F - 5. 2. 2. Study on the Decline in the Biodiversity of Coral Reef Community and its Accompanying Change of Community Metabolism

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Total Budget for FY1997-2000 9,641,000Yen (**FY1999**; 2,896,000Yen)

Abstract Measurements of carbon dioxide system parameters and nutrients revealed a potential influence of terrestrial inputs on community structure as well as carbon budget in a fringing coral reef of Ishigaki Island, where currently coral reefs are greatly stressed by human activities. Land derived fresh waters including river water and groundwater are extremely high in the fugacity of carbon dioxide up to 6,400 μatm, reflecting enrichments in total alkalinity and dissolved inorganic carbon. Since dissolved inorganic C:P ratio is anomalously high in terrestrial waters compared to mean C:P ratios of primary production, excess carbon has a potential to be released to the atmosphere and to decrease saturation degree of reef waters with respect to calcium carbonate. Terrestrial inputs deliver large quantity of C relative to P, probably resulting in modification of community structures.

Key Words Coral Reefs, Biodiversity, Carbon Dioxide, Circulation, Nutrients, Groundwater

1. Introduction

Coral reef flats are characterized by high rates of gross community primary production (mean 7 gC $m^{-2}day^{-1}$)[1]. Most organic matter produced is, however, consumed by community respiration. Consequently, the net community primary production is close to zero (0 ± 0.7 gC m^{-2} day^{-1})[2]. On the other hand, net community calcification (mean 10.8 g$CaCO_3$ m^{-2} day^{-1} on reef flats)[1] releases CO_2 into the water column, and the precipitated carbonate is stable due to its oversaturation in the surface water. For understanding of carbon processes in coral reeefs, one important aspect seems to be missing - the influence of terrestrial inputs. Especially in the case of a fringing reef, terrestrial inputs could play an important role because land-derived nutrients may enhance community primary production and lead to a decrease of fCO_2 in reef waters. The effect of terrestrial inputs on community metabolism has received little attention so far. Here we present data on CO_2 in groundwater, river water, beach water, and reef water in the Shiraho fringing reef in order to evaluate the effect of terrestrial inputs on the community structure and net carbon budget of the fringing reefs.

2. Study area

It lies in the path of the warm nutrient-depleted Kuroshio current (Fig. 1A). Pleistocene reef carbonate sediments (Ryukyu Limestone) are widely distributed in the southern part of

Ishigaki Island and are dominant in the Todoroki River catchments. Field studies were carried out on the Shiraho and Todoroki sections of the Shiraho fringing reef situated on the southeastern coast of the island (Figs. 1B and 1C). Both sections contain well-developed fringing reefs about 800 m in width and 0 - 3 m in depth. The southern boundary of the Shiraho section is delineated by a shallow area called "Watanji". The reefs are classified into four topographic sub-areas based upon depth, gradient and surface roughness: (1) moat, (2) inner reef flat, (3) reef crest and (4) outer reef flat (from the coast to the offshore).

