

Marine Debris Distribution and its Capture by Coastal Plants along the Western Coast of Kyushu, Japan

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Marine Debris Distribution and its Capture by Coastal Plants along the Western Coast of Kyushu, Japan

(九州西海岸における海ごみの分布と海浜植物による捕捉に関する研究)

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Chapter 1 Introduction

1.1 Marine debris

1.1.1 The origin of marine debris

The coastal region, demarcated as the land adjacent to the sea, along with the nearshore zone encompassing the shallow waters bordering the land, holds a pivotal geographical position. This unique juxtaposition fosters diverse coastal ecosystems, characterized by a rich array of habitats including estuaries, salt marshes, mangroves, and coral reefs. These ecosystems are not only ecological hotspots contributing to global biodiversity but are also crucial for their economic significance in supporting fisheries, tourism, and transportation industries (Masataro Hatsutori, 2011). Coasts are broadly classified into artificial and natural categories. The former predominantly comprises sandy beaches, while natural coasts are further segmented into sandy, rocky, and muddy types. This classification underscores the diverse nature of coastal environments and their respective ecological roles (Masataro Hatsutori, 2011). Japan's geographical composition includes its four major islands—Hokkaido, Honshu, Shikoku, and Kyushu—along with over 3,000 smaller islands. This extensive archipelago boasts a cumulative coastline exceeding 34,000 kilometers, translating to an average per-person coastline length of 30 centimeters. The economic and aesthetic value of these coastal areas is substantial, contributing significantly to both the national economy and environmental beauty (Masataro Hatsutori, 2011).

However, these vital regions face escalating environmental challenges. Urbanization, industrialization, and climate change-related impacts such as sea-level rise and increased storm frequency are causing habitat destruction, erosion, and water pollution. These factors contribute to the deterioration of coastal ecosystems, as evidenced by alarming trends like the decline in sea turtle nesting sites and the disappearance of rare coastal plant species. This ongoing degradation necessitates a balance between environmental preservation and the demands of a rapidly expanding economy.

A prominent issue within this context is the crisis of marine plastic waste, an environmental concern since the 1960s. Defined by the Global Program of Action for the Protection of the Marine Environment from Land-based Activities (GPA) as one of the nine major marine pollutants, marine debris encompasses persistent solid waste of human origin, man-made or processed, found in marine and coastal environments. Notably, microplastics, resulting from the breakdown of larger plastic items, permeate every part of the ocean, posing significant risks to marine life and ecosystems. International and national bodies have responded with various policies and initiatives. The United Nations Environment Program (UNEP) leads global partnerships and action plans focusing on plastic reduction, waste management improvement, and recycling promotion. Individual countries have implemented strategies like banning single-use plastics and investing in sustainable coastal infrastructure (Williams A. 2019; Sherry L. S. 2013; Barry J. et al. 2020).

The future of coastal and marine conservation lies in adopting more comprehensive and integrated management approaches. This involves strengthening regulations, enhancing community engagement, and fostering international collaboration. Innovations in biodegradable materials and improved waste management practices are essential for mitigating the human impact on these ecosystems. The conservation and sustainable use of coastal and marine resources are imperative for the health of our planet and the well-being of future generations.

Since the 1980s, extensive systematic data accumulation surveys of marine debris have been undertaken in various oceanic regions, including the North Atlantic Subtropical Circulation and the Pacific Gyre (Law et al., 2010; van Franeker and Law, 2015). These studies have expanded over time to encompass the marine environment across all the world's oceans. Notable research includes Evan A. Howell et al.'s (2012) examination of the North Pacific Gyre and its associated oceanic marine debris concentrations, as well as Christine A. Ribic et al.'s (2010) analysis of trends and drivers of marine debris along the U.S. Atlantic coast from 1997 to 2007. Additionally, recent research by Bergmann, M. (2022), focuses on plastic pollution in the Arctic region, highlighting the global reach of this issue.

Marine debris, a pervasive environmental problem, originates from various sources, including land-based, riverine, and ocean-based origins (Galgani et al. 2015; Browne 2015; Jambeck et al. 2015). Land-based sources encompass public littering, inadequate waste management, industrial activities, and sewage-related debris, which rivers can transport to the sea (Morritt et al. 2014; Free et al. 2014; Hoellein et al. 2014). Conversely, ocean-based sources include fishing activities, shipping, and offshore oil and hydrocarbon industries (Mouat et al. 2010), with these sources contributing a significantly higher proportion of marine debris than land-based sources.

The first documented interaction between marine life and persistent litter dates back to the late 1960s. Kenyon and Kridler (1969) discovered plastics in the stomachs of albatross chicks in the northwestern Hawaiian Islands, with an average of 2 grams of plastic per bird. Similar incidents were reported in other marine species. Plastic ingestion was found in Leach's storm petrels (*Oceanodroma leucorhoa*) as early as 1960 (Harper and Fowler 1987), and elastic threads were identified in the stomachs of non-breeding Atlantic puffins (*Fratercula arctica*) between 1969 and 1971 (Berland 1971; Parslow and Jefferies 1972). The 1950s saw reports of sea turtles ingesting plastic bags, often with fatal outcomes (Cornelius 1975; Balazs 1985). Additionally, fishing line and other debris caused intestinal blockages in manatees (*Trichechus manatus*) in 1974 (Forrester et al. 1975), and by the mid-1970s, stranded cetaceans were also found to have consumed plastic (Cawthorn 1985). Northern fur seals (*Callorhinus ursinus*) entanglement in nets and other artifacts in the Bering Sea was regularly reported by 1964, with a noticeable increase in such incidents over the years (Fowler 1987). Gochfeld (1973) noted how entanglement in marine debris, including nylon fishing lines and other materials, posed a significant threat to coastal birds, as observed in black-billed gulls (*Rhynchops niger*) on Long Island. Bourne

(1976, 1977) also highlighted the risks associated with using persistent polymers in fishing gear, leading to entanglement and death in seabird chicks.

Research on marine debris, which began in earnest in the late 1960s, saw significant growth in the following two decades (Peter G. R. 2015). Studies during this period identified the impacts of marine debris on marine systems, and collected baseline data on its distribution, abundance, and effects, leading to the development of policies to address this environmental challenge. However, despite the increasing prevalence of marine debris, research in this area experienced a decline in the 1990s (Ryan and Moloney 1990, 1993). It was not until the last decade, following alarming reports about ocean conditions, that research interest reemerged, as depicted in Figure 1.1, which illustrates the trend in the number of relevant academic papers.

