2-5 Terrestrial inflow of soils and nutrients

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1 Introduction

The deterioration of the coral reef environment as a result of human activities has been reported from all over the world. Eutrophication and pollution from increasing sedimentation are among the threats to coral reefs that originate on land (Wilkinson 2002). Owing to the intensive soil erosion that accompanies land development projects, coral reefs along the coasts have been repeatedly covered by silt throughout the modern history of the Ryukyu Islands, causing decay (Omija 1992). Moreover, in the Ogasawara Islands south of Tokyo, introduced ibex have run wild, consuming the vegetation and resulting in top-soil run-off that negatively affects the coastal environment (Kawakubo 1988; Inaba and Suzuki 2000). This section introduces the soil inflow of Okinawa Prefecture of the Ryukyu Islands as a case study and also describes research of the nutrient content of the surrounding sea water.

2 What is red soil pollution?

When heavy rain falls on the islands of Okinawa, coral reefs near the river mouths often develop a 'cloudy red' appearance where there was once clear water (Photo. 1). Such inflow disturbs coastal coral reef ecosystems and negatively affects the fishery and marine-related tourism industries. These remarkable soils are made up of not only *Kunigami maaji* soil, generally called a red soil, but also the gray soil *Jaagaru* and the country rock mud-stone, *Kucha*. In this section, these soils are collectively referred to as 'red soil' and their adverse effects on coastal waters as 'red soil pollution'.

3 Why does red soil pollution occur?

Red soil pollution tends to occur when human impacts, such as land development, are affected by natural factors. These natural factors include the following in Okinawa: soils that easily disperse due to a lack of organic matter, geographical features in which mountains are steep and rivers are short, and rainfall that is three times as erosive as the national average (Fig. 1). Of course, such natural factors alone do not always cause red soil pollution. Red soil pollution occurs most often after human factors are added, such as development projects that turn the mountain greenery into bare land. Farming, land development, and activities within the U.S. military training area cause enormous amounts of run-off and are considered the three major outflow sources in Okinawa. Most of the red soil carried to the sea by rivers is deposited on semi-

Photo 1. Coral reef exposed to the turbidity of terrestrial soil (e.g., red soil) run-off.

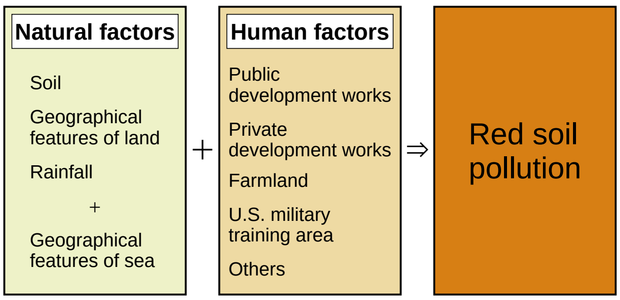

Fig. 1. Mechanisms of red soil pollution.
Larger amounts of soil begin to run off when human impacts are added to preexisting natural factors. On reef moats, discharged soils often remain owing to limited circulation of seawater and thus damage coral communities continually despite only periodic run-off.

enclosed reef moats adjacent to the coast, and often the red soil is repetitively stirred up by turbulence induced by typhoons and monsoons. The water becomes cloudy again, and the soil is redistributed over the reefs. In other words, red soil pollution is not a temporary phenomenon that occurs only during heavy rains; it can continue causing damage to coral reefs indefinitely.

4 Red soil pollution monitoring

Some of the evaluation techniques for measuring red soil pollution in Okinawa are as follows: processing sediment with hydrochloric acid, as used in the fisheries environmental survey by Okinawa Prefectural Fisheries Experiment Station (1978); categorizing the grading of sediment, as used by Ujiie (1986) in granulometry research of silts at the sea floor; a five-stage visual observation method of bottom state used in coral reef research by the Department of Planning and Development, Okinawa Prefecture (1993, 1994), and the sediment traps used for coral reef ecological surveys by Fujioka (1997).

In addition, the Content of Suspensible Particles in Sea Sediment method (referred to as SPSS) was developed by the Okinawa Prefectural Institute of Health and the Environment to monitor soil pollution in 1985 (Omija 1987; Omija in press). The use of this method requires little time input, convenient tools and materials, simple operational skills, and no specific laboratory to provide scientific data (Fig. 2). As a result, the method is used extensively in the research efforts of various administrative bodies, universities, NGOs, school environmental education programs, and fisheries' management agencies. A database of collective results began to be assembled in 1983, and the total number of data points had reached approximately 4,000 as of September 2003. The value measured by SPSS corresponds well to the actual benthic appearance of a reef (Table. 1); thus, it is useful in explaining the current condition of a specific coral reef area. This method has been elected as the standard procedure for monitoring red soil pollution in the marine environment of Okinawa Prefecture.

