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Thermodynamics of Coral Diversity — Diversity Index of Coral Distributions in Amitori Bay, Iriomote Island, Japan and Intermediate Disturbance Hypothesis

Shinya Shimokawa, Tomokazu Murakami, Akiyuki Ukai, Hiroyoshi Kohno, Akira Mizutani and Kouta Nakase

Additional information is available at the end of the chapter

Abstract

The relationship between coral distributions and physical variables was investigated in Amitori Bay, Iriomote Island, Japan. Amitori Bay is located in the northeast region of Iriomote Island, Japan. Broad areas of coral have developed in the bay, and their life forms, coverages, sizes, and species vary depending on their locations. In addition, Amitori Bay has no access roads, and the bay perimeter is uninhabited. Thus, this small bay, with its variety of environments and lack of human impact, is considered to be one of the most suitable areas for studying the relationship between coral distribution and physical variables.

Field observations were conducted to obtain data on coral distributions, sea temperature, sea salinity, wind speed, and river flow rate. The observed data were then used in ocean and wave model numerical simulations and soil particle tracking analysis to obtain the spatial and temporal distributions of wave height and the numbers of soil particles. Our results showed that the life forms, sizes, and species of corals significantly varied depending on their locations in the bay, because the physical variables differed significantly among these locations.

From the results of the above observations and simulations, we calculated diversity index of coral distributions and its relation to physical variables. The diversity index, DI is defined as DI=-Σ c_i log$_2$ c_i, where ci is the ratio of i-th group coverage to total coverage. DI is a quantitative measure for the degree in which a dataset includes different types and is related closely to entropy concept in Thermodynamics. The value of DI increases when both the number of types and the evenness increase. For a given number of types, the value of DI is maximized when all types are equally abundant. The results show that Averages of diversity index of the coral types at the mouth and inner parts of the bay are lower than average of the whole region, but average of diversity index at the intermedi-

ate part of the bay with the intermediate physical disturbances is higher than it. This seems to support the intermediate disturbance hypothesis which states species diversity in local area is maximized when environmental disturbances is neither too weak not too strong.

1. Introduction

"Corals" is the general term for *cnidaria* which inhabit the tropical and sub-tropical oceans and have an external skeleton [1, 2]. They are classified as either reef-building or non-reef-building corals. "Reef-building corals" is the general term for the species which inhabit the shallow oceans and have a relatively hard skeleton. They are the focus of this study. "Non-reef-building corals" is the general term for the species which inhabit the deep oceans and have a relatively soft skeleton. They include the so-called red, or precious, corals. Reef-building coral characteristics are deeply related to zooxanthellae existence. Zooxanthellae are a type of phytoplankton called dinoflagellate (mainly marine protozoa having two flagella). All reef-building corals live symbiotically with zooxanthellae. Instead of obtaining a secure habitat from reef-building corals, zooxanthellae contribute nine-tenths of their photosynthetic energy production to such corals. Reef-building corals can form their skeleton more rapidly and abundantly than non-reef-building corals by applying the photosynthetic energy production obtained from zooxanthellae. Reef-building coral skeletons are used as habitats by various organisms, and are the raw material for coral reefs. Reef-building corals also form mucus by applying the photosynthetic energy production not used for skeleton formation. The mucus plays a role in protecting the body surface of reef-building corals. Various organisms living in coral reefs treat them as a food. In other words, reef-building corals supply a large proportion of the habitats and foods for organisms in coral reefs, and thereby support abundant ecological systems in oligotrophic tropical oceans. Moreover, humans benefit in various ways from reef-building corals and coral reefs. Corallite, solidified from the skeletons of reef-building corals, is used for traditional daily necessaries and stone walls, and abundant sea foods obtained around coral reefs support our dietary requirements. Beautiful underwater views of coral reefs are treasured as tourist attractions around coastal areas of the tropics and sub-tropics. The function of coral reefs as a natural sea wall is important from disaster prevention viewpoint. In this study, "corals" is referred as "reef-building corals."

The distribution of corals is diverse and is affected by various factors such as human activities (including red soil erosion due to land development and sea temperature rise due to global warming), their predation by *Acanthaster* (crown-of-thorns starfish) and *Drupella fragum* (a species of sea snail), and environmental properties related to waves and soil grains. In these factors, environmental properties are the most important factors related to the long-term distribution of coral. Thus, investigating the relationship between coral distributions and environmental properties is useful in understanding coral and its diversity.

Some studies on the relationship have focused on wave height [3-7]. However, these studies did not consider spatial distribution. The relationship between wave forces and the spatial distribution of corals with a specific form in the Hawaiian Islands was investigated in [8]. However, their studies did not consider the effect of other environmental property such as soil grains. Recently, the relationships between coral habitat and some environmental properties were investigated in [9]. However, their studies focused only on the qualitative tendency.

This relationship includes short- and long-term physical processes along with direct responses to environmental properties. For example, in relationship to destruction by high waves, it is widely accepted that the structure of branching corals is more fragile than that of tabular corals. However, this destruction can also cause broader distribution due to the high regenerative power of corals. That is, high waves can reduce coral distribution in the short term but can broaden it in the long term. Conversely, extreme wave height, due to strong typhoons, can severely damage or destroy coral colonies [10, 4, 11, 12]. This seems to be related to the intermediate disturbance hypothesis (IDH) [13], which postulates that local species diversity is maximized when environmental disturbances are neither too weak (or rare) nor too strong (or frequent) and is often used to investigate the relationship between species diversity and environmental disturbances.

Environmental properties affect not only coral distribution but also coral life forms [1, 2]. Most corals make colonies consisting of many individuals called polyps. This type of coral is called a colonial coral, and all the corals in this study are classified as this type. Coral colonies have various forms such as tabular, branching, massive, foliose, and encrusting corals. They deform as per the environmental properties, and corals of the same species can show different forms. Reef-building coral classification is currently based on morphological features such as the shape of the individual polyps, their sequence manner on the colony, and the colony forms; however, classification is difficult because the surfaces of living corals have a molluscous covering [14]. In addition, although molecular phylogenetic analyses are needed for strict identification, there are cases when gene consistency within a species is lacking because gene exchanges among different species occur because of their unique mass-spawning trait (i.e., simultaneous release of eggs and sperm among different species) [15-17]. Currently, the right approach to investigate the relationship between coral distribution and environmental properties is considered to be one which regard habitat adaption as important, and one which focuses on the life form rather than the species.

Amitori Bay is located in the northeast region of Iriomote Island, Japan (Fig. 1), which is 2 km in width at its mouth, 4 km in length, and has a maximum depth of 70 m in the central mouth area, two rivers (the Ayanda and Udara) and the accompanied mangrove environments in the inner part of the bay. Broad areas of coral have been developed in the bay and their life forms, coverage, size, and species vary depending on their location. In addition, Amitori Bay has no access roads, and the bay perimeter is uninhabited. Thus, this small bay, with its variety of environments and lack of human impact, is considered to be one of the most suitable areas for studying the relationship between coral distribution and environmental properties.