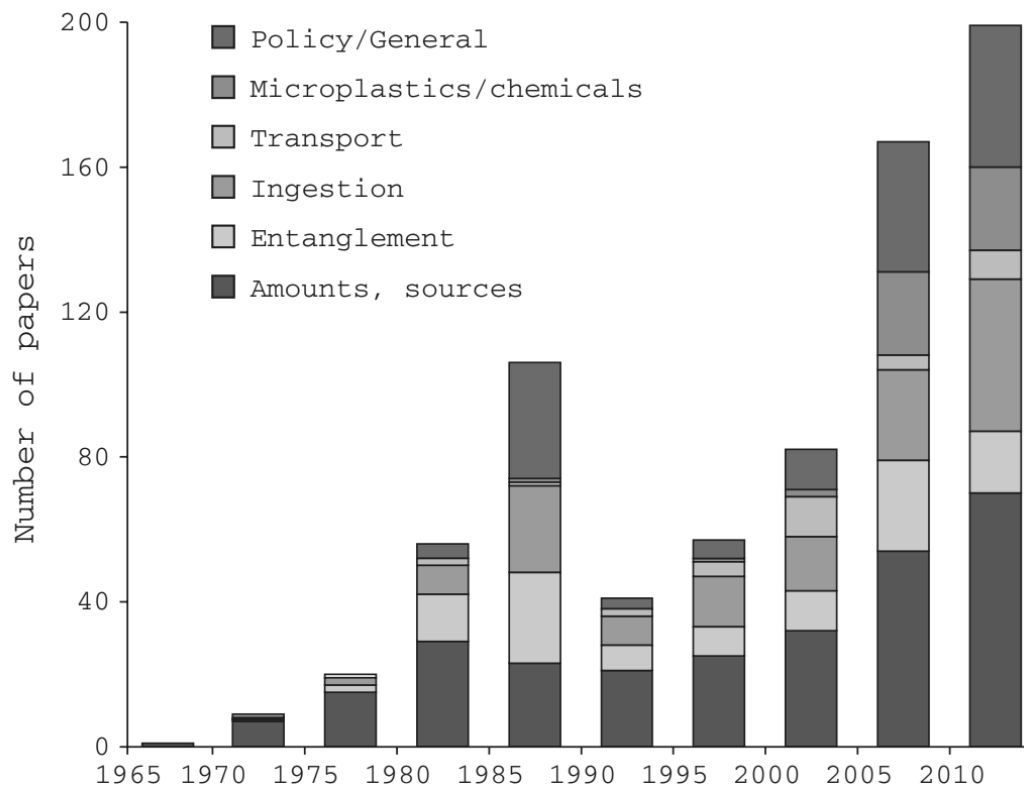


Fig. 1.1 Numbers of papers on different aspects of the marine debris issue published in five-year intervals over the last 50 years (based on a Web of Science search and unpublished bibliography; note that the final column only covers three years, 2011–2013).

A comparative analysis of the Marine Debris Monitoring and Assessment report by NOAA under the U.S. Marine Debris Program and the European Commission's 'A European Threshold Value and Assessment Method for Macro Litter on Coastlines' reveals distinct approaches to marine debris evaluation (Sherry Lippiatt S O C A 2013; Barry J. et al. 2020). The U.S. program is distinguished by its comprehensive survey scope, encompassing litter in coastal zones, sea surfaces, and seafloors.

Conversely, the EU program primarily focuses on coastal litter. Furthermore, these programs vary in their categorization of litter sizes. The U.S. program differentiates between large (>2.5 cm) and medium (0.5-2.5 cm) litter, including both coastal and floating debris. The EU program, on the other hand, limits its investigation to litter larger than 2.5 cm. Both programs have similar classification schemes for marine debris, with the U.S. categorizing coastal litter into types like plastic, metal, glass, rubber, paper/processed wood, cloth/fabric, and others. The EU categorizes litter into plastics, wood products, metals, glass, ceramics, paper, textiles, rubber, and other unidentifiable items, with an emphasis on hazardous waste, notably cigarette butts comprised of cellulose acetate and containing harmful substances such as nicotine, nitrite, and polycyclic aromatic hydrocarbons (PAHs) (Novotny T E, Slaughter E. 2014). Additionally, the EU has developed comprehensive methodologies and databases, including the 'Analysis of the pan-European 2012-2016 beach litter dataset' and the 'EU shore and beach litter thresholds' for evaluating coastal litter pollution (Montero M. 2020).

Various regional studies offer insights into the sources and compositions of marine debris. In the southern Baltic Sea, approximately 70% of urban coastal litter is attributed to tourism activities (Zalewska T. 2021). Data from 12 beaches on the west coast of Qatar in West Asia indicates that about 47% of bottles originate from Persian Gulf coastal countries, primarily transported by wind and water currents (Veerasingam S. 2020). In South Asia, India's Mandvi coastal belt shows a direct impact of human activities, such as kite festivals, on the increase in specific types of litter (Behera D P 2021). These studies underscore that while sources, types, and abundances of marine debris vary regionally, plastic remains the predominant component. In both the Baltic Sea and the West Coast of Qatar, plastic waste constitutes about 70% of the total litter (Zalewska T. 2021; Behera D P. 2021).

The compositional analysis of marine debris globally reveals a striking predominance of plastic. Studies, such as those by L Van Cauwenberghe et al. (2015) on the Belgian continental shelf, M. Thiel et al. (2003) in the southeastern Pacific Ocean, and Aurélie V. Duhec et al. (2015) in the western Indian Ocean, consistently show plastics as the most abundant form of marine debris. These plastics range from bags to monofilament lines, with a notable presence even in remote locations, confirming their ubiquity as marine pollutants.

1.1.2 Plastic debris

Geologists have proposed the term "Anthropocene" to describe the current geological era, characterized by significant human influence on Earth's ecosystems and geology (Lewis, S., et al., 2015). A key indicator of this era is the widespread distribution of plastics in both terrestrial and marine environments, marking them as distinct stratigraphic components of the Anthropocene. Plastics are not only prevalent in terrestrial sediments but are also increasingly found in marine sediments across both shallow and deep-water environments. These materials, abundant as macroscopic debris and nearly ubiquitous as microplastic particles, are transported by various physical and biological

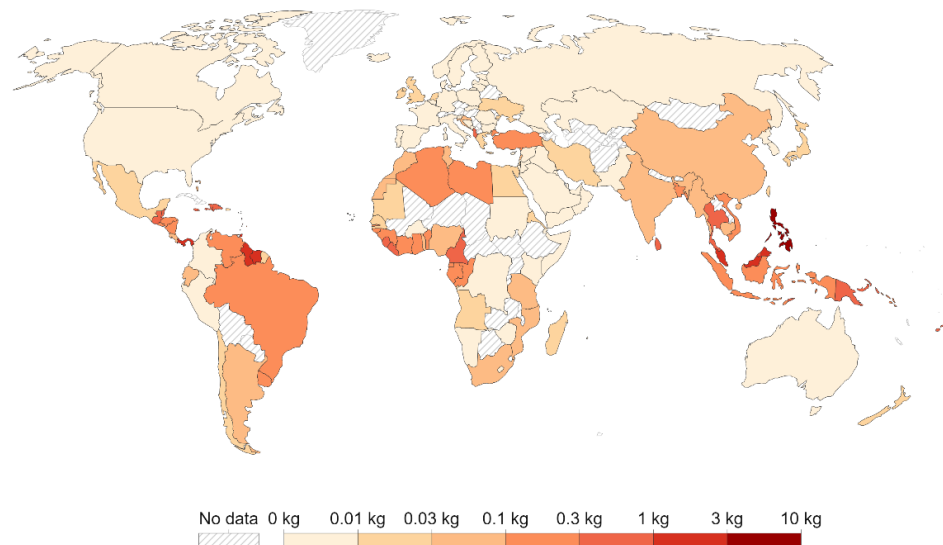
processes. Their presence in sediments is widespread and expected to multiply in the coming decades, continuing to enter the depositional cycle for thousands of years, especially as temporary landfill sites erode (Jan Zalasiewicz, et al., 2016).

Plastics, synthetic or man-made polymers, share similarities with natural resins found in trees and other plants. Polymers, as defined by Wechsler's Dictionary, are complex organic compounds produced through polymerization, capable of being molded or shaped and used in various applications, from textiles to packaging (Life Cycle of a Plastic Product). The term 'plastic', initially signifying flexibility and moldability, has evolved to denote a group of materials known as polymers, comprising long molecular chains.

