Physical Factors Involved in the Isoyake (Seaweed Forest Depletion) at Mio, Pacific Coast of Central Japan

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Abstract

In Japan, seaweed forest depletion is known as isoyake. We conducted a study on the marine environment to clarify the cause and the persistence of the isoyake in the sea area at Mio, on the west coast of the Kii Peninsula, central Japan. In the sea area at Mio, a layer of high-turbidity seawater formed on the sea surface (lowest Secchi disc depth: 1m) during and after precipitation. The average accumulation of sediment on the bedrock was 6.7 mg/cm². This value was approximately four times that recorded in the sea area at Noshima, where seaweed communities were present. These results imply that the large amounts of suspended particles in the seawater and sediment particles that settled on the bedrock were the major factors contributing to the continuation of the isoyake at Mio. The mineral composition of the suspended particles in the seawater during the periods of low Secchi disc depth was similar to that of sediment particles collected from a dam upstream of the Hidakagawa River on the east side of Mio. Thus, it is probable that the Hidakagawa River is the origin of the particles in the sea area at Mio.

Keywords

Brown algae; Dam; Formation; Marine forest; Sediment; Suspended particle; Turbidity

Introduction

Marine forests dominated by large brown algae belonging to the orders Laminariales and Fucales play important roles in providing habitat, food, and nurseries for a wide range of organisms. Although large brown algae have decreased in abundance or have been extirpated along urbanized temperate coasts worldwide [1-6], the factors causing these declines in marine forests are often unclear. This depletion of the marine forest is known as the isoyake in Japan. In the present study, we compared the marine environment between an isoyake area (Mio), and a nearby site with intact seaweed communities (Noshima), to clarify which factors were involved in the isoyake.

The sea area at Mio in Wakayama Prefecture is located on the west coast of the Kii Peninsula, central Japan. The area is approximately 6 km west of the Hidakagawa River estuary, and to the west is the Kii Channel (Figure 1). Until around 1990, a thick marine forest of Eisenia bicyclis grew in the sea area at Mio, and local fishermen managed and harvested the near-shore fisheries resources. However, the marine forest rapidly disappeared after 1990, resulting in the so-called isoyake marine forest depletion [7]. Although the catch of abalones at Mio was 17 tons in 1988, it has continually decreased since then, and there was no commercial catch recorded in 1998 (Wakayama Pref., unpubl. data, 1989 and 1999). In contrast, in the sea area at Noshima, offshore from Gobo City, located ca. 2 km to the southeast of the Hidakagawa River estuary, there are abundant seaweed communities and near-shore resources. Thus, there is a marked contrast in the quantity of marine resources between the west and the east side of the estuary.

The main cause of the isoyake was previously suggested to be an increase in the water temperature due to the approach of the Kuroshio Current near the shore [8] and grazing pressure from herbivorous animals [9,10]. However, the isoyake in this region is limited to the sea area at Mio and it cannot be explained solely by the causes mentioned above. The sea area at Mio is open to the ocean in the south, so it is influenced by the Kuroshio Current. To the west, the water of the Seto Inland Sea flows in through the Kii Channel. River water from the Hidakagawa River flows in from the east. There are potentially large environmental fluctuations in the sea area at Mio. Yamauchi and Midorikawa [7] investigated the Mio isoyake, and they suggested that suspended sediment might be one of the causes. However, the main cause of the isoyake in this area has not been clarified.

The purpose of this study was to clarify the reasons for the occurrence and persistence of the isoyake at Mio. We quantified many of the environmental factors in this area, and focused our attention on the effects of suspended particles in the seawater and particles that...
had settled on the bedrock forming a thin layer (hereafter referred to as 'sediments') on the marine forest.

**Materials and Methods**

We conducted three surveys to study the marine environment: 1) investigations of the coastal oceanographic characteristics; 2) continuous observations of the environment at Mio; and 3) quantitative and qualitative analyses of sediment particles on the bedrock.

To record current direction, current velocity and water temperature, we installed an electromagnetic current meter (Alec Electronics, Model; Compact EM) on the bedrock (water depth: 4 m) at Mio and Noshima (Stas. 1 and 2, Figure 1). Both sites have a broad, rocky reef, but the reef at Mio is narrower and has a steeper slope compared with that at Noshima. The measurements were conducted in May, August, and November in 2002 for 5 days. Data obtained from the Shirahama Tidal Station of the Japan Meteorological Agency [11] were used to determine hourly tidal levels.