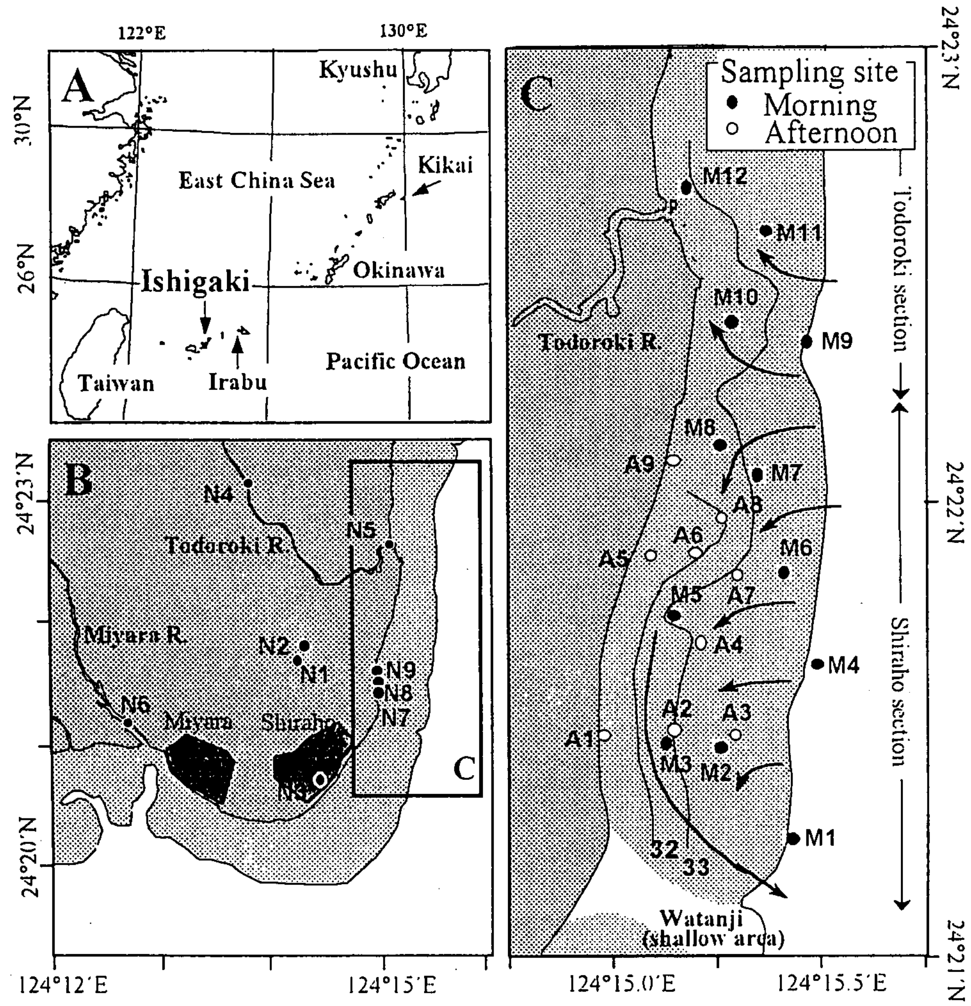

Fig. 1. Location map of Ishigaki Island, Ryukyu Islands and studied area in Shiraho reef (A). Sampling locations for groundwater (Sts. N1-N3), river water (Sts. N4-6), beach water (Sts. N7-N9) and reef water (Sts. M1-M12, A1-A9) around Shiraho area (B, C). Distribution of salinity with estimated general direction of currents was obtained using an automated self-recording salinometer during morning survey [3]

The general circulation pattern of water on the reef flat was deduced from current measurements, arrangement of the coral patches, and the distribution of sea surface temperature and salinity [3,4]. Offshore water enters the reef across the reef edge around the boundary between the Shiraho and Todoroki sections and flows landward across the outer reef flat, reef crest and inner reef flat in that order. The currents then turn south in the Shiraho section and north in the Todoroki section. The warmed water is drained to the offshore mainly through the depression to the north of "Watanji".

3. Material and methods

Seawater and fresh water samples were collected at 30 stations with temperature and salinity measurements on 23 and 24 of June, 1997 (Fig. 1C). Offshore seawater were taken at Sts. M1 and M9. Groundwater samples were taken at Sts. N1 and N2 in the cave while groundwater sampled at St. N3 near the coast was pumped up from 10 m depth.

Methods for measurements of pH and total alkalinity (A_T) were similar to those described in Suzuki et al.[5]. The pH measurements at 25.0°C (pH_{25}) were carried out in a laboratory within 4 hours after sample collection, using a combined electrode (GK2401C, Radiometer) with a Radiometer ION - ANALYZER (Model: ION85). Total alkalinity (A_T) of seawater passing through a GF/F filter was obtained by the potentiometric acid titration method, using a Radiometer titrator (Model VIT90). The precision and accuracy of the method have been estimated to be 0.15% for A_T. A self-recording salinometer (MDS-CT, Aleck Electr. Co.) was used to measure salinity and seawater temperature with precision of 0.04 and 0.05°C, respectively. Concentrations of dissolved inorganic nutrients (phosphate and silica) were determined in water samples filtered through 0.45 μm acetate filters according to the methods described by Strickland and Parsons[6]. Precision was 0.02 $\mu mol\ kg^{-1}$. Densities of all solutions were calculated from salinity and temperature[7]. Total CO_2 (C_T) and fugacity of carbon dioxide (fCO_2) were calculated from data sets of temperature, salinity, pH_{25} and A_T, using appropriate thermodynamic constants[8,9,4,5].