The journey of synthetic polymers began in 1869 with John Wesley Hyatt's invention, inspired by the quest for an ivory substitute to alleviate the pressure on natural ivory supplies. Hyatt's creation, derived from treating cellulose with camphor, could mimic substances like tortoiseshell and ivory, marking a significant step in reducing the reliance on natural resources (Dorel Feldman, 2008). In 1907, Leo Baekeland invented Bakelite, the first fully synthetic plastic, marking a breakthrough in developing synthetic materials. Bakelite's properties, including durability, heat resistance, and suitability for mass production, made it a versatile material dubbed as a "material with a thousand uses" (Imogen Ellen Napper, Richard C. Thompson, 2020).

Plastics have become integral to numerous industries. In the food industry, they are used for packaging to prevent contamination and reduce spoilage, thereby lowering disease risks (UNEP, 2011). The transportation industry benefits from lightweight plastics, reducing operating costs and carbon emissions (Andrady and Neal, 2009). In agriculture, plastics in the form of sheds and sheeting minimize water loss and soil erosion (Scott, 1997; PlasticsEurope, 2012). Notably, about 40% of plastic products in the EU are used for packaging, with significant utilization in construction and the automotive industry. From 1950 to 2017, the global production of plastics reached approximately 83 million tons (Geyer et al., 2017). Roland Geyer et al. provided the first global analysis of all mass-produced plastics, revealing that as of 2015, around 6,300 Mt of plastic waste had been generated, with only a small fraction recycled, and the majority ending up in landfills or the natural environment (Roland G. et al. 2017). **Figure 1.2** illustrates the per capita plastic waste emitted to the ocean in 2019. The ecological impact of plastic waste has been evident since the 1960s, with numerous marine animals suffering from entanglement and ingestion of large plastic debris. One notable issue is ghost fishing gear, which continues to entrap and harm marine life (NOAA 2023). UNEP reports estimate the global marine debris density at about 18,000 pieces/km², with plastics constituting approximately 72% (UNEP, 2006). In Japan, analysis of coastal litter from 2011 to 2021 revealed a significant presence of plastic debris, particularly from single-use items like food containers and beverage bottles, accounting for almost half of the global plastic waste (UNEP 2018; Hideo K. 2020), as shown in **Table 1.1** The transient nature of plastic use is highlighted by the fact that the average usage time of a plastic

bag is only 12 to 20 minutes (NSWEPA 2016), with the United States and Japan being among the



Source: Meijer et al. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Science Advances. OurWorldInData.org/plastic-pollution • CC BY

Fig. 1.2 Plastic waste emitted to the ocean per capita, 2019. This is an annual estimate of plastic emissions. A country's total does not include the waste exported overseas and may be at higher risk of entering the ocean.

Table 1.1 Top 10 types of stranded garbage based on quantity, 2011-2021 (Hideo K., 2020).

NO.	Coastal Litter	Number	Percentage (%)
1	Caps and lids of bottle	36,726	15.8
2	Plastic rope and string	33,575	14.5
3	PET bottle	29,310	12.6
4	Wood (pallets for logistics)	15,279	6.6
5	Plastic food containers	10,635	4.6
6	Plastic bag	9,012	3.9
7	Other plastic fishing gear	8,247	3.6
8	Other plastics	7,826	3.4
9	Urethane foam	7,686	3.3
10	Plastic tape	7,664	3.3

largest consumers of plastic packaging and containers.

Japan's approach to managing recycled plastics predominantly involves incineration. As reported by

the Ministry of the Environment, in 2013, Japan generated 9.4 million tons of waste plastics. Of this, approximately 67% was incinerated, 25% recycled, and the remaining 8% disposed of in landfills (Ministry of the Environment 2019). The decomposition of the incinerated plastics reveals a nuanced picture: 10% was directly burned, while a significant 57% underwent thermal recycling, a process that includes heat recovery. In Japan, thermal recycling is considered a form of recycling. This classification, which aggregates 57% of thermally recycled materials with 25% of materials recycled through other methods, results in an overall recycling rate of 82%. However, this practice is unique to Japan; internationally, heat recovery is not typically recognized as recycling. Consequently, when applying international standards, Japan's pure recycling rate stands at only 25% (Hideo K. 2020). This distinction in categorization is critical as it reflects Japan's strategy for waste management and its implications for environmental sustainability. The high proportion of plastics being incinerated, coupled with the relatively low rate of traditional recycling, highlights a potential area for policy and process improvement.

A significant concern with the current waste management practices is the generation of secondary microplastics. Large quantities of plastic waste, when not efficiently recycled or contained, become a major source of these microplastics. As plastics break down, especially those released into the environment, they fragment into smaller pieces, contributing to the pervasive issue of microplastic pollution. This pollution poses a significant threat to marine ecosystems and human health, as these tiny particles can infiltrate food chains and water supplies.

1.1.3 Microplastics

Microplastics, defined as plastic debris smaller than 5 millimeters, emerged as a widely recognized term during a marine debris meeting hosted by the United States National Atmospheric and Oceanic Administration (NOAA). This concept, first proposed by Thompson et al. (2004), has been variously defined, with Barnes et al. (2009) and GESAMP (2015) describing microplastics as particles ranging between 1 and 1,000 micrometers, or 1 and 500 micrometers, or under 5 millimeters in size.

The sources of microplastics are primarily categorized into primary and secondary types (Andrady 2011; Cole et al. 2011). Primary microplastics include minute particles such as plastic microbeads in toiletries and plastic raw material particles. These are often less than a few micrometers in size and can also result from by-products of various products or activities. This category encompasses a broad spectrum of sources, including tire dust, synthetic fibers from clothing, debris from vehicle tires, fragments of building and vehicle paints, accidental leakage of plastic raw materials, plastic shedding from artificial lawns and running tracks, and microbeads from care products (Boucher and Friot, 2017; Kole et al., 2017; Sundt et al., 2014; Van et al., 2016). Secondary microplastics, on the other hand, are small-sized pieces produced by the decomposition of larger plastic litter in environmental settings (Rochman et al., 2013). Factors influencing this fragmentation include environmental aspects such as

UV light, sand, temperature, and seawater action; biological factors like microbial degradation; and the inherent properties of the polymers themselves (Auta et al., 2017). Coastal areas, in particular, exhibit high rates of secondary plastic production due to intense UV radiation, sand and wave abrasion, and high oxygen exposure (Cole et al., 2011; GESAMP, 2015).

Microplastics are found in various aquatic environments, including ocean surface waters, the water column, sediments, polar regions, remote islands, and deep-sea trenches (Song et al., 2015; Lattin et al., 2004; Browne et al., 2011; Barnes et al., 2009; Van and Jassen, 2014). The Great Pacific Garbage Patch, stretching from the west coast of North America to Japan's waters, is a prime example of an area where plastic debris, predominantly non-biodegradable, breaks down into increasingly smaller fragments (Eriksen et al., 2013; Goldstein et al., 2013; Moore et al., 2001; Ryan, 2014).

Microplastics, due to their small size, shape, and color, are easily ingested by marine organisms. They are ingested directly or through the food chain, accumulating in the digestive tracts, tissues, and cells of organisms, posing risks to their growth and development (Wright et al., 2013). These plastics are found in marine organisms across different trophic levels, including mussels, barnacles, sea cucumbers, telopods, zooplankton, fish-eating birds, sea turtles, and mammals (Avio et al., 2015; Besseling et al., 2014; Green, 2016; Matthew et al., 2013; Moos et al., 2012; Rehse et al., 2016; Von Moos et al., 2012; Batel et al., 2016; Caron et al., 2016; Ferreira et al., 2016; Fossi et al., 2016), and can be transferred up the food chain (Hollman et al., 2013).