Continuous observations of water temperature, salinity, and Secchi disc depth were conducted over 2–3 years in the Mio sea area. Water temperature was continuously monitored from May 2000 to October 2002 with one interruption from April to August 2002, and salinity was monitored from May 2000 to March 2002. Seawater from the sea area at Mio was pumped into a water tank (Sta. A, Figure 1) located at the Mio Fisheries Cooperative Association, and the water temperature was measured at hourly intervals by a self-recording water temperature sensor (Onset Computer Co., Model; Stow Away TiDiBiT) installed in the water tank. The water for salinity measurements was collected using a bottle at 10AM every day, and salinity was measured using a salinometer (YEO-KAL Co., Model; 601MK III). The Secchi disc depth was measured every morning from May 2000 to October 2002 at Sta. B at Mio (at a water depth of ca. 20 m) by the staff of the Mio Fisheries Cooperative Association. The amount of precipitation at the Hidakagawa River basin (Ryujin section; 33°56.7’N, 135°33.4’E and Kawabe section; 33°53.6’N, 135°13.0’E) was obtained from the AMeDAS data of the Japan Meteorological Agency [12].

We conducted qualitative and quantitative analyses of sediment particles on the bedrock five times: in July and October of 2001 and January, April, and August of 2002. The sampling locations were at Sta. 1 at Mio and Sta. 2 at Noshima of Gobo City. At both observation stations, five artificial seaweed reefs [13] made of porous concrete were installed in September 2000. The sizes of these reefs were 2 m wide, 2 m deep, and 0.7 m high. The reefs were set at depths of 4.0 m at Mio and 4.4 m at Noshima. On the artificial seaweed reef, a quadrate with a side-length of 20 cm was placed by SCUBA diving. Sediment particles inside the square frame were sucked up using the airlift method and placed in a 20-L polyethylene bottle. In April 2002, samples were also collected from the river bed of the Hidakagawa River estuary (Sta. 3) and from near the Tsubayama Dam of the Hidakagawa River (Sta. 4) with an SK dredge (Rigo Co.). The amount of sediment was determined as follows: the collected particles were screened with a 2-mm mesh sieve, filtered with gentle suction onto a paper filter (Advantec, No. 7), oven-dried 60°C for 72 h, and then weighed. The particle-size distribution was measured in the range of 0.4 to 2000 μm with an LS200 particle size analyzer (Beckman Coulter Inc.).

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**Results**

**Comparison of seawater temperature and currents**

The current characteristics at Mio and Noshima are shown in Figure 2. In the sea area at Mio, the eastward component of the current velocity varied markedly each month on a periodic basis. The velocity of the westward component (negative values) of the current in May and November was especially high, often reaching 10 cm·s⁻¹.

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Figure 2: Velocity of northern and eastern components of the coastal current at Mio and Noshima, and tidal levels in the area.
The current in May and August tended to flow north (i.e., onshore). In the case of Noshima, the eastward component of the current in May was generally to the west (i.e., offshore), and no periodic variations were evident. The northward component of the current was hardly observed. In August, both the eastward and northward components of the current increased slightly. In the northward component in November, the velocity to the south was often greater than 5 cm·s⁻¹.

We superimposed these current velocity components on the tidal variations. The periodic variations in the current velocity at Mio corresponded closely with the tidal variations. The current flowed slightly to the northeast during the ebb tide and strongly to the west during the flood tide. In contrast, the velocity of the current in May and August at Noshima did not clearly correspond to the tide. In November, however, the current tended to flow south during the ebb tide.

Table 1 shows the average values and standard deviations of the current velocity and water temperature calculated from data collected at both stations during each period. The average velocities at Mio were 3.6–3.8 cm·s⁻¹, which were significantly (Student's t-test; p < 0.05) faster than those at Noshima during all observation periods. The average water temperatures at Mio were 21.9, 27.6, and 20.1°C in May, August, and November. In August, there was no significant difference (>0.05) in water temperature between Mio and Noshima.