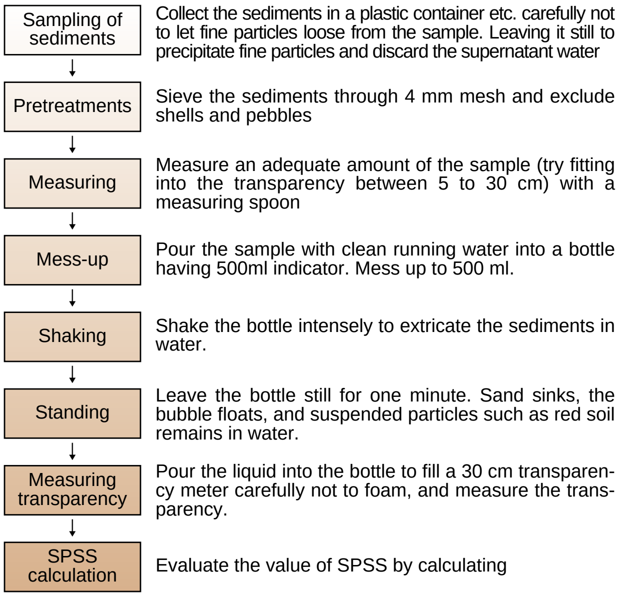

Fig. 2. Procedure of SPSS (content of Suspensible Particles in Sea Sediment) estimation.
Most of the sediment on coral reefs is made up of sands derived from organisms such as corals. These sands have a different particle size from that of terrestrial soils. Using this distinction, SPSS evaluates how many kilograms of suspended particles (e.g., red soil) are inside 1 m^3 of suspended matter.

Table 1. Relationship between SPSS (content of Suspensible Particles in Sea Sediment) values and benthic properties.

SPSS (kg/m^3)			Status of bottom sediment and other properties
Rank	Lower bound	Upper bound	
1	—	< 0.4	Below determination limit. Fine particles are not suspended even when bottom sediment is stirred. White sand extends the area and organisms are rarely observed.
2	0.4 ≦	< 1	Fine particles are not easily suspended even when bottom sediment is stirred. White sand extends the area and organisms are rarely observed.
3	1 ≦	< 5	Fine particles can be suspended by stirring the bottom sediment. A lively coral reef ecosystem can be observed. Water transparency is high.
4	5 ≦	< 10	Water becomes little turbid when bottom sediment was stirred, although it will not occur in calm conditions. A lively coral reef ecosystem can be observed.
5a	10 ≦	< 30	Fine particles can be observed on the surface of bottom sediment by careful observation. This rank corresponds to the SPSS upper bound where lively coral reef ecosystem can be observed.
5b	30 ≦	< 50	Dust-like fine particles cover the sediment surface. The transparency declines and adverse effect on coral coverage starts to occur.
6	50 ≦	< 200	Sediments such as red soil can be seen at a glance. If the bottom sediment is stirred, suspension is apparent in dark color. Above this rank, it is judged that obvious pollution by the man-caused outflow of red soil occurs.
7	200≦	< 400	Shoe sole's patterns are left clearly on the surface. Sedimentation of red soil is remarkable, but sands can still be seen. Large colonies of branching *Acropora* will are not seen, and massive corals increases.
8	400 ≦	—	Feet get bogged in mud. Sands can rarely be observed. A massive type corals which have strong sediment-resistance distributes.

5 Influence of red soil pollution on coral reefs

A rich coral reef ecosystem centering on coral communities can be seen in the coastal areas of Okinawa. Coral reefs are said to hold the largest number of species per unit area on earth, along with tropical rain forest ecosystems. Branching and tabulate coral colonies have a maze of internal, three-dimensional spaces that offer shelter to small reef animals. As larger animals tend to predate on these smaller animals, a multi-leveled community structure evolves. *Acropora* species are the main corals of such reef structures. When corals die out and three-dimensional space decreases, eventually the numbers of fish and other organisms also decrease.