The impacts of microplastics on organisms range from physical harm, such as blocking digestive tracts, to ecotoxicological effects, including inflammation, liver stress, growth retardation, tissue lesions, reproduction issues, and altered gene expression (Wright et al., 2013b; Wu F. Z., 2019). Furthermore, microplastics can serve as transporters for organic pollutants, such as persistent organic pollutants (POPs), heavy metals, and endocrine disruptors, contaminating various ecosystems through ocean currents (Ashton et al., 2010; Cole et al., 2011; Ng and Obbard, 2006; Zarf and Matties, 2010).

1.1.4 Plastic waste control measures and policies

Globally, countries are implementing diverse strategies to reduce marine pollution caused by plastic waste. In the United States, theme parks are eliminating the use of approximately one billion plastic straws annually. Fast food restaurants aim to transform all their wrappers into environmentally friendly materials by 2025. The United Kingdom is at the forefront with multiple initiatives, including university-led research to convert plastic waste into car fuel, the development of edible cups, and a ban on microbeads in skincare products. The Netherlands is innovating by constructing bicycle paths and water parks using recycled plastic waste and establishing plastic-free supermarkets. France has enacted a law to ban single-use plastic containers and cutlery starting in 2020, with plans for mineral water brands to use 100 percent recycled bottles by 2025.

In Asia, Indonesia is developing edible wrapping paper from seaweed, and India has introduced edible

plastic bags and lunch boxes. India enforced a complete ban on plastic bags in October 2019, imposing heavy fines for violations. Additionally, Indian children are encouraged to bring empty plastic bottles to school to be converted into eco-bricks, which can be used as tuition fees (Ministry of the Environment, 2023). On May 21, 2018, the Council of the European Union passed a law to ban the sale of single-use plastics by 2021. The EU's circular economy measures are projected to reduce costs by 600 billion euros, increase annual sales within the Union by 8 percent, and decrease total greenhouse gas emissions by 2-4% (UNEA 5.2, 2022).

In Japan, the Law Concerning the Protection of Beautiful Coastal Landscapes and the Environment, enacted on July 15, 2009, focuses on the preservation of nature and the promotion of coastal waste disposal. The Act on Promotion of Coastal Garbage Disposal, which came into force in March 2010, was revised on June 22, 2018, to enhance the protection of coastal landscapes and marine environments. The revised law emphasizes comprehensive and effective measures for the prevention and control of coastal litter. At the 2019 G20 Osaka Summit, Japan proposed the "Osaka Blue Ocean Vision," aiming to eliminate additional pollution from marine plastic waste by 2050. In March 2022, the United Nations Environment Assembly (UNEA 5.2) adopted a resolution to address plastic pollution, including marine plastic pollution, and established an Intergovernmental Negotiating Committee (INC) for a new legally binding agreement (Ministry of the Environment, 2021).

Japan's Marine Plastic Litter Action Plan includes various measures: promoting global cooperation as the G20 Chair, supporting the development of domestic waste plastic processing and recycling facilities, implementing special recycling bins by soft drink organizations, managing fishing gear to prevent leakage, and conducting nationwide cleanup operations during "Zero Marine debris Week." Additionally, Japan supports local governments and fishermen in collecting and disposing of marine debris and emphasizes technological innovation by increasing the production capacity of marine biodegradable plastics and supporting waste management capacity-building initiatives, such as the establishment of the ASEAN Knowledge Hub (Ministry of the Environment, 2019).

1.2 Coastal plants

1.2.1 Coastal plants

Coastal habitats, including dunes, beaches, salt marshes, mangroves, seagrasses, and seaweed beds, play a crucial role in mitigating the impacts of coastal hazards (Rebecca L. Morris et al., 2018). These ecosystems are vital in preventing episodic coastal erosion and flooding caused by storms, hurricanes, and tsunamis. They also contribute to mitigating the chronic loss of coastal land due to ongoing erosion and minimizing the effects of future sea level rise (Spalding et al, 2014). These protective services are provided through ecosystem processes such as increased streambed friction, localized water shallowing, sediment deposition, and the establishment of vertical biomass. These processes lead to changes in the coastal profile and elevation relative to sea level, as well as wave attenuation. For

instance, vegetated coastal habitats like seagrasses, salt marshes, and mangroves can reduce current and wave heights, and coral reef systems can have similar effects due to their rough surfaces (Spalding et al, 2014). Additionally, sediment accumulation around coastal vegetation can elevate land height, reducing flood risk during storms (Shepard et al., 2011). This link between environmental conditions and plant characteristics has been recognized since the early development of plant ecology (Schimper 1898; Cowles 1899; William K. Cornwell and David D. Ackerly, 2009).

Many coastal plants thrive in harsh environments like dry, saline sandy beaches due to their high environmental tolerance (Environment Agency of Japan, 2000; Osaka Prefecture Green Environment Maintenance Office, 2000; Keiko Oshida and Akiharu Kamihogi). They disperse their seeds via ocean currents, enabling them to expand their habitats. However, these species face endangerment due to significant environmental changes. Land reclamation and seawall construction have reduced the total length of natural beaches (Nature Conservation Bureau of the Environment Agency of Japan, 1998), and coastal beach widths are diminishing due to erosion and hinterland development (Yura, 2014). Even on preserved beaches, vegetation damage from vehicles and human trampling is common (Matsu Shima et al., 2000). This leads to habitat disappearance, isolation, and fragmentation for coastal plants, making recovery challenging. Consequently, many of these species are listed on the Red List of the Ministry of the Environment or prefectures, underscoring the growing importance of conservation (Sawada et al., 2007).

According to the Ministry of the Environment's 5th Basic Survey of Natural Environmental Conservation (1998), Japan's coastline stretches over 32,799 kilometers. This includes "natural coasts," which remain unaltered by human development, and "semi-natural coasts," which have some artificial structures but maintain a natural intertidal zone. The total length of these coastlines is 21,667 kilometers (66% of the total coastline), while the artificial coasts, altered by civil engineering works and unsuitable for vegetation, extend for 10,822 kilometers (33% of the total coastline). Comparing the results of the 4th and 3rd Basic Surveys, there was a decrease of about 300 kilometers in natural coastlines and an increase of about 650 kilometers in artificial coastlines. A time-lapse comparison between the second and third surveys revealed a decrease of approximately 570 square kilometers in natural coast areas (Sawada Yoshihiro, 2014).

1.2.2 The research review of coastal plants

Contemporary research on coastal plants encompasses a broad spectrum of ecological, physiological, and conservation-related aspects. Barbour et al. (1999) investigated the role of different species in enhancing coastal ecological resilience, emphasizing the crucial function of coastal plants in stabilizing shorelines and preventing erosion. The habitat provided by coastal vegetation supports a diverse array of wildlife, a topic explored in depth by Bertness et al. (2004), who studied the intricate ecological interactions between plants and associated animal species.

Given their exposure to high salinity environments, studies by Flowers and Colmer (2008) delved into the mechanisms of salinity tolerance and acclimatization in coastal plants, shedding light on their ability to thrive in such harsh conditions. Hasegawa et al. (2000) focused on the genetic and physiological basis of this salinity tolerance, providing insights into potential applications in areas like crop breeding and land reclamation. The impact of climate change, including sea-level rise and increased storm intensity, poses a significant threat to coastal vegetation. Burdick (1992) predicted the potential mechanisms of this impact, while Kirwan et al. (2016) explored adaptation strategies for protecting coastal plants, emphasizing managed retreat and ecosystem resilience.

Conservation efforts for coastal plants are multifaceted, including the identification of threatened species, protection of critical habitats, and restoration of damaged ecosystems (Olney et al. 2003). Restoration techniques like the use of native plant species and bioengineering have been investigated by Temmerman et al. (2013) to enhance the resilience of coastal habitats. Furthermore, many coastal areas are biodiversity hotspots with numerous endemic species. Myers et al. (2000) cataloged and assessed the diversity of these coastal plant communities.