On the contrary, observations of environmental properties in Amitori Bay are not many and are hard to conduct due to the access difficulty. Thus, we compensated for the shortage of
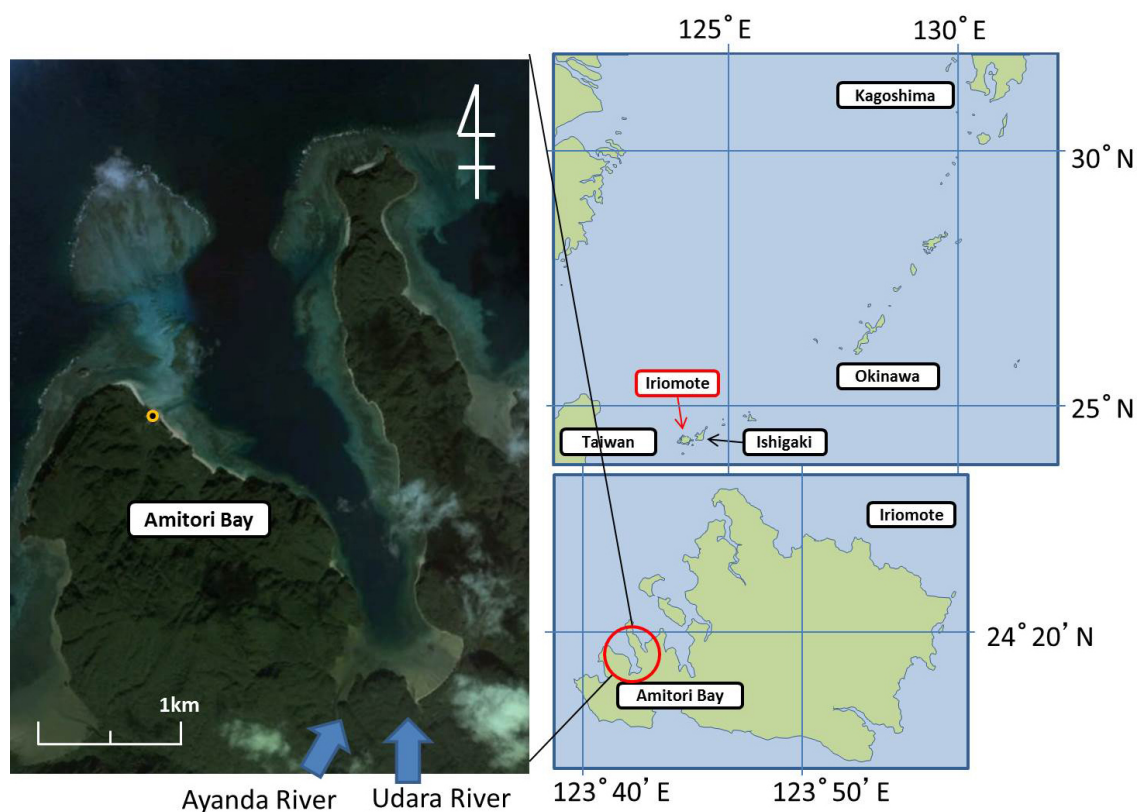
Figure 1. Locations of Amitori Bay and Iriomote Island. The top of the reef slope in Amitori Bay is indicated in Fig. 2 (after [18]).

observation by using numerical simulations. That is, when observational data were available, they are used to determine the parameters in the numerical simulations; on the other hand, when observational data were unavailable, methods without observational hypotheses in the numerical simulations are used.

This study [18] attempts to clarify these relationships in the corals of Amitori Bay, Iriomote Island, Japan, by observing the ocean, atmosphere, and rivers, which is performed through numerical simulation using ocean and wave models along with particle tracking analysis.

In Section 2, we state the investigation methods of the coral distribution and observation methods of the oceanic, atmospheric and river observations, and the numerical simulation methods to reproduce detailed oceanic and atmospheric states in Amitori Bay and to investigate the effects of waves and soil grains on coral distribution. In Section 3, we provide the results of our coral distribution investigation, our oceanic, atmospheric, and river observations, and the numerical simulations. In addition, we compare the coral distributions with our observational and numerical results, and discuss the relationship between coral distributions and environmental properties. In Section 4, we discuss the generality of the results obtained in Section 3 by conducting a statistical analysis. The analysis is related to diversity index, which is a quantitative measure for the degree to which a dataset includes different types and which is closely related to the information entropy concept. The results are also discussed from IDH perspective. We summarize and discuss our findings in Section 5.

## 2. Methods

2.1. Coral distribution investigation

Coral distributions were investigated at 44 locations in Amitori Bay, including 18 locations in 2009 and 26 locations in 2011 (Fig. 2). For the 2009 investigation, indicated by A–R in Fig. 2, three quadrats measuring 1 m on each side were placed at 1–4 points at various depths and life form, coverage, and coral size were recorded. For the 2011 investigation, indicated by 1–26 in Fig. 2, three quadrats measuring 2 m on each side were placed within a 3 m depth at the top of the reef slope and on the reef slope at a depth of 5–8 m, and life form, coverage, and coral size were recorded. The types of coral life forms treated in this study are shown in Fig. 3. States of the coral investigations in Amitori Bay and an example of the photographs of the quadrats are shown in Figs. 4 and 5, respectively. An electronic weighing instrument was used to determine the weight of trace pieces cut from the photographs of the quadrats and then, the coverage of each coral type was calculated. In this study, "coral individuals" and "coral size" mean the individuals and maximum diameters of a coral colony for a specific coral, respectively.

2.2. Oceanic and atmospheric observations

Fixed-point observations were conducted to obtain data on sea level, sea pressure, and horizontal current velocities in Amitori Bay from July 2008 to October 2009 using a WH-403 wave height/wave direction/current speed measuring instrument (I. O. Technic Co. Ltd.). Two measuring instruments were placed at each of Stations 1 and 2 at depths of 10 and 20 m, respectively, and measurements were conducted for 20-min periods at 1-h intervals. Also, moving shipboard observations were conducted to obtain sea temperature and salinity in the bay on October 18, 19, and 24; November 9 and 22; and December 14, 2011 using a RINKO conductivity, temperature, and depth profiler (JFE Advantech Co. Ltd.). The number of observation sites varied between 15 and 31 depending on the weather conditions. At each location, observations were conducted from the sea surface to the sea floor at 0.1-m intervals. At Station Z (Fig. 2), continuous measurements have been conducted for wind speed, wind direction, humidity, insolation, air temperature, sea surface temperature, and rainfall amount since 1976 [19]. During the study, the measurement interval was 10 min except for sea surface temperature measurement, which was 2 min.