### Fluctuations in water qualities at Mio

The fluctuations in the water temperature, salinity, and Secchi disc depth at Mio during the three years from 2000 to 2002 are shown in Figure 3. From 2000 to 2002, the highest water temperatures (>28°C) were during several days in August/September, and the lowest (approx. 10–13°C) were in February/March. The salinity fluctuated largely within the range of 33.0 (PSU) to 34.5 (average, 33.4), but occasionally abruptly dropped to less than 30 (on 12 days out of 494 days). The lowest salinity recorded was 21.1 in June 2001. The mean Secchi disc depth during the observation period was 12.5 m, but decreases in transparency to less than 5 m were sometimes observed (on 34 days out of 676 days).

For the 12 days when the salinity decreased to less than 30, there was heavy rainfall on that day or the preceding day, with total precipitation ranging from 66 to 229 mm. Among the 34 days when the Secchi disc depth was less than 5 m, 28 days corresponded to the days of heavy rainfall, and the remaining 6 days to days on which there was a strong swell.

Precipitation in the Hidakagawa River Basin (Ryujin and Kawabe sections), salinity, and Secchi disc depth at Mio during June to October 2001 are shown in Figure 4. There were four occasions (Figure 4a).

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Table 1: Average current velocity and water temperature at Mio and Noshima.

<table>
<thead>
<tr>
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<th>Mio</th>
<th>Noshima</th>
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<tbody>
<tr>
<td>Velocity ± SD (cm·sec⁻¹)</td>
<td>Temperature ± SD (°C)</td>
<td>Velocity ± SD (cm·sec⁻¹)</td>
</tr>
<tr>
<td>May 2002</td>
<td>3.6 ± 2.3*</td>
<td>21.9 ± 0.2*</td>
</tr>
<tr>
<td>Aug. 2002</td>
<td>3.6 ± 1.9*</td>
<td>27.6 ± 0.6</td>
</tr>
<tr>
<td>Nov. 2002</td>
<td>3.8 ± 2.2*</td>
<td>20.1 ± 0.6*</td>
</tr>
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* indicate significant differences (p < 0.05) at both station.
when the salinity was lower than 30 during this period. All days with low salinity matched the days with rainfall. There were four occasions when the Secchi disc depth was less than 5 m; three of these matched to rainfall events (Figure 4b, symbol ⭕), and the other matched to a day on which there was a strong swell (Figure 4b, symbol ⬤). This was especially notable on 21 and 22 August 2001, when typhoon 0111 passed, and 376 mm of rainfall was recorded over 2 days. During this event, the salinity and Secchi disc depth at the Mio sea area were 28.8 and 1.7 m, respectively.

We also analyzed the characteristics of suspended particles in the seawater during periods with low Secchi disc depth. On the eight occasions when the Secchi disc depth was less than 3 m, the surface seawater was collected and the suspended sediment (SS) was investigated. The SS indicated was 1.7–14.6 mg L−1.

### Amounts of sediments on the bedrock

The amount of sediments on the artificial seaweed reefs is shown in Figure 5. In the sea area at Mio, the minimum amount was 2.2 mg cm−2 in July 2001, and the maximum was 10.4 mg cm−2 in January 2002. The average value was 6.7 mg cm−2. At Noshima, the minimum amount was 0.11 mg cm−2 in July 2001, and the maximum value was 3.1 mg cm−2 in August 2002. The average value was 1.5 mg cm−2. There was no clear seasonal variation in the amount of sediment at both stations. The trends in the variations of the amounts of sediments were similar at Mio and Noshima. However, there was much more sediment at Mio than at Noshima in each sampling occasion.

No large seaweed beds were present on the artificial seaweed reef at Mio. However, the artificial seaweed reef at Noshima shows extensive settlement and growth of *Ecklonia cava* [15]. The average amount of sediment on the bedrock off Mio was about four times that on the bedrock off Noshima, where seaweed communities were present.

The particle-size distribution of the sediments on the bedrock at Mio and at Noshima is shown in Figure 6. The particle-size distributions showed two peaks: at around 20–40 µm in diameter and at around 200–400 µm diameter. These distributions showed no clear seasonal changes. There was no marked difference in the particle size distributions of sediments between the two seas areas, suggesting that their sediments share the same origin.