Recent years have seen coastal plant communities often impacted by human activities such as development, pollution, and over-harvesting. Dugan et al. (2011) examined the consequences of these activities and proposed sustainable management practices. Additionally, ethnobotanical studies, such as those conducted by Khan et al. (2013), have explored the traditional uses of coastal plants by indigenous communities and their potential contributions to modern medicine.

A key area of focus in this study is the repositioning of coastal plant communities within the ecological environment. This includes exploring their potential role as natural barriers to prevent coastal drifting garbage from re-entering inland areas, thereby causing repeated pollution. Understanding the role of these plant communities provides diverse thought schemes for addressing the problem of marine debris.

1.3 Purpose, significance, and methodology of the research

In the face of escalating coastal ecological pollution and the pressing issue of marine garbage, humanity's long-standing reliance on plastic products has led to significant environmental harm. Recognizing the necessity of sustainable natural resource development is an imperative responsibility for mankind. It is evident from the research background that coastal environments act as crucial temporary "sinks" for marine garbage. Addressing the problem of coastal floating garbage not only alleviates the burden of marine debris pollution but also preserves the ecological diversity of coastal environments and enhances their aesthetic value for human society.

This study takes a dual approach, focusing on both source control and the current status of marine debris. For source control, research sites such as Hakata Bay, Tsushima Island, and the Goto Islands archipelagos, each with distinct geographic characteristics, were selected. The study involves analyzing geographic and anthropogenic sources of marine debris, discussing the varying pollution

conditions faced by bays and islands along the coastline, and proposing solutions for managing local debris and addressing transboundary litter issues. Additionally, the study sheds light on the ecological hazards of microplastics, emphasizing the need to reduce secondary sources of these micro-litters.

Regarding the current situation, the study aims to offer innovative ideas for existing marine debris control measures. It repositions the functional role of coastal plant communities within the coastal environment, considering their potential to capture litter debris, akin to their ability to prevent winds and consolidate sand. This includes examining their potential to act as natural barriers, preventing marine debris from re-entering inland areas.

Further, the study proposes planting species recommendations for the regeneration of coastal vegetation, based on the common plant species found along the west coast of Kyushu. This approach could provide effective solutions for mitigating the impact of marine debris and enhancing the ecological resilience of coastal areas (**Fig. 1.3**).

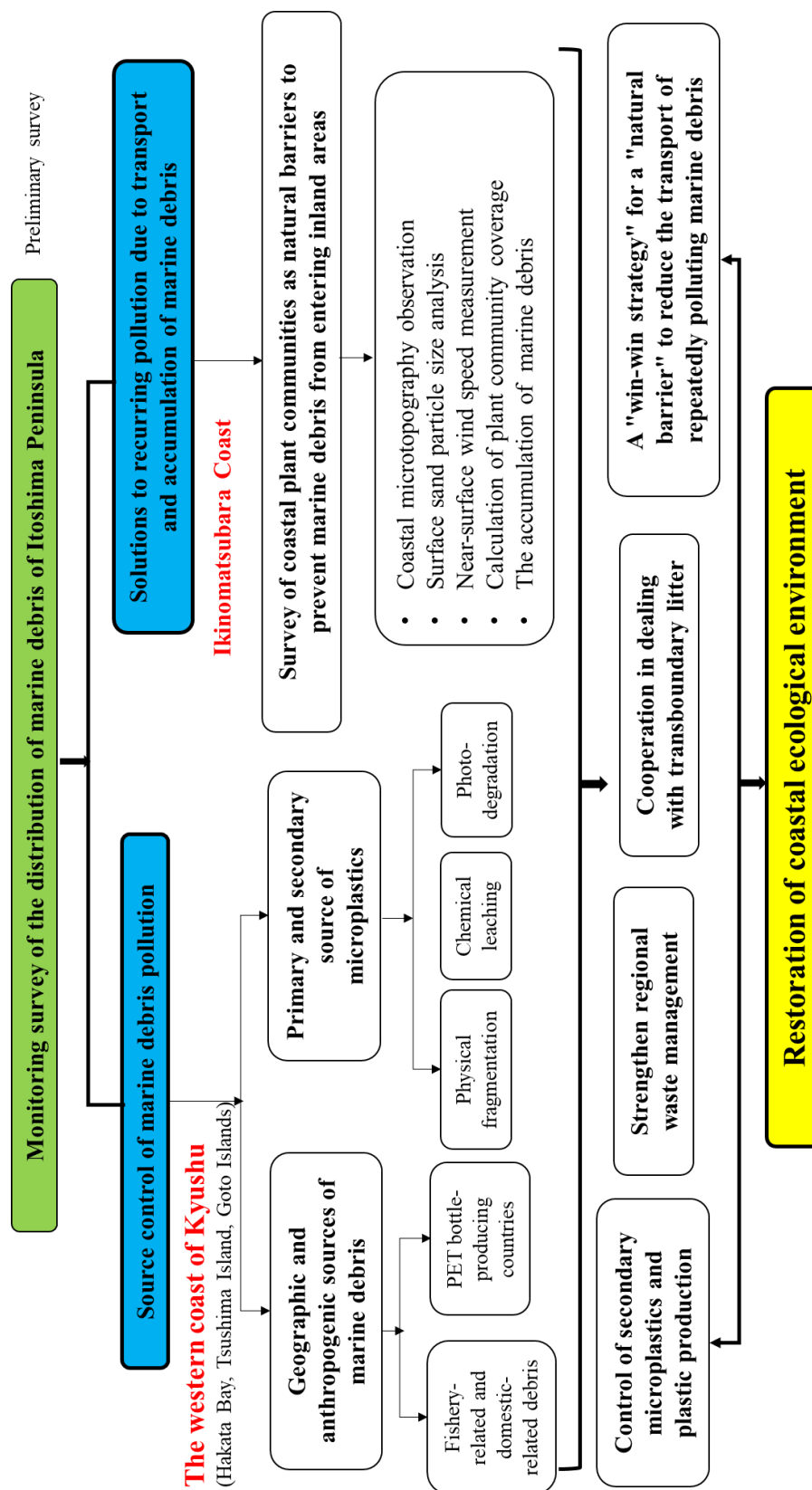


Fig. 1.3 The flow diagram of this research

Chapter 2 Research sites and methods

2.1 Research sites

2.1.1 Itoshima Peninsula

The Itoshima Peninsula, situated in northwestern Kyushu and facing the Sea of Japan, is a region of considerable historical and geographical importance. It is bordered by Hakata Bay to the east and lies adjacent to Karatsu City and Saga City to the south. The peninsula, extending from Imajuku in Nishi-Ward, Fukuoka City, to Kafuri in Itoshima City, is a prominent feature protruding from the Genkai-nada Sea.

Historically, the area of the present-day peninsula is believed to have been the location of the ancient Ido State. It is referenced as Ito in classical Japanese texts such as the Manyōshū and the Wamyōshō. The region is rich in historical sites, including the Sone site, which dates back to the early Yayoi period and extends to the middle of the Kofun period. Other notable sites include the Itoshima City plains site from the late Yayoi period and the Mikumo and Ihara site complexes, which span the middle of the Yayoi period to the beginning of the Kofun period.

Research suggests that during the Yayoi period, the alluvial soils of the Zuibaiji and Kawabaru Rivers expanded to form a delta. However, until the medieval period, the northern part of the peninsula, particularly the area between Shito and Haku, was predominantly mudflats, visible at low tide but submerged at high tide. Despite these challenging conditions, evidence shows that people have been residing in the northern area since the Jomon and Yayoi eras. The proximity to the sea allowed inhabitants to sustain themselves with fishing activities, even in areas unsuitable for rice cultivation (Okazaki Takashi, 2003).