In moats adjacent to the open sea, where strong winds tend to cause high waves, the suspended sediment is easily stirred up. In such areas, seasonal variation in SPSS levels sometimes occurs (Omija *et al.* 1993). In that case, the highest SPSS values correspond well with the upper bound of the coral coverage area (Omija *et al.* 2000a). The relational expression between coral coverage and SPSS derived from a dataset of 97 points on Okinawan reefs is shown below.

$$Y^{(1/2)} \leq -5.43\log X + 15.6$$

X: SPSS (kg/m^3)
Y: Coral coverage (%)

In the Kerama Islands, where red soil pollution is rare, coral coverage is generally high and *Acropora* dominates the area (Photo. 2). When red soil pollution progresses and SPSS levels begin to exceed 30 kg/m^3, coverage of *Acropora* decreases. As red soil pollution further progresses, large colonies of *Acropora* disappear and coral coverage also decreases. In contrast, the percentage of massive corals that have few interior hiding places (e.g., *Porites spp.* and Faviidae) increases. When the highest value of SPSS exceeds 400 kg/m^3, the appearance of the reef becomes desert-like and only massive corals are scattered in the turbid water. *Acropora* species can recruit under such conditions,but they cannot grow large and most die within 1 to 2 years (Omija *et al.* 2003). Coral reefs that have reached this stage lose almost all value as a resource for fisheries or tourism.

A certain relationship between the highest value of SPSS and the composition of coral species can be recognized.

Photo. 2. Coral reef communities in the Kerama Islands, where red soil pollution is scarcely seen. In such areas, *Acropora* species are dominant.

The massive *Porites* species have a relatively high emergence ratio in any sedimentation level and tend to have strong bleaching tolerance as well (Omija *et al.* 2000b). Owing to this, they can be considered one of the corals that are best able to tolerate variations in environmental conditions. Also, *Oulastrea crispata* appears characteristically in high SPSS areas and may be valid as an index species for turbidity (Omija *et al.* 1999).

6 History of red soil pollution

Notable red soil pollution problems are said to have emerged when the U.S. military brought in heavy equipment such as bulldozers to make pineapple fields in mountainous areas of northern Okinawa Island and the Yaeyama Islands after World War II. After Okinawa was handed over to Japan in 1972, large-scale public construction projects were completed, one after another, to develop social infrastructure on Okinawa. The aim was to achieve a level of development equal to that of mainland Japan. At that time, prevention measures for soil run-off were practically nonexistent and, if practiced at all, were implemented at the level of halving the amount of outflow. Large-scale development projects thus caused some reefs to become covered with red soil, resulting in complaints of damage to fisheries.

Mass media in the prefecture led a campaign to stop the red soil pollution in the late 1980s, and public opinion in Okinawa changed, with a switch in priority from development projects to the prevention of soil run-off. Six groups related to the fishing industry collected signatures from 55,000 people in 1992 and requested that the prefecture promptly enact an ordinance to prevent soil run-off. As a result, Okinawa Prefecture established The Okinawa Prefecture Red Soil Erosion Prevention Ordinance (referred to simply as the Red Soil Ordinance) in 1994, and it was enforced by October 1995.

According to the Red Soil Ordinance, the leaders of a development project of 1,000 m^2 or greater are required to submit a written report in advance. Moreover, the effluent standard from the development site is set at 200 mg/l or less of the suspended solid (SS) as an indicator of water impurity. For example, when a reclamation project is conducted with no countermeasures, SS reaches up to 10,000 mg/l in red soil areas and 80,000 mg/l in mudstone areas. In other words, developers are required to take measures to cut 98-99% of the soil run-off.

7 Future prospects on red soil pollution

The database of SPSS was analyzed to assess the changes in red soil pollution on Okinawan coasts, comparing results from before and after the red soil ordinance was enforced in 1995. The results showed that nearly 40% of the coast was still exposed to red soil pollution, although soil run-off from the development sites was restricted and extreme sedimentation decreased. The main run-off source was considered to be farmlands (Omija *et al.* 2002) (Photo. 3).

While the administrative body has proposed some effective measures against soil run-off from farmlands and their effectiveness has been shown, the use of these measures by farmers has been slow to spread, owing mostly to the required cost and labor. In the future, therefore, it is necessary to introduce and establish a system in which farmers can easily take measures. For that to occur, a discussion on the necessary reduction level of soil run-off for coral reef conservation is inevitable. Comprehensive research will be necessary to connect land and coral reefs in the future. This research should include the establishment of environmental guideline values, the establishment of forecasting models of outflow and diffusion, the accumulation of demonstrative data on the effects of various farmland measures, and the evaluation of the cost of farmland measures versus the economic value of coral reefs.

Photo. 3. Decayed farmland. Major terrestrial soil (e.g., red soil) run-off is from this kind of farmlands in Okinawa.