4. Results and Discussion

Properties of fresh water — Salinity of beach water samples were definitely lower than offshore seawater (Fig. 2A). The fact that salinity declines with increasing distance from the river mouth of the Todoroki and Miyara Rivers indicates the significant influence of groundwater inputs from many seepages along the beach-sea interface. Dissolved silica concentrations were negatively correlated with salinity (r = 0.83) due to the mixing of groundwater and offshore water. On the other hand, phosphate concentrations were more rapidly depleted than dissolved silica, which suggests that phosphate concentrations were much more controlled by the consumption by benthic metabolism than the water mixing. Phosphate still remained in the water samples taken at Sts. N7 and N9 although reef water in most of the Shiraho section except along the beach is generally depleted in nutrients below the analytical detection limits.

The carbon budget of coral reefs can be affected by the initial water properties, together with biological processes due to reef organisms. These processes can be represented as changes of A_T and C_T on the A_T - C_T diagram[10] (Fig. 2).

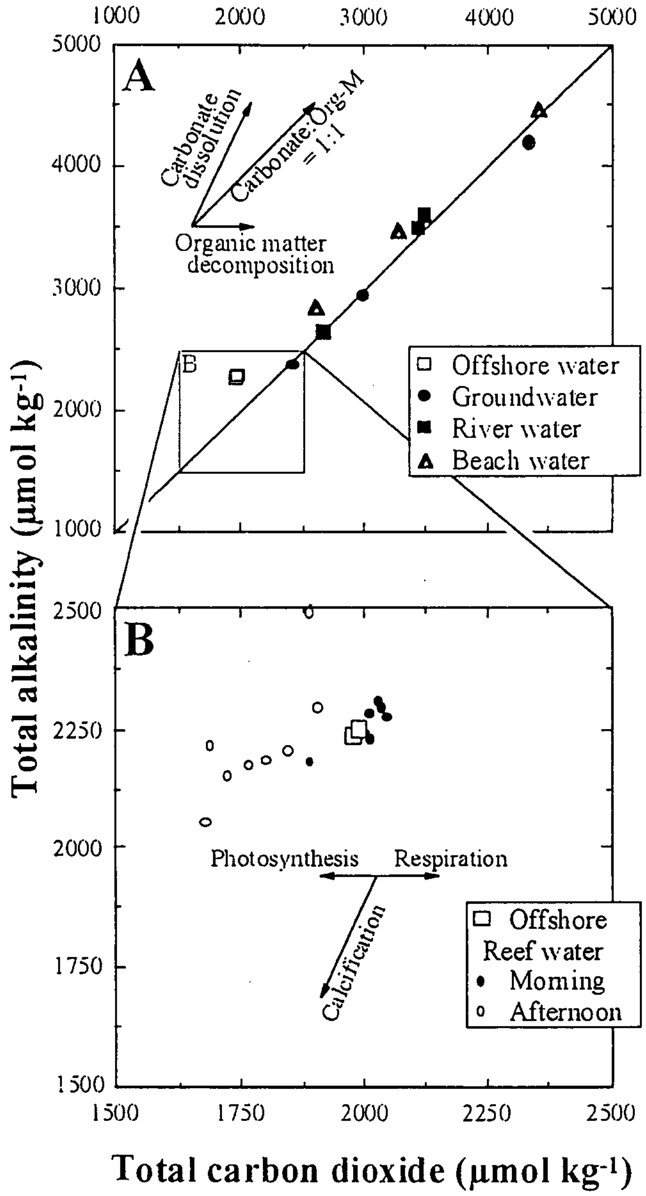

Fig. 2. Total alkalinity (A_T) versus total carbon dioxide (C_T) diagram for the Shiraho and Todoroki sections of Ishigaki Island (A, B). Values of A_T and C_T are expressed as µmol kg^{-1}.

The distribution of groundwater in the Ryukyu Islands has been reported by Matsuda et al.[11]. They shows that Irabu Island (Fig. 1A) is underlain by a freshwater lens (<1 % seawater), which has maximum thickness of 12 m in the central part of the island. The freshwater lens overlies a freshwater-seawater mixing zone (1 - 90% seawater) ranging in thickness from 7 m to more than 30 m, with the thickness increasing toward the coast. A similar picture is also reported from Kikai[11] (Fig. 1A) and this type of groundwater distribution is also expected in Ishigaki Island. Groundwater samples from Sts. N1 and N2 were spring water which passed through the Ryukyu Limestone. Judging from the salinities (ca. 0), they came from the freshwater lens. On the other hand, groundwater sampled at St. N3 near the coast was pumped up from 10 m depth. The salinity of about 5.9 shows that the water came from the freshwater-seawater mixing zone. The St. N3 sample gave maximum A_T and C_T values of 4, µmol kg^{-1} and 4,362 µmol kg^{-1}, respectively, which were approximately twice those of offshore water. Fresh water taken from the Todoroki River gave high A_T and C_T, which were comparable to the mean values of fresh groundwater.

