificial reefs added after 1978 may have contributed less to increased octopus catches in West Shimamaki than the same volume of artificial reefs added when fishing effort, artificial reef volume, or both were lower. Hence, managers need to consider that the benefits of artificial reefs may vary with the level of fishing effort, and regulation of fishing effort should be considered when artificial reefs are deployed.

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