2.3. River observation

To obtain the flow rates of two rivers, the Ayanda and Udara (Fig. 2) from July 21 to October 3, 2011, an AEM213-D electromagnetic current meter (JFE Advantech Co. Ltd.) were placed in an upstream stretch of each river. Water depths and cross-sectional area were also obtained at each location. The rain volumes were measured at Station Z. Then, a regression model equation was constructed to estimate the flow rate from the rainfall volume. This was performed because the measurement of flow rates throughout the year was difficult due to the need for ongoing instrument maintenance. The correlation coefficients between the calculated results and the observations were high over 0.8.
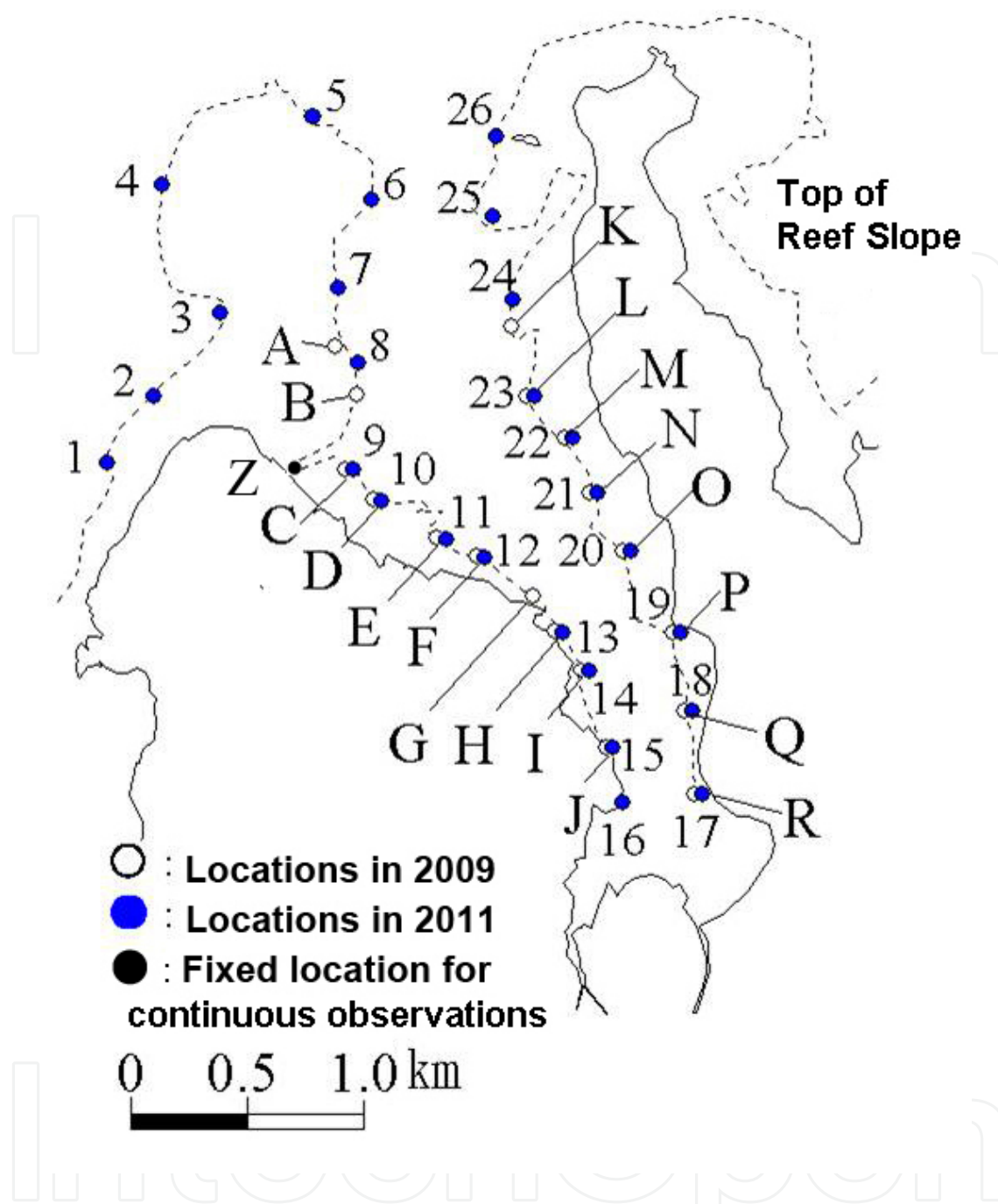
Figure 2. Locations for coral distribution investigations in Amitori Bay. Stations A–R and 1-26 show the locations in 2009 and 2011, respectively. Station Z shows the location for continuous measurements (position: 24°19′51.6″N, 123°41′21.6″E, and height: 4.2 m; after [18]).

2.4. Wave simulation

Numerical simulations were conducted to calculate wave heights and directions in Amitori Bay according to [7]. The calculation was conducted during a one-year period from November 1, 2008 to October 31, 2009 and in the following two regions: the large region including Yaeyama islands of 150 km × 100 km with 500-m grid spacing and the small region (i.e., Amitori Bay) of 4.5 km × 3 km with 20-m grid spacing. Offshore wave conditions from Japan Mete-
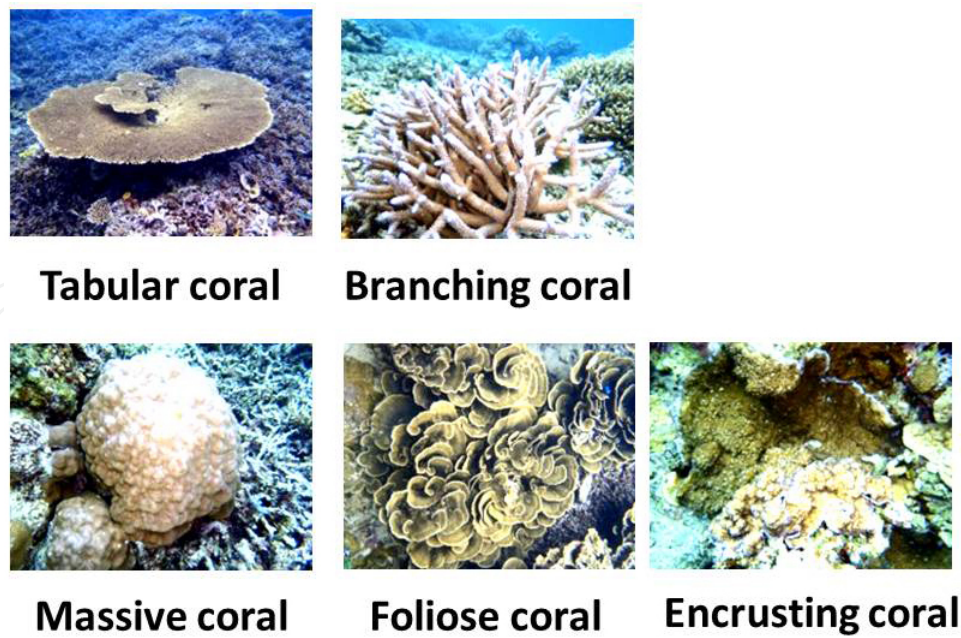
Figure 3. Types of coral life forms treated in this study (after [18]).

orological Agency Grid Point Value [20] such as wave heights, directions and periods were used as input data for the calculation. Three basic wave heights and directions were determined on the basis of the offshore wave conditions. Nine case calculations, as combinations of the basic wave heights and directions, were conducted using an energy balance equation and a wave breaking model developed by [21]. Then, a transformation table was created from the calculation results for every mesh in Amitori Bay, which was used to combine wave heights and directions in Amitori Bay with offshore wave conditions of wave height, direction and period. By using this table, time series of wave heights and directions in Amitori Bay during the target term were obtained from the corresponding offshore wave conditions.

2.5. Soil grain simulation

Lagrangian particle tracking analysis was conducted to obtain the transport properties of soil grains in Amitori Bay. For the purpose, numerical simulations were conducted to reproduce the flow fields in Amitori Bay from 1600 JST on October 18 to 0400 JST on October 25, 2011 using the coastal ocean current model (CCM). The details of the model are described in [22, 23]. Observational data (temperature, salinity, wind speed, wind direction, humidity, insolation, air temperature and rainfall amount), the flow rate from the regression model and astronomical tides calculated by the North Atlantic Oscillation oceanic tide model [24] were used as initial and boundary values for the numerical simulations. The reproductively of the observations in the model was confirmed with high precision [18]. The details of the simulation methods are described in [18]. The particle tracking analysis was conducted using the above flow fields calculated from the CCM and assuming the following conditions: (1) sedimentation of a soil grain due to the own weight was calculated using Rubey's [25] experimental equation, (2) there is no diffusion effect, (3) soil grains that reached the sea floor were not fixed but

Figure 4. Photographs of coral investigations in Amitori Bay.