The dissolution of carbonate raises the A_T by two moles and the C_T by one mole for each mole of $CaCO_3$ dissolved whereas organic carbon degradation raises the C_T by one mole without any change in the A_T. If the dissolution of $CaCO_3$ is mainly responsible for the increase in A_T and C_T (approximately 3,200 and 1,600 μmol kg^{-1}), the rest of C_T (1600 μmol kg^{-1}) could be ascribed to the CO_2 derived from organic matter decomposition. This suggests that CO_2 production from organic matter degradation is equivalent to that from carbonate dissolution, and explains the observed A_T and C_T values in the freshwater. fCO_2 for four freshwater samples were calculated to be 3,400 μatm.

Groundwater sampled at St. N3 displayed extremely high fCO_2 (6,435 μatm), approximately 20 times higher than that of offshore water (364 μatm). Since the fCO_2 is much higher near the beach than that in the atmosphere, CO_2 should be released into the atmosphere.

Properties of reef water — Two biological processes play an important role in the modification of water properties with respect to carbon budget in the coral reef ecosystem: organic carbon metabolism (photosynthesis fixation and respiration/degradation) and inorganic carbon reactions (precipitation and dissolution of calcium carbonate). The contribution of planktonic primary production to reef metabolism is negligible[1].

The fCO_2 ranged from 297 to 660 μatm, averaging 410 μatm, during the morning survey. The elevated fCO_2 is ascribed to accumulated respiration/degradation effect during nighttime. In contrast, during the afternoon survey, most of the samples with salinity of 31.15 to 33.80 showed significant decrease in A_T and C_T, which were accompanied with lower fCO_2 values from 107 to 224 μatm. This decrease in A_T and C_T is presumably the results of active photosynthesis during daytime and short residence time (~13 hours) of seawater on the reef flat. These properties were within the range of diurnal change reported previously from the Shiraho fringing reef [4,12,13]. On the other hand, two less saline samples (A1 and A5) with significant amounts of groundwater had high A_T and C_T values with high fCO_2, which is due to large contribution of fresh water, because groundwater (av. A_T = 3,161, C_T = 3,260 μmol kg^{-1}) exhibits higher A_T and C_T than offshore seawater (av. A_T = 2,247, C_T = 1,980 μmol kg^{-1}). Although A_T and C_T should be reduced by photosynthesis and calcification during the daytime, less saline beach water showed much higher A_T, C_T and fCO_2 than the offshore water. Although we presented CO_2 data for only one day, the residence time of groundwater is over several months and this kind of freshwater is responsible for less saline beach water, therefore it is plausible that high values A_T, C_T and fCO_2 are observed during the entire year in the beach water in the Shiraho fringing reef despite possible changed in magnitude.

Effects of freshwater on the carbon budget in the coral reef ecosystem — Coral reefs often have little net excess primary production because they are surrounded by tropical oligotrophic (nutrient-poor) ocean, and little nutrient supply is supposed to limit new production in reefs. In fact, the phosphate and nitrate concentrations of surface water in the Kuroshio Current are below the detection limit (<0.02 μmol kg^{-1}) around the Ryukyu Islands[14]. On the other hand, nutrient-rich fresh water contributes 0.5 - 1.2 % of the water volume to the Shiraho fringing reef[3]. Therefore, appreciable amounts of terrestrial input will modify the carbon budget in this fringing reef.

The median C:N:P atomic ratio of benthic marine macroalgae and seagrass from tropical coastal areas including coral reefs is about 550:30:1[15]. This is very different from Redfield ratio of 106:16:1 for phytoplankton[16]. Fenchel and Jorgensen[17]. stated that the C:N ratio of benthic plants ranges from 10:1 to 70:1 and that the C:P ratio is about 200:1. Thus in comparison to phytoplankton, benthic plants are much more depleted in P and less in N relative to C. When terrestrial water delivers nutrients to coral reefs, benthic plants can fix CO_2 by photosynthesis and decrease fCO_2. On the other hand, CO_2 dissolved in terrestrial water is transported into reefs and raises fCO_2. Therefore the effects of terrestrial inputs on the net carbon budget in coral reefs depend on the C:P ratios in terrestrial water. When the ratio is smaller than 550:1, benthic plants may absorb all dissolved CO_2 by photosynthesis during daytime and the reef will act as a sink for CO_2. But when terrestrial water inputs have C:P of >550:1, the fringing reef will raise fCO_2 in the seawater[15].