The mineral composition of the sediment particles on the bedrock at Mio and at Noshima was determined by X-ray diffraction (Figure 7a and 7b). Sediment particles at both locations contained mica, kaolinite, quartz, and feldspar. The most abundant component was quartz, followed by feldspar. The mineral composition of sediments at both locations was the same. For comparison, the compositions of sedimentary particles from the lake bottom of Tsubayama Dam, the Hidakagawa River estuary, and that of the particles suspended in the seawater on the day with the highest SS value (14.6 mg L−1, Mar. 2002) at Mio are shown in Figure 7c, 7d, and 7e, respectively. Mica, kaolinite, quartz, feldspar, smectite, and chlorite were detected in the sediment particles from the lake bottom at Tsubayama Dam, the estuary of Hidakagawa River, and suspended particles in the high turbidity seawater at Mio. Particles from the Tsubayama Dam contained a high proportion of mica and kaolinite. The mineral compositions of particles of the lake bottom at Tsubayama Dam indicated the same origin as that of the suspended particles in the seawater at Mio.

### Discussion

#### Factors involved in the isoyake at Mio

In previous studies, the main factors proposed to explain the *isoyake* were as follows [16]: high water temperature [17,18], low salinity [19], low nutrient salts [20–22], grazing pressure by herbivorous animals [9,10] and high levels of turbidity and sediments [23–29].

According to the results of the present study, the water temperature at both Mio and Noshima reached 28°C in summer. This indicates that the summer water temperature in this sea area poses a potential threat to the survival of *E. bicyclis* [17,18,30]. However, as there was no difference in temperature between the two areas, higher water
One unique environmental factor of the sea area at Mio is the abundance of particles in the seawater and sediment particles on the bedrock. The mean Secchi disc depth value during the observation period at Mio was 12.5 m, indicating low turbidity. However, the value sometimes showed drastic and rapid turbidity increases (to 1–3 m). The high-turbidity conditions corresponded closely to periods of high precipitation. The amount of sediment particles on the artificial reefs at Mio ranged between 2.2 and 10.4 mg·cm⁻², showing a large variation. From October 2001 to January 2002 and from April to August 2002, the amount of sediment particles increased markedly. There was no clear relationship between these increases in sediments and precipitation. The changes in the amounts of sediment particles may reflect resuspension by tidal surges or swells. It is clear, however, that the Mio sea area contained much greater amounts of particles than did that at Noshima. Therefore, we speculate that the suspended particles in the seawater and sediment particles on the bedrock are the major cause of the isoyake at Mio.

Effects of sediments on E. bicyclis survival

When scuba diving at Mio, we noticed that milky white fine particles were stirred up when we fanned the top of the bedrock by hand. Fine particles were adhered to the surface of the current meter after it had been in place on the seabed for 1 week.

There have been several studies on the effects of marine particles on the early stages of seaweed growth. Suspended particles in seawater can adsorb onto seaweed zoospores and disturb their settlement onto the substrate. Particles already settled on the substrate can prevent adhesion to the substrate, and negatively affect the growth and survival of gametophytes [24,26,27,29].

The effects of suspended particles and sediment particles on the seaweed community at Mio have been evaluated previously. Arakawa (2005) [27] derived the following equation by examining the relationships between the concentration of suspended particle/amount of sediment particles and the initial depletion of zoospores and gametophytes of E. bicyclis.

$$TL = 100(1 - \exp (-0.0339C - 1.24Q)),$$

where TL (%) is total loss, C (mg·L⁻¹) is the concentration of suspended particles in the seawater, and Q (mg·cm⁻²) is the amount of sediment particles on the substrate. In those experiments, kaolinite particles with mean diameters of 3.2 μm and 14.9 μm were used as suspended particles and sediment particles.

In the sea area at Mio, the maximum concentration of suspended particles in the surface seawater reached 14.6 mg·L⁻¹. The vertical distribution of turbidity at this time was not determined. In an estuary area, the turbidity is generally high at the surface layer. However, in the sea area at Mio, there were often strong swells, and the sediment particles on the bedrock were resuspended by the swell. If the concentration of SS near the seabed is assumed to be the same as that on the sea surface, we can calculate the effects of the particles using the equation shown above. The total loss at maximum turbidity concentration was calculated to be 39.0% when the initial depletion was assumed to be caused only by suspended particles at Mio.