In terms of its historical architecture, Edo Castle, constructed between 756 and 758, was originally a Chinese-style fortress, as recorded in the “Shokunihonki”. Additionally, the region played a significant role in maritime activities. Tangpo (Kantei) was designated as a port of call for ships traveling between Chikushi, Tang, and Silla, highlighting the peninsula's strategic importance in regional trade and communication.

The Itoshima Peninsula, located in northwestern Kyushu, is renowned for its picturesque coastlines, including the celebrated Sakurai Futamigaura Beach and the Keya Coast. Characterized by rocky cliffs and sandy beaches, these coastal areas attract a significant number of tourists each summer. The peninsula's verdant hills and mountains are a haven for outdoor enthusiasts, offering activities such as hiking, bicycling, and motorcycling. Various observation decks across the hilly terrain provide panoramic views of the surrounding landscapes, further enhancing the area's natural appeal.

In terms of cultural heritage, the peninsula is dotted with historic temples and shrines, including the venerable Seikyoji Temple and Sakurai Shrine. The former site of the Imazu Genko Borui offers visitors a glimpse into the region's rich history. The peninsula's artistic and cultural legacy is celebrated

through numerous events and festivals held annually. The summer fireworks display, a spectacle covering much of the peninsula, is a highlight. The Yamakasa Matsuri festival in Chikuzen Maebaru, honoring Hifusejizo and Oimatsu Shrine, imbues the town with vibrant energy and echoes of tradition, appealing to both the older generation and engaging the younger generation in the area's cultural legacy. The Itoshima Peninsula is also famed for its culinary offerings, particularly oysters from local fishery farms, available from October to February. The seasonal oyster huts draw visitors nationally and internationally. In recent years, the locally grown vegetables have gained renown, attracting new residents to the area. Accessibility to the peninsula is convenient, with comprehensive bus routes connecting the entire peninsula, especially to major tourist spots. Taxis provide efficient services for easy pick-up and drop-off, and shared bicycles are available for those seeking to combine outdoor activities with sightseeing. Located just 40 minutes from the center of Fukuoka by train, the peninsula is a popular destination for day trips, offering a blend of natural beauty, cultural richness, and recreational activities.

This study's preparatory research encompasses two notable survey sites on the Itoshima Peninsula: the Nagahama Coast on the east side and the Niginohama Coast on the west. These locations are selected for their representative natural and cultural characteristics of the peninsula (**Fig. 2.1**).

The Nagahama Coast, located on the eastern side of the peninsula, is notable for its proximity to the historically significant Genkou Defense Ruins. The coastline here faces the mouth of Hakata Bay and is backed by an expansive area of windbreak pine forests. Despite the development of seabathing beaches, the Nagahama Coast has largely retained its natural coastal landscape. The coast's gentle slope and well-developed transportation infrastructure make it an appealing outdoor teaching site for nearby primary and secondary schools, as well as universities and other educational institutions.

Due to its strategic location at the mouth of Hakata Bay, the Nagahama Coast is annually influenced by the northwest monsoon and the movement of sea currents in the adjacent ocean area. This geographical positioning results in a unique confluence of coastal flora typical of Kyushu and the accumulation of marine debris. The coast becomes a repository for various types of marine debris that tend to get stranded, providing a crucial area for studying the impact and management of coastal pollution.

The Niginohama Coast, situated on the western side of the Itoshima Peninsula, faces Iki Island and spans between Keya Gate and Nokita Beach. This approximately 6-kilometer-long coastline is distinguished by its bow-shaped sandy beaches and pine forests, preserving much of its natural coastline. Recognized as one of the representative white-sand and green-pine coastlines of Genkai National Park, Niginohama Coast has been honored as one of Japan's "100 selections of white-sand, green-pine coastlines."

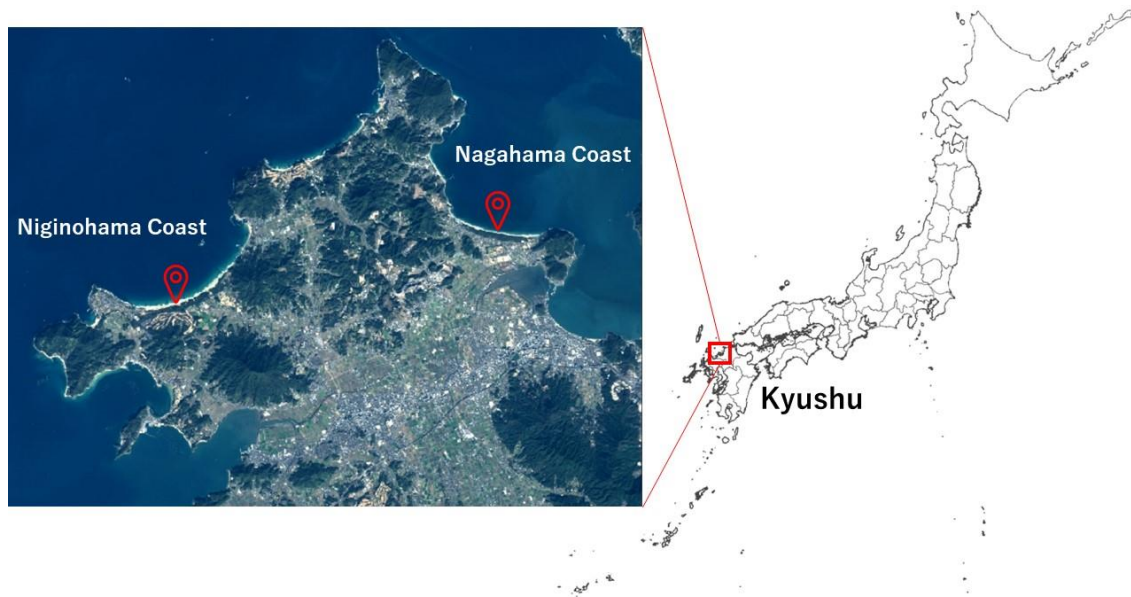


Fig. 2.1 Survey sites in Itoshima Peninsula

The extensive coastline of Niginohama, with its singular entrance and exit, remains largely undisturbed by human activities. The coastal section features elevated topography, while the middle section is bordered by hills. Here, tumbled rocks can be found stranded in the sub-tidal zone. The eastern section boasts a broad sandy beach and an estuary that extends approximately 70 meters inland. Over time, this area has developed a distinctive sandbar terrain. This secluded part of the coast is also a haven for rare coastal plants indigenous to Kyushu, offering a unique opportunity for ecological exploration.

Due to its location facing the open ocean, Niginohama Coast experiences vigorous wind and wave activity. These conditions make it a popular destination for surfing and paragliding enthusiasts. The coast's dynamic natural environment not only contributes to its recreational appeal but also plays a significant role in shaping its unique ecological and geological features.

2.1.2 Hakata Bay

Hakata Bay, a crescent-shaped, enclosed bay, is situated on the northwest coast of Kyushu, overlooking the Genkai Sea. It forms a natural boundary between Fukuoka City to the east and the Itoshima Peninsula to the west. As one of the most vital economic and industrial hubs in Kyushu, Hakata Bay harbors numerous ports, including Hakata Port and Shingu Port. These ports facilitate a wide range of maritime activities, encompassing shipping, fishing, and shipbuilding, crucial to the region's economic vitality.