continued to flow when the Shields number exceeded a critical value, and (4) calcareous sediment produced by the reefs themselves was not considered. The Shields number represents mobility of soil grains on sea or river bottoms, and the critical value was set to 0.05 [26].
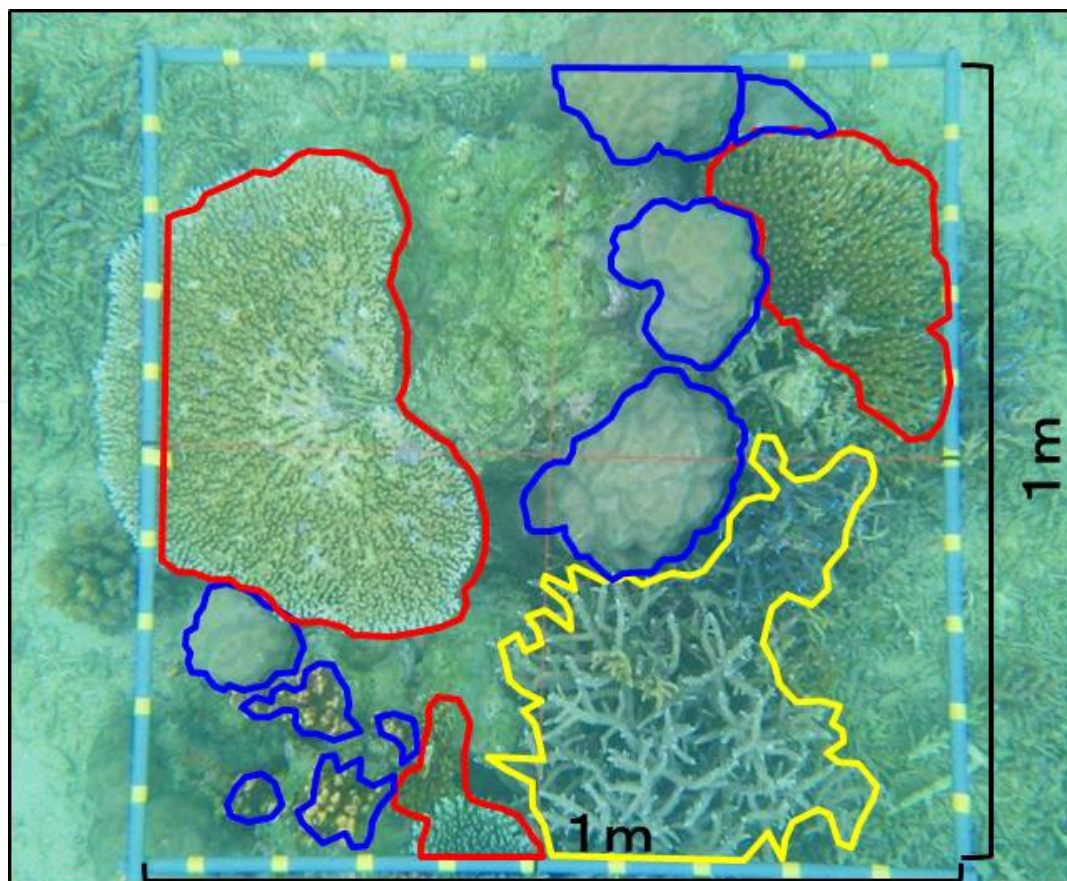
Figure 5. An example of photographs of quadrats. Red, yellow and blue lines show tabular, branching and massive corals, respectively.

Diameters of soil grains were set to 0.1, 1, 3, 5, 8, 10, 15, 20, and 30 μm because sediment trap observations at the mouths of the rivers showed that the diameters were distributed from 0.1 to 50 μm [18]. They were released every 15 s from the Ayanda and Udara rivers.

2.6. Focus of our study and representativeness for the normal state

In this sub-section, we highlight a few points relating to the focus of our study and the representativeness of the normal state. Further details are given by [18].

1. In considering the effect of river inflows on corals in the bay, we focused on soil grains rather than salinity because the effect of low salinity due to inflows from the rivers is smaller and shorter than that of soil grains. In considering the effect of oceanic mechanical force on corals in the bay, we focused on wave height rather than tidal current because tidal full and residual currents have a smaller effect on corals than does wave height.

2. The periods of oceanic simulation (October 18–25, 2011) and soil grain tracking analysis (June 2–22 and November 1–21, 2011) were considered to be in a normal state during these months at Iriomote Island. This was determined by comparison between observational data during the target periods and those for the most recent 33 years.

3.   The normal wave state of the bay is calm compared with that of open oceans. Wave heights in the bay are only slightly affected by offshore wave direction because of the relationship between the overhanging coral reefs at the mouth of the bay, which limit the wave direction to the north, and the most prevalent wind direction. For the same reasons, the effect of waves due to typhoons on corals in the bay is small.

3. Relationship between coral distributions and environmental properties
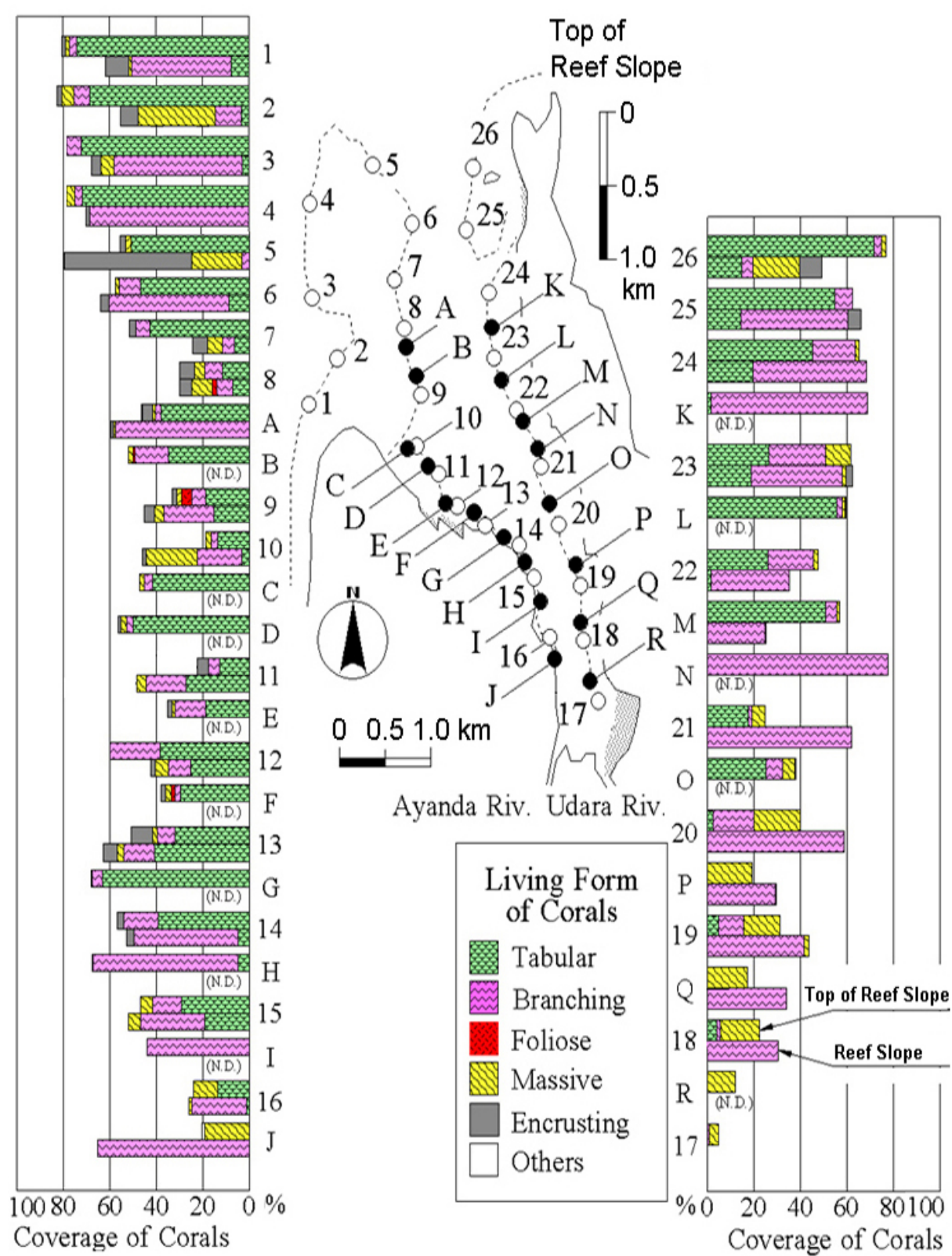
3.1. Distribution of coral life forms