Groundwater and river water from Ishigaki Island have high C:P ratios, ranging between 3,600 and 35,000: several times to two orders higher than those of benthic plants. These inputs will supply large quantity of C relative to P into the Shiraho fringing reef and raise fCO_2 even during daytime, consequently leading to release CO_2 into the atmosphere near the beach. During nighttime both respiration and terrestrial CO_2 inputs should enhance the release of CO_2 to the atmosphere (Fig. 3). Even though there is a tight connection between calcification and photosynthesis[13], it is widely accepted that calcification plays an important role in the net carbon budget of coral reef ecosystems. This view has been confirmed by investigations conducted in atolls and barrier reefs with lagoons, where the residence time of water is long enough for organic matter to be decomposed[18,19,20]. The site in this study was a source of CO_2 at the time of measurement and such situation is likely to prevail all year round and it may occur elsewhere. Therefore our results provide one of the best examples that this concept may be extended to fringing reefs, which receive more land-derived material in comparison with atolls and barrier reefs although further investigation is required to generalize the concept to three types of coral reefs - fringing and barrier reefs and atolls[21].

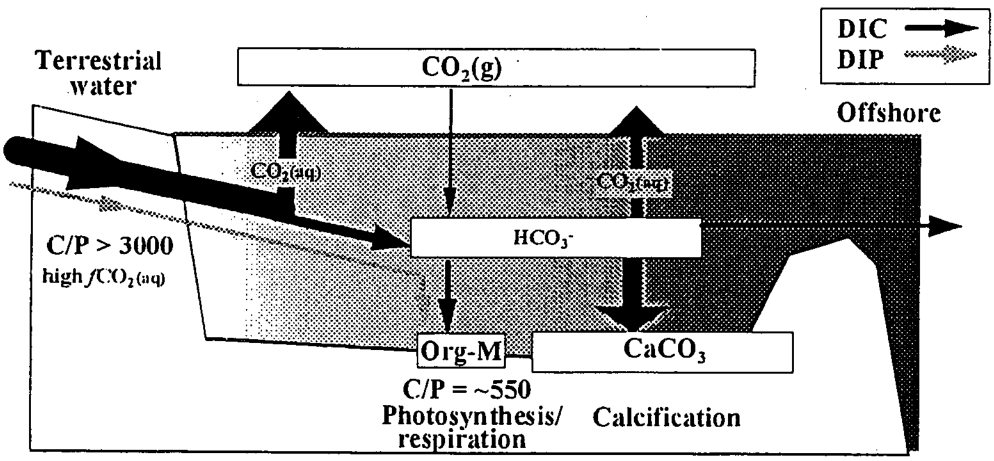

Fig. 3. Schematic diagram for carbon cycle in the Shiraho fringing reef. Groundwater and river water showed high C:P ratios, ranging between 3,600 and 35,000, several times to two orders higher than those of benthic plants. Probably degassing for CO_2 could occur near the beach. Calcification plays an important role in net carbon cycle especially in the reef crest. Although phosphate is consumed to produce organic matter in the reef flat during daytime, organic matter is quickly decomposed to CO_2 as

indicated by very low organic content in the reef sediments. Therefore the Shiraho fringing reef potentially work as a source of CO_2

As is the case with many currently developed tropical islands, the fringing reefs of the Ryukyu Islands are being greatly stressed by human activity. Fertilizer application might stimulate primary production in coral reefs, which will cause them to retain more CO_2. In fact, fertilizers enriched in nitrogen, phosphorus and potassium are applied at the rate of 700 kg $ha^{-1} yr^{-1}$ in the intensive farming (e.g., rice and sugar cane) in Ishigaki Island (Yaeyama Agricultural Agency, personal communication). Recent ecological study of the coral reefs around Ishigaki Island has demonstrated that higher nutrients inputs modify the community structure and distribution of coral and other benthic organisms (personal communication, Prof. R. van Woesik) as is observed in Kaneohe Bay, Hawaii[22)]. However, judging from the water properties of Todoroki and Miyara Rivers and groundwater, terrestrial dissolved material inputs enriched in CO_2 relative to phosphate still overcomes the artificial nutrient supply around the Shiraho fringing reef.

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