There is a variance in the definition of Hakata Bay's boundaries by different authorities. Fukuoka City

delineates the bay's boundary as the line connecting Akagami Hana on Genkai Island in Katsuma, in the northern part of Shikanoshima Island, to Nishiuragasaki on the northern part of the Itoshima Peninsula. Conversely, the Ministry of the Environment defines the bay's waters as extending from Akagami Hana on Kashima Island to Nishiuragasaki on Itoshima Island. The Japan Geospatial-Intelligence Agency categorizes the waters as Hakata Bay on the eastern side and Fukuoka Bay on the western side. This classification is also echoed in the charts issued by the Japan Coast Guard, with the harbor line described from the western end of Nishi-Urasaki (near Kashima Ohashi Bridge abutment) through the northern part of Nokonoshima Island to Go Shihana in Tsu City.

In recent years, Hakata Bay's name has been frequently utilized in important governmental documents and parliamentary minutes, reflecting its significance in regional governance and policy (Hakata Bay Environmental Protection Program, 2016). The bay's environmental protection and sustainable management are crucial, given its role in the economic, industrial, and cultural landscape of Kyushu. Hakata Bay, spanning an area of approximately 133 square kilometers, is characterized by its elongated shape, measuring 20 kilometers from east to west and 10 kilometers from north to south. The bay boasts a coastline extending 128 kilometers, with the mouth of the bay being relatively narrow at a width of 7.7 kilometers. This geographical structure leads to the bay being highly enclosed, classifying it as an occluded sea.

The bay's unique geographic features result in smoother wave motion within the bay compared to the more turbulent outer oceanic Genkai Sea. However, this enclosed nature also makes the bay more susceptible to the deposition and accumulation of various substances. These include sediment and marine debris, which are often discharged from rivers feeding into the bay.

The average water depth in Hakata Bay is approximately 10 meters, reaching a maximum depth of 23 meters. The bay experiences a tidal level variation of about 2 meters between high and low tides. The seabed geology predominantly consists of a sedimentary layer known as the Hakata Bay silt layer. This layer is characterized by a composition of fine-grained sand, interspersed with coarser sand and clay elements (Ministry of the Environment, Japan, 2011).

Since the pre-Meiji Era, substantial land reclamation has been carried out along the southern coast of Fukuoka City, adjacent to the city center. Post-1945, approximately 1,167 hectares of land have been reclaimed. This extensive reclamation primarily aimed to enhance the port functions of Hakata Port and to create additional residential areas. A significant development occurred in July 1994 when 401 hectares of shallow water near the Wajiro Mudflats were reclaimed and transformed into an artificial island known as "Island City."

The Wajiro Mudflats serve as critical habitats for benthic animals like snappers and sandworms. Additionally, these mudflats are vital as wintering and stopover sites for various bird species, including white-spotted plovers, sandpipers, and endangered migratory birds such as black-faced spoonbills and black-backed gulls. Recognizing their ecological importance, 254 hectares of sea adjacent to the

mudflats were designated as a nationally recognized Wajiro Mudflats Wildlife Sanctuary in 1978 (Yamamoto Hiroko, 2004).

Originally, there was a proposal to reclaim the entire Wajiro Mudflats. However, due to opposition from civil society groups, this plan was withdrawn. Subsequently, an alternative plan emerged to construct the artificial island, Fukuoka Island City, off the coast of the Wajiro Mudflats, covering an area of about 401 hectares, comparable to the size of Fukuoka City Center (Fukushima Yasuo, 2007). Following the commencement of the artificial island's construction around 1995, an unexpected ecological issue arose. Large quantities of seaweed (*Ulva Linnaeus*) began to proliferate in the Wajiro Mudflats during the summer. This phenomenon was attributed to the disruption of natural seawater exchange caused by the island's reclamation (Nabata Shiniti, 2005). While moderate amounts of sea lettuce can serve as a food source for wild birds, excessive growth leads to the depletion of oxygen, resulting in the death of bivalves, sandworms, and other organisms in the mudflat's sediment, coupled with the production of unpleasant odors. Despite the completion of Island City, the environmental challenges associated with the site remain unresolved.

Recent observations at the Hakata Tide Station indicate a significant spring tide level difference of 2.20 meters. There has been a notable increase in the annual mean tide level in recent years, a phenomenon largely attributed to global warming. This rising mean tide level raises concerns about the potential decrease in the area of mudflats, which are crucial for various ecological processes. Furthermore, a reduced tidal velocity could lead to the proliferation of red tides and the formation of anoxic water masses, posing a threat to the bay's marine life and overall ecosystem health.

The tidal currents in Hakata Bay, particularly between Genkai Island and Shikanoshima Island, and between Nokonoshima Island and Shikanoshima Island, are characterized by their swiftness. These currents flow back and forth along the bay's topography, from the mouth to the back of the bay, following the ebbing tide. This dominant flow of the tidal current plays a significant role in shaping the bay's marine environment (Ministry of the Environment, Japan, 2011).

Hakata Bay hosts a diverse array of seaweed beds, with species such as kelp, nori, and sargassum commonly found around Genkai and Shikanoshima Islands. The waters east of Nokonoshima Island are known for a wide range of sea lettuce species. Notably, eelgrass and *Sargassum muticum* (Yendo) Fensholt can be observed growing around Island City. In recent years, the eelgrass regeneration program in Hakata Bay has gained significant attention. Eelgrass is crucial for absorbing and fixing carbon dioxide, but challenges such as global warming and oceanic water quality degradation have led to a decline in seaweed farms. Consequently, seaweed conservation has become an urgent matter. The 2023 Eelgrass Conference in Hakata Bay highlights the importance of this issue and the ongoing commitment to support the sustainable development of the seaweed regeneration program. This initiative aims to address the environmental challenges faced by Hakata Bay and contribute to the conservation and restoration of vital marine habitats.