Fig. 6 shows the ratios of coverage of each coral type in Amitori Bay during the 2009 and 2011 investigations classified according to life form. Tabular and branching corals were dominant, covering a total area of more than 90%. The former were dominant at the top of the reef slopes, and the latter were dominant on the reef slopes. On the east side of the bay, the coverage of tabular corals tended to decrease from the mouth of the bay (Station 26) to the inner bay (Station 17) though the tendency was not clear on the west side of the bay. These results suggest that Amitori Bay, although small, has various types of corals.

3.2. Relationship between coral distributions and wave heights

Fig. 7a shows the spatial distribution of wave heights with a corresponding 95% probability of non-exceedance calculated by the wave simulation described in Section 2.4. The wave heights in the mouth of the bay (Stations 4 and 26) were considerably higher than those in the inner bay (Station 17) and on the east side of the bay (Station 20). Fig. 7b shows the relationship between the coverage of tabular or branching corals and wave height. The results showed that a larger coverage of tabular coral and smaller coverage of branching coral corresponded to larger wave heights. These results suggest that tabular coral is strengthened by high wave disturbances and that branching coral is easily broken by them, which is consistent with the results of previous studies [27, 28].
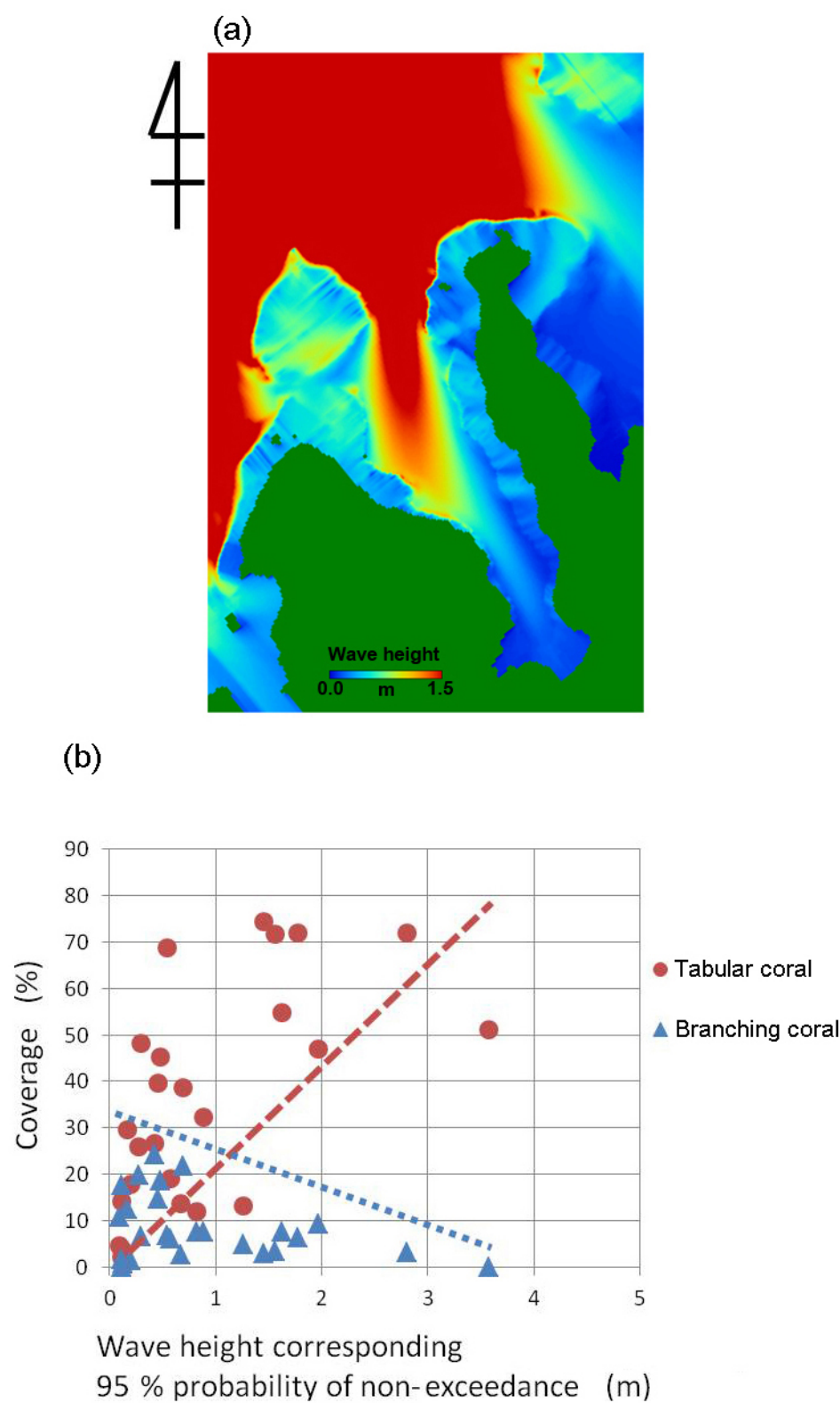
3.3. Relationship between coral distributions and the number of soil grains

Fig. 8 shows the number of soil grains on the sea bottom calculated by the particle tracking analysis described in Section 2.5 and the coverages of tabular and branching corals at Stations 1–26. A comparison between the number of soil grains on the sea bottom (Fig. 8a) and the coverage of the tabular corals (Fig. 8b) showed that smaller coverage of the coral related to a larger number of grains. However, the same comparison with branching corals (Fig. 8c) showed that the coverage of the coral did not relate to the number of grains. These results suggest that tabular coral is affected by soil grains, but branching coral is not because soil grains are easier to accumulate on tabular coral than on branching coral because of their shape.

Figure 6. Ratios of coverage of each coral type in Amitori Bay during the 2009 and 2011 investigations classified according to life form, and the corresponding investigation locations. N.D. indicates no data on reef slope. Types of coral life forms treated in this study are shown in Fig. 3 (after [18]).