Moreover, through training courses organized by the Japan International Cooperation Agency (JICA), the SPSS monitoring procedures, techniques, and information regarding soil run-off prevention in Okinawa are being transferred to trainees from developing countries that have coral reefs. The experience with and results from the soil run-off prevention measures on Okinawa are expected to contribute to these countries in the near future.

8 Nutritional research

Field studies analyzing the effects on coral reefs of nutrients originating from the Okinawan land are extremely scarce compared with studies of soil run-off. Nakano (2002a) reviewed laboratory tests on the impacts of the nutrients on corals. Below are the results of some field studies concerning nutrient outflow onto reefs around Okinawa.

In Okinawa Prefecture, total nitrogen (TN) and total phosphorus (TP) are measured two to six times a year at 53 fixed points in ten locations as part of water quality monitoring. The results are reported annually. The Ministry of the Environment determines the environmental quality standards for TN and TP according to the intended use of marine areas. This set of standards applies only to designated marine areas where phytoplankton might proliferate remarkably, while oligotrophic coral reef regions are not considered. Consequently, this set of standards does not apply to Okinawa. The most severe environmental quality standards in Japan define the annual means (arithmetic mean) as 0.2 mg/l for TN and 0.02 mg/l for TP. Assuming that these standards were applied to Okinawa, the public marine areas would exceed these standards by 16 points (30%) for TN and 5 points (9%) for TP, according to measurements by Okinawa Prefecture in fiscal year 2001 (Department of Culture and Environment, Okinawa Prefecture 2003).

Excess nutrients in waters surrounding coral reefs are supplied from the land by means of surface water and/or underground water. Umezawa *et al.* (2001) focused on the fact that the ratio of nitrogen (N^{15}) was significantly higher in river water and in underground water as compared to the ratio in the outer sea of the coral reefs off Ishigaki Island. There are N^{14} and N^{15} isotopes of nitrogen, possessing mass numbers of 14 and 15, respectively. Umezawa *et al.* inferred nutrient outflow from the land based on the fact that measured N^{15} ratios in seaweeds decreased with increasing distance from the shore. In addition, dilution by river and/or underground water outflows into the sea causes salinity levels to decline. This led Omija *et al.* (2003) to consider the excessive nutrients on Okinawan reefs to be of land origin because the areas that had high nutrient concentrations tended to have lower salinity.

There seems to have been no long-term observation of fixed points around Okinawa in terms of the relationship between nutrients and corals. In a short-term case study, Shimoda *et al.* (1998) monitored the condition of corals and the nutrient concentration at 25 points and found that corals did not grow well with a TN level of 0.1 mg/l or more or a TP level of 0.01 mg/l or more.

Omija *et al.* (2003) added nutrient and salinity analyses to ongoing long-term research on SPSS and coral growth in 2 × 2-m quadrats at 24 fixed points over the prefecture. In the quadrats where relatively high levels of TN and TP were observed, recruits of *Acropora* were seldom seen. As *Acropora* recruits were observed even in areas with equivalent or higher rates of SPSS, it was determined that nutrients have a negative impact on *Acropora*.

The Department of Health and Environment, Okinawa Prefecture (1989) conducted a research study on red soil sedimentation and coral growth in Kin Bay in 1988. Coral assessment was conducted at 27 points, and there was no point at which *Acropora* was predominant. In fact, *Acropora* was observed at only one point. Around Kin Bay, the geographical features are semi-enclosed, the population is high along the coast, and there is a complex of hog farming. This leads to a high nutrient concentration in the bay. The reason for the observation of less *Acropora* could be the influence of the high nutrient concentration.

9 Environmental guidelines for coral reef conservation

One of the threats to coral reefs from the land is an excessive outflow of soils and/or nutrients. Under current circumstances, environmental quality standards for permissible amounts of soil sedimentation and nutrients should be strengthened; it is also necessary to control land activities to achieve these standards. Unfortunately, this is not considered by existing policies for environmental quality standards in Japan. The results of our long-term observation of fixed points around Okinawa, in combination with other research of various points, show SPSS values of 30 kg/m^3 or less at locations where corals that are vulnerable to soil sedimentation, such as *Acropora* species, appear to grow well. Therefore, it was proposed that to conserve coral reefs on Okinawa, the environmental guideline for soil sedimentation should set an annual maximum SPSS of 30 kg/m^3 or less (Omija *et al.* 2003). In addition, it would be beneficial to immediately set a guideline for the allowable nutrient concentration.