The concentrations of sediment particles at Mio ranged from 2.2 to 10.4 mg·cm⁻², and the average value was 6.7 mg·cm⁻². In Arakawa (2005), kaolinite particles with a mean diameter of 14.9 μm were used as sediment particles. The effects of particle size on the initial depletion of seaweed have not been studied yet. However, it is thought
that sediment particles with diameters of 30 μm or less were involved in the *isoyake* at Mio. According to the particle-size distribution in October 2001, 25.9% (1.73 mg·cm⁻²) of the sediment particles at Mio were 30 μm or less in diameter. If these values are used in the equation above, then the initial depletion of zoospores and gametophytes of *E. bicyclis* is calculated to be 86.6%.

The average amount of sediment particles on the seabed at Noshima was 1.5 mg·cm⁻². Approximately 30.5% (0.47 mg·cm⁻²) of these particles had diameters of 30 μm or less. If these values are used in the equation above, the initial depletion of zoospores and gametophytes of *E. bicyclis* at Noshima is calculated to be 42.2%. If the initial depletions by suspended particles are the same in the two sea areas, then the threshold value for the formation of a forest must be between the values of initial depletion in the two sea areas caused by sediment particles. Based on the amount of sediment particles at Mio, most of the *E. bicyclis* will die at the initial stages of development.

Origin of particles in the sea area at Mio

Our analyses indicate that there was a remarkable initial depletion of *E. bicyclis* at Mio because of the negative effects of suspended particles and fine sediment particles. The seawater in this area became muddy after heavy rainfalls and during strong swells.

The high turbidity of the seawater during the rainfall events was probably a result of inflow from the Hidakagawa River. The mouth of this river is on the east side of Mio, and it affected the salinity levels in that area. For example, the minimum salinity level (21.2%) recorded in this study was in this area after 432 mm rainfall.

We found that the variations in current velocity at Mio corresponded closely with the tidal variations. The current flowed slightly to the northeast during the ebb tide and strongly to the west during the flood tide. Cross correlation coefficients between the tide and velocity components at Mio were 0.76, 0.56, and 0.78, in the case of the eastward component for May, August, and November, measured for delays of 230 minutes, 270 minutes, and 250 minutes from the tide, respectively. Therefore, the current direction and current velocity at Mio corresponded closely with the tide. At delays of 230–270 minutes from the flood tide, the westward current strengthened, and this strong current carried particles from the direction of the Hidakagawa River. The fine particles that were flushed out from the Hidakagawa River tended to flow into the sea area at Mio located to the west of the river mouth. While the high turbidity of seawater after rainfall was because of particles flushed from the river, the high turbidity in seawater during strong swells was because of resuspension of previously settled fine particles deposited during heavy rainfall events.

To determine the origin of the abundant fine sediment particles in the sea area at Mio, the sedimentary particles at the Tsubayama Dam located upstream from the Hidakagawa River, those at the estuary of the Hidakagawa River, and suspended particles in seawater when the Secchi disc depth decreased were analyzed by X-ray diffraction (Figure 7). The sedimentary particles at the Tsubayama Dam matched, in mineral composition and relative mineral quantities, with those sampled during the periods of low Secchi disc depth. We presume that the particles that originated from upstream of the Hidakagawa River flowed into the sea area at Mio and settled onto the sea floor.

Until around 1990, approximately 10 tons of abalones per year were harvested from the Mio sea area (Wakayama Pref., unpubl. data, 1989). The Tsubayama dam was completed and began to be used in 1988. However, no quantitative data were collected to evaluate changes in the turbidity of seawater and seaweed abundance. Workers in the fishing industry observed that the turbidity of seawater increased and the seaweed forest decreased after the dam came into use. Yamauchi and Midorikawa [7] reported that a marine forest of *E. bicyclis* was present at depths of up to 10 m in Mio until 1988, although it collapsed quickly in the 1990s.

In conclusion, the main origin of the sediment particles in the sea area at Mio is the Hidakagawa River. In order for the seaweed community at Mio to recover, it is necessary to reduce the supply of fine particles from this river.

References


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