Figure 7. a) Spatial distribution of wave heights with a corresponding 95% probability of non-exceedance calculated by the wave simulation described in Section 2.4. (b) Relationship between the coverage of tabular or branching corals and wave height. The red- and blue-dotted lines show the lower boundary of coverage of the tabular corals and the upper boundary of coverage of the branching corals, respectively (after [18]).
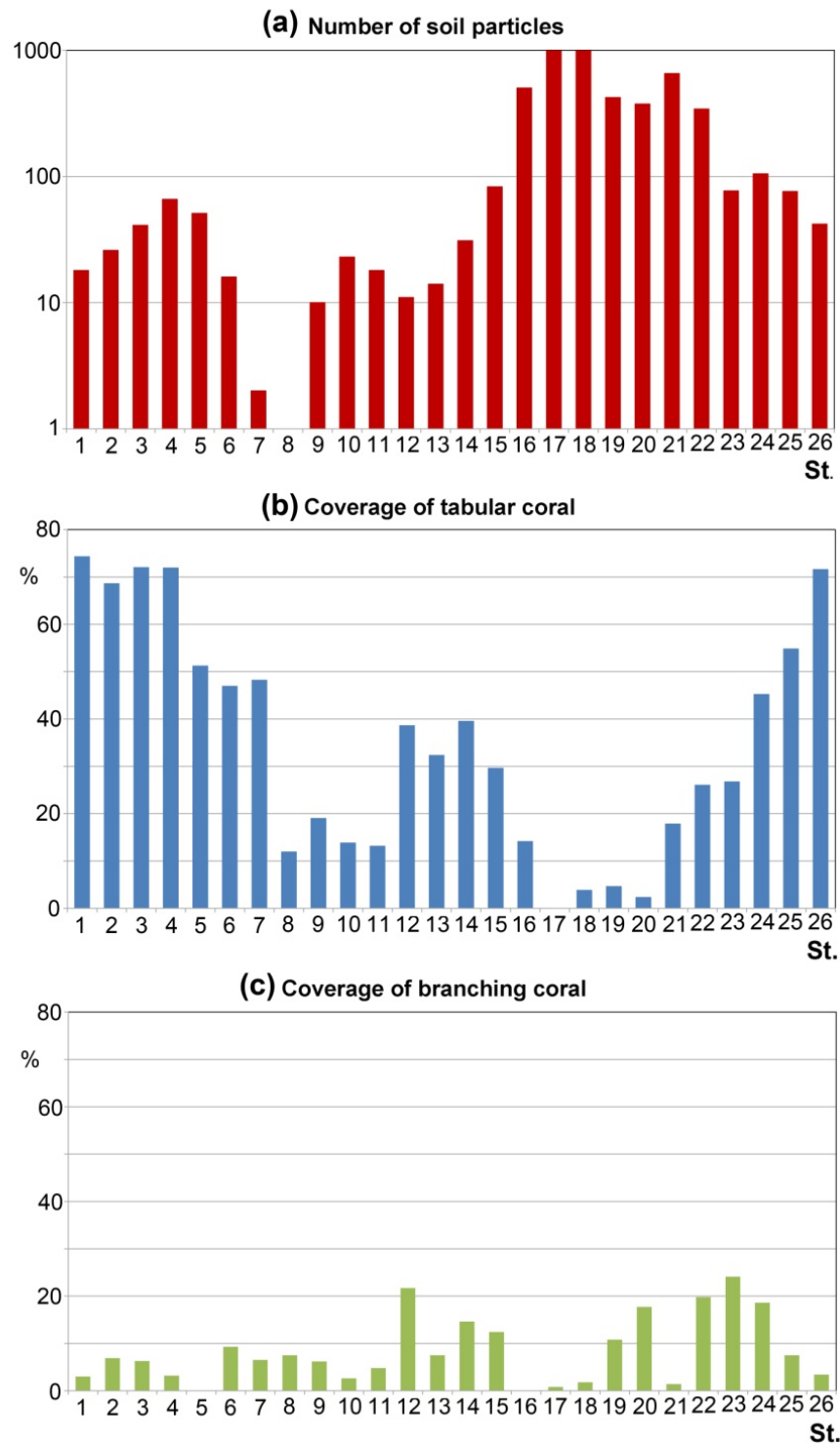
Figure 8. a) Number of soil grains that reached the sea floor by the end of the period (0400 JST on October 25, 2011) calculated by the particle tracking analysis described in section 2.5 and coverage of (b) tabular coral and (c) branching coral at Stations 1–26. The sizes of grains counted in (a) were 1, 3, and 5 μm in diameter. The number of soil grains at Stations 17 and 18 in (a) were over 1000 (after [18]).

4. Diversity index analysis

4.1. Diversity index and its physical meaning

In this section, the generality of the results is discussed by conducting a statistical analysis of the data obtained in the previous sections. The diversity index, H′ [29-32] is calculated and is defined as follows:

$$H' = -\sum c_i \log_2 c_i,$$

(1)

where c_i is the ratio of the ith group population to the total population. H′ is a quantitative measure for the degree to which a dataset includes different types and is closely related to the information entropy concept. The value of H′ is larger than zero and has no upper limit. It increases when both the number of types and evenness increase.

For a given number of types, it is maximized when all types are equally abundant. For example, a case with 5 individuals of only 1 type, i.e., H′ = −(5/5) $\log_2$ (5/5) = 0.0. In this case, the result is zero when a sample has been taken because the type of the sample is determined. Conversely, in a case with 1 individual of each of 5 types, H′ = −(1/5) $\log_2$ (1/5) × 5 = 2.32. In this case, the result is greater than zero when a sample has been taken because the type of the sample has multiple possibilities. In a case with a constant number of types, for example, cases with either 1 individual or 10 individuals of each of 5 types, i.e., ci = 1/5 = 10/50, and thereby H′ = 2.32. That is, in a case with a constant number of types and the same distribution of those types, H′ is unaffected by the number of individuals.

Conversely, in a case with a constant number of individuals, for example, a case with 2 individuals of each of 5 types, H′ = −(2/10) $\log_2$ (2/10) × 5 = 2.32, but in a case with 1 individual of each of 10 types, H′= −(1/10) $\log_2$ (1/10) × 10 = 3.32. That is, in a case with a constant number of individuals, the greater the number of types, the greater is H′. Thus, H′ can be considered as an index that represents diversity and considers the distribution of individuals, not the individuals themselves.

Apart from this index, Simpson's λ index [33] represents diversity based on the number of types and individuals. In addition, Warwick and Clarke's Δ+ and Δ− index [34] represents diversity by considering the taxonomic composition of the types present (i.e., taxonomic distinctness index). Refer to [31, 35] for the characteristics of these indices and the differences among them.

In our case, "group" refers to the coral type (Fig. 3); that is, the number of the group is five although "group" is originally defined as the species [30]. This is because we have focused on the coral type instead of the species as stated in the introduction. In addition, we used coverage instead of population because corals form colonies although ci is originally defined as the ratio of the i-th group population to the total population.

4.2. Distribution of the diversity index and the IDH

Fig. 9 shows the values of H' in Amitori bay. The mouth, intermediate, and inner area of the bay are indicated in green, blue, and red, respectively. Averages of H' at the mouth of the bay (0.60) and the inner area of the bay (0.62) were lower than the average value for the entire area (0.83). However, the average of H' at the intermediate area of the bay (0.97) was higher than the average for the entire area. This distribution of H' is due to the existence of large environmental disturbances, i.e., large wave height and large numbers of soil grains, in the mouth and inner area of the bay, respectively.

This seems to support the IDH demonstrated by [13], which postulates that local species diversity is maximized when environmental disturbances are neither too weak (or rare) nor too strong (or frequent) and is often used to investigate the relationship between species diversity and environmental disturbances. When the strength or frequency of disturbances to a biological community is low, competitive elimination of certain species by more dominant species in the community occurs, and the dominant species become the majority. When the strength or frequency of disturbances to a biological community is high, only specific species that are tolerant to the disturbances can survive, and these species become the majority. That is, when disturbances are either low or high, diversity decreases; thus, diversity is maximized when disturbances are intermediate. In addition, the IDH suggests that the environment is in a non-equilibrium state (i.e., due to the existence of disturbances and the subsequent recovery processes), which helps maintain diversity. In other words, if the environment is in a non-equilibrium state, frequent disturbances can provide a survival opportunity to those species which cannot survive in an equilibrium state; thereby, diversity is maintained.