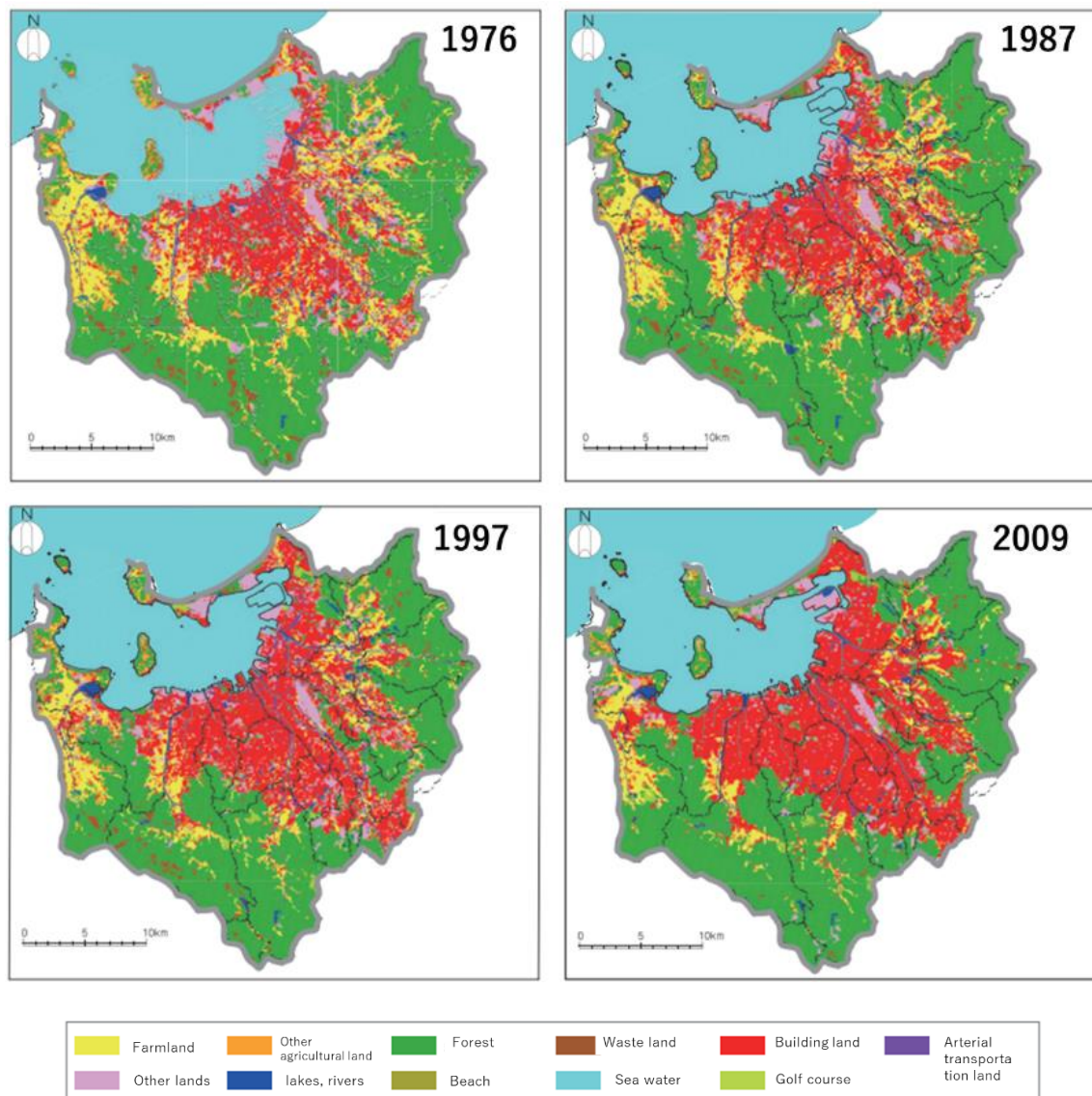


Fig. 2.2 Land use in the Hakata Bay watershed from 1976 to 2009

The Hakata Bay watershed has experienced significant changes in land use, particularly in terms of construction and development in recent years. Analyzing the evolution of land utilization reveals distinct regional variations and trends in this area. In the western region of the Hakata Bay watershed, the majority of the area has traditionally been designated for agricultural purposes. While the primary use of land for agriculture has remained relatively stable, there has been a gradual increase in the area being allocated for construction purposes. This shift indicates a moderate but noticeable change in land utilization, reflecting developmental pressures even in predominantly agricultural zones.

Contrastingly, the eastern region of the watershed has undergone more pronounced changes. This area has seen a decrease in the extent of rice paddies and forests, with a corresponding increase in land

designated for construction. This trend indicates a clear progression towards urbanization, as natural land cover gives way to built-up areas. The transformation in this region points to a significant shift in land use priorities and the impacts of expanding urban development. **Figure 2.2**, as referenced in the Ministry of Environment, Japan's 2011 report, illustrates the changes in land use within the Hakata Bay watershed from 1976 to 2009. This visual representation provides a comprehensive overview of the evolving land use patterns over several decades, highlighting the extent of urban expansion and the reduction in natural and agricultural land cover in the area.

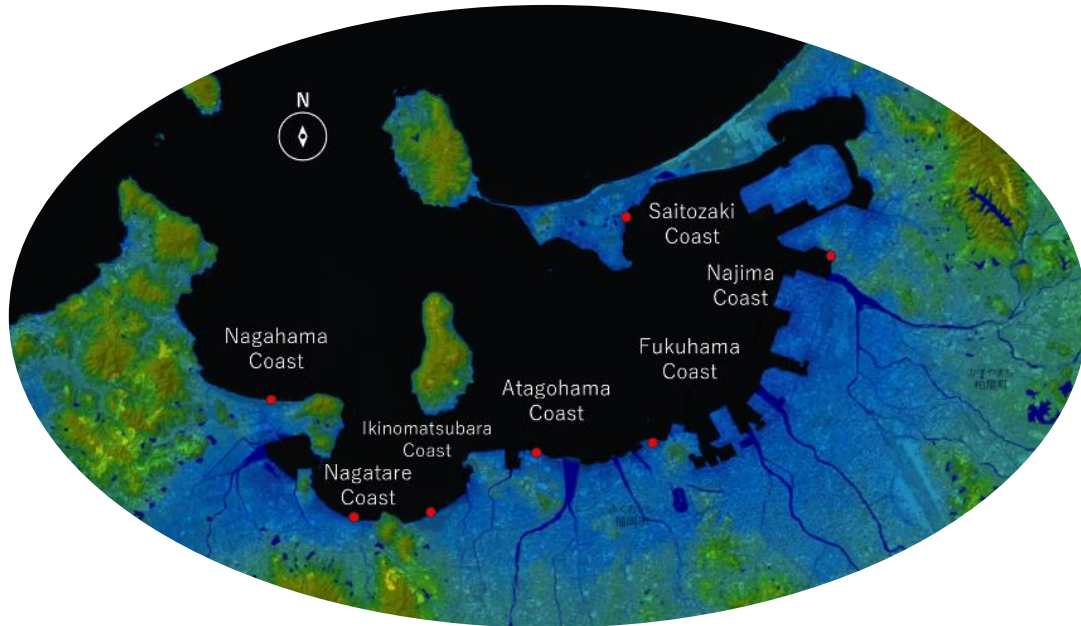


Fig. 2.3 Survey sites in Hakata Bay

In the study of marine debris distribution within Hakata Bay, specific coastal areas have been earmarked for sampling. These include the Nagahama Coast, Nagatare Coast, Ikinomatsubara Coast, Atagohama Coast, Fukuhamma Coast, Najima Coast, and Saitozaki Coast. Among these, the Nagahama and Ikinomatsubara Coasts are distinguished as naturally occurring coastlines (**Fig. 2.3**).

In contrast, the remaining coasts – Nagatare, Atagohama, Fukuhamma, Najima, and Saitozaki – are artificial. A key observation arising from this distinction is the impact of these artificial coasts on marine debris dynamics. Artificial coasts generally demand more frequent maintenance and cleaning efforts compared to their natural counterparts. This increased need for human intervention is a significant anthropogenic influence factor in the context of marine debris management.

The distinction between natural and artificial coastlines has implications for the accumulation and management of marine debris. Artificial coasts, due to their constructed nature and altered environmental dynamics, often present unique challenges in litter accumulation and subsequent removal. Understanding these variations in litter dynamics is crucial for effective coastal management strategies and environmental conservation efforts in the Bay Area.

This section provides a detailed overview of several notable coastal areas around Hakata Bay, each with its unique characteristics and significance. Having previously discussed the Nagahama Coast, we will now focus on the Nagatare, Ikinomatsubara, Atagohama, Fukuhamma, Najima, and Saitozaki Coasts.

The Nagatare Coast, located near Imajuku, is a narrow stretch of coastline featuring a small beach with minimal vegetation. This area includes steps along the coast, a beach park on the east side, and a river outlet at the coast's end. The proximity of residential areas offers a broad view almost immediately adjacent to the beach. This coast is a popular recreational spot for residents and hosts the annual Imajuku Area Fireworks Festival.

Adjacent to Shimoyamato, the Ikinomatsubara Coast is bordered by a substantial coastal pine forest, which also serves as a regeneration forest for Kyushu University. This forest contains numerous century-old black pine trees. The coast itself is home to various coastal plants such as *Carex kobomugi*, *Imperata cylindrica*, *Vitex rotundifolia*, and *Glehnia littoralis*. As a naturally occurring coast near a densely populated area, its ecological environment has been well-preserved. Wildlife, including bird flocks and occasionally the *Tachypleus tridentatus*, can be observed here.

In Nishi Ward, the Atagohama shore, previously a dumpsite for Hakata Bay, covers an