For sites with good coral conditions, for example, Badul Island Waters, Ujung Kulon, Indonesia [36] and the Gulf of Aqaba and Ras Mohammed, Red Sea, Egypt [37], the averages of H' were 2.183 and 0.84, respectively. H', in this study (Fig. 9), seemed to be slightly lower than the reported values. However, a simple comparison of H' among different area and/or studies is difficult because H' is sensitive to the degree of sampling effort (e.g., the number of individuals and types) [31]. In this study, H' was calculated from only five types because the object for calculating H' was coral forms not coral species. We consider this explains the slightly lower value of H' in our study.

4.3. Relationship between diversity index and environmental properties

Next, the relationships among H', wave height (Fig. 10) and the number of soil grains (Fig. 11) are discussed. In general, the H' value of organisms has a large dispersion. In addition, H' is dependent on the number of individuals, and the dispersion of H' decreases with an increase in the number of individuals [31]. Thus, the discussion of H' should be performed using the maximum or average values. In the inner area of the bay with nearly constant (and low) wave height, no correlation between H' and wave height was found. Conversely, in the intermediate area of the bay with changes in wave height, the maximum (or average) of H' at a wave height increased with an increase in wave height up to 1 m. However, H' decreased sharply when wave height was over 1 m (Fig. 10). Thus, it is considered that the diversity of coral types increases with an increase in wave disturbance; however, when the wave disturbances exceed

a limit, coral types which are vulnerable to such disturbances are limited, and the diversity decreases. Conversely, H' peaked at average soil grain numbers of approximately 900 and 40,000 (Fig. 11), and the increased tendency of H' to increase with disturbances (up to a limit) is unclear when compared to the relationship of H' to significant wave height. H' reached a maximum at an average soil grain number of approximately 900 at Stations 8 and 9 in the intermediate area of the bay. At Stations 8 and 9, the ratio of tabular coral was low; thus, the ratios of other corals, especially foliose coral, were high (Fig. 6). These characteristic were not seen at other locations but, at Stations 8 and 9, were considered to be the cause of high H' values. Foliose coral may prefer conditions with low numbers of soil grains and intermediate wave heights, which are typical of the conditions at Stations 8 and 9. When Stations 8 and 9 are excluded from Fig. 11, the tendency of H' to increase with an increase in disturbances (up to a limit in the average number of soil grains of approximately 40,000) becomes slightly clearer. The distribution of H' in Fig. 9 is considered to be explained by these relationships of H' to wave height and the number of soil grains.
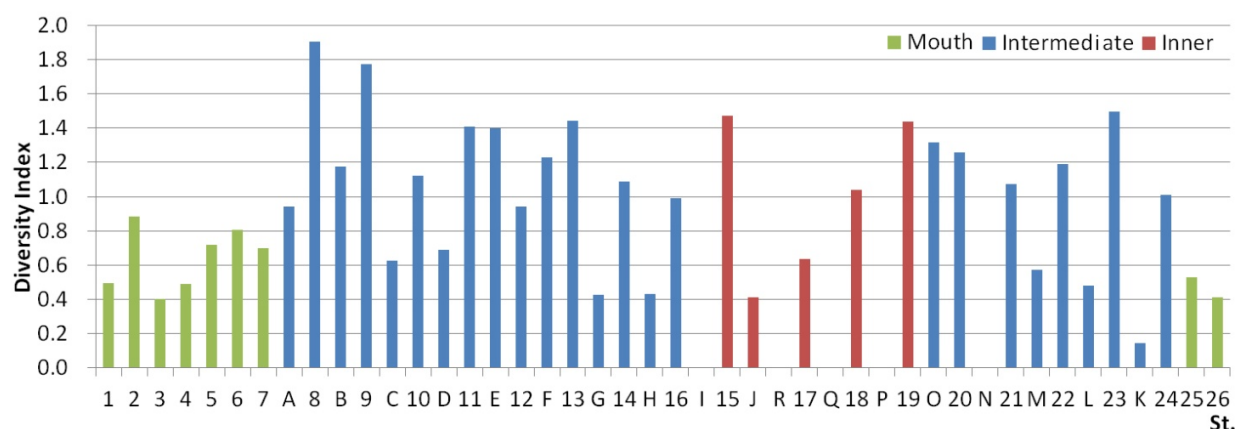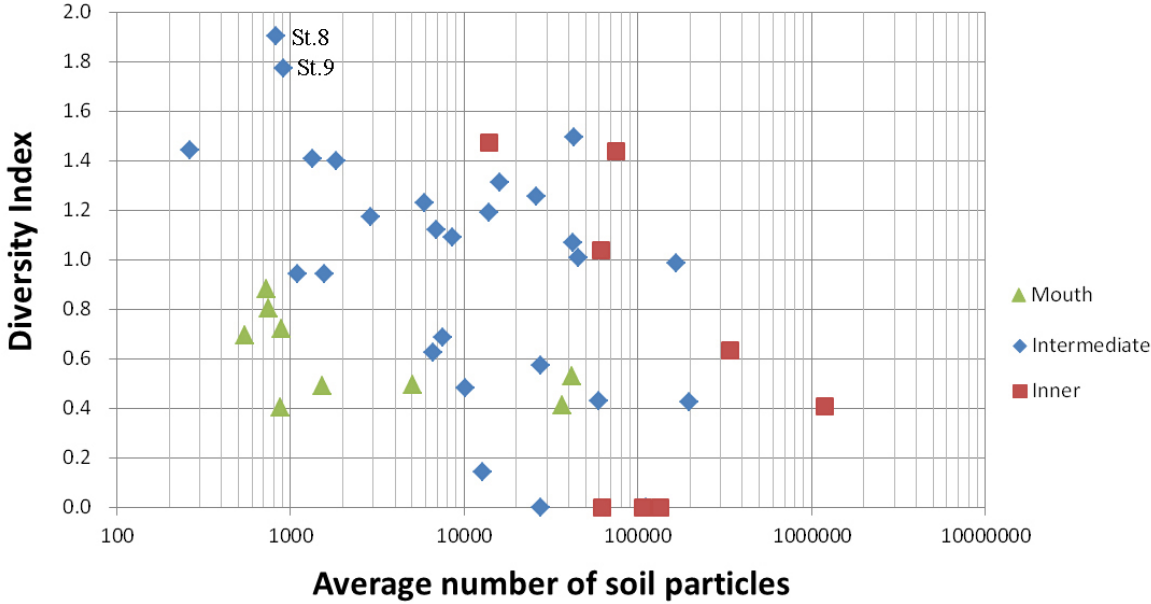

Figure 9. Diversity index at Stations 1–26 and A–R. The mouth, intermediate, and inner area of the bay are indicated in green, blue, and red, respectively (after [18]).

Note that high diversity does not indicate high coverage. Low diversity and low coverage indicate that the area is not a niche for organisms or biocoenosis distributed in the area. However, low diversity and high coverage indicate that the area is a niche only for organisms or biocoenosis distributed in the area. Fig. 12 shows the relationship between H' and the coverage of tabular or branching corals. For both corals, a high H' value (over 1.4), which is higher than the average of H' (0.83), corresponds to coverage from 5% to 30%, and high coverage (over 50%) corresponds to a H' value lower than 0.6, which is lower than the average of H'. An area with high diversity of corals is not considered to high coverage of a specific coral type (tabular or branching coral in this case) because the area is not a niche only for the species. An area with high coverage of a specific coral type is not considered to have high diversity of corals because the area is a niche only for the species.
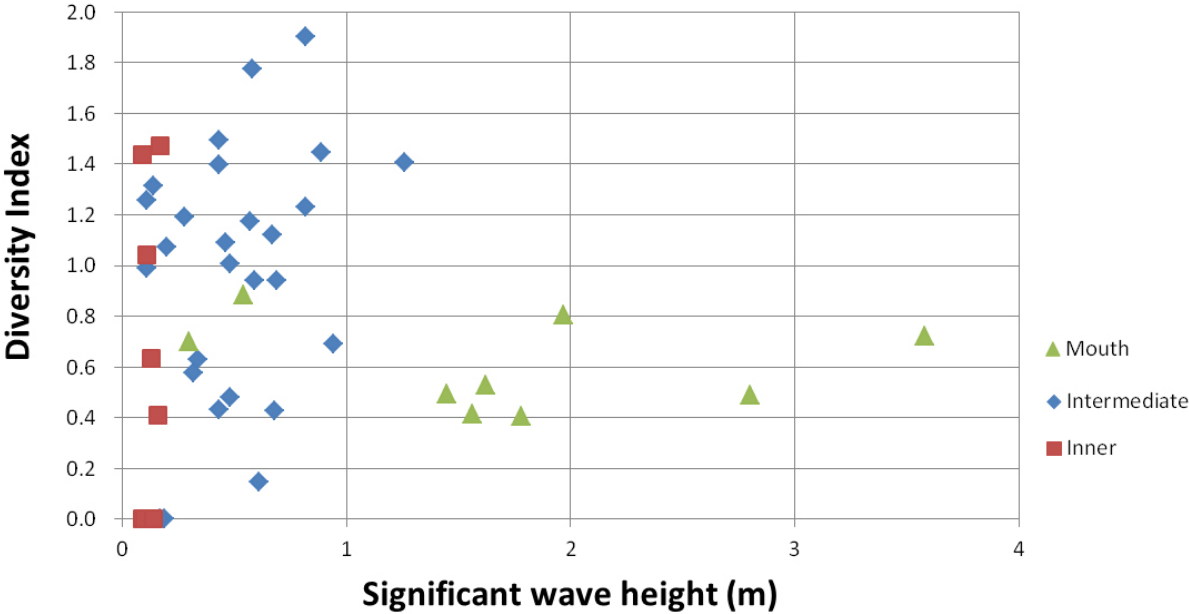
Figure 10. Relationship between diversity index and significant wave height at Stations 1–26 and A–R. The mouth, intermediate, and inner area of the bay are indicated in green, blue, and red, respectively (after [18]).

Figure 11. Relationship between diversity index and average number of soil grains reaching the sea floor per day at Stations 1–26 and A–R. The mouth, intermediate, and inner area of the bay are indicated in green, blue, and red, respectively. The numbers in the figure are the sum for all grain sizes (after [18]).
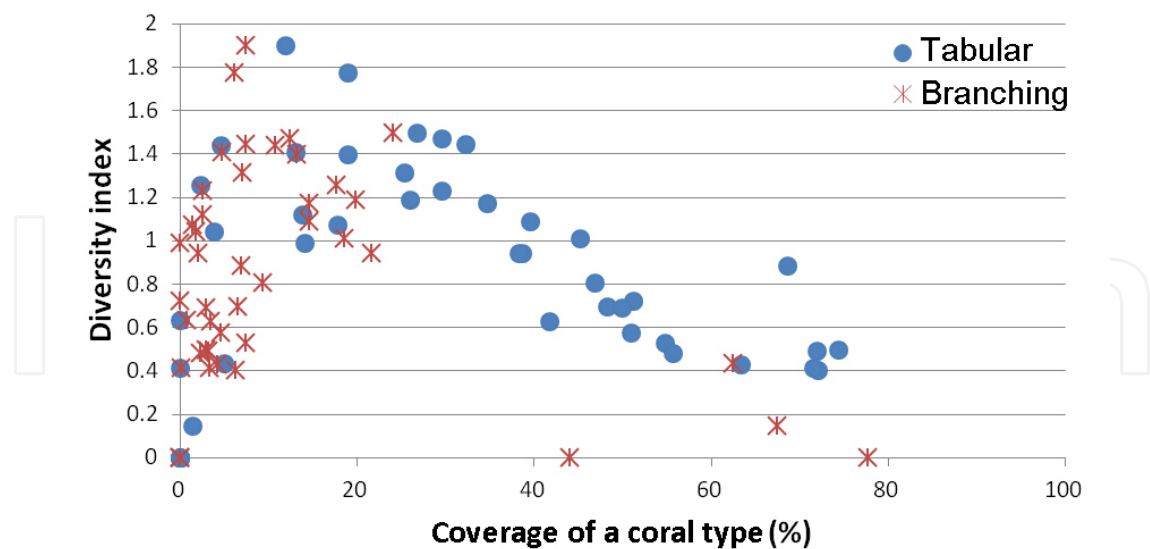
Figure 12. Relationship between diversity index and the coverage of tabular or branching corals at Stations 1–26 and A–R (after[18]).

5. Conclusion

In this study, field observations were conducted to obtain data on coral distributions, sea temperature, sea salinity, wind speed, and river flow rate. Ocean and wave model numerical simulations and soil grain tracking analysis were also conducted to obtain the spatial and temporal distributions of wave height and the number of soil grains. Using these observational and numerical data, the relationship between coral distributions and environmental properties in Amitori Bay, Iriomote Island, Japan, were investigated. Moreover, diversity indices (which are a quantitative measure for the degree to which a dataset includes different types and which are closely related to information entropy concept) of coral distributions were calculated and their relationships to environmental properties were investigated. Our results showed that the life forms, sizes, and species of corals significantly varied depending on their locations in the bay because the environmental properties differed significantly between these locations.

The main results of this study can be summarized as follows:

1. Coral distribution had a large correlation with wave height and number of soil grains. Larger coverage of tabular coral and smaller coverage of branching coral correlated with larger wave heights. Smaller coverage of tabular coral related to a larger number of soil grains, whereas branching coral coverage did not correlate with the number of soil grains.

2. Averages of diversity index of the coral types at the mouth and inner area of the bay with high environmental disturbances were lower than the average of the entire area. However, the average of the diversity index at the intermediate area of the bay with intermediate environmental disturbances was higher than it. This seems to support the IDH demon-

strated by [13], which postulates that local species diversity is maximized when environmental disturbances are neither too weak nor too strong.

Currently, many coral reefs around the world are endangered [1, 2]. Possible causes for this include red soil erosion (due to land development), sea temperature rise (due to global warming), and *Acanthaster* (crown-of-thorns starfish) and *Drupella fragum* (a species of sea snail) infestations. Red soil erosion causes a turbidity rise in sea water and soil adhesion to the coral surface, thereby hindering zooxanthellae photosynthesis and coral growth. Sea temperature rise causes zooxanthellae decolorization in the corals or discharge from the corals (i.e., coral breeching). Lengthening of coral breeching may cause coral death. Large outbreaks of *Acanthaster* and *Drupella fragum* prey on the molluscous portion of corals cause a direct decrease in coral numbers. The cause of large outbreaks of *Acanthaster* and *Drupella fragum* is regarded as human activities such as eutrophication (caused by inputs of domestic sewage). The corals in Amitori Bay have also been affected by various factors such as coral bleaching by high sea temperatures in 1997, 1998, and 2007; damage by *Acanthaster* infestations between 1980 and 1983; the recoveries from these incidents. To conserve corals in our oceans and regions such as Amitori Bay, the relationship between corals and their environmental properties must be clarified and continuously monitored. Further studies of this relationship in other coral regions are strongly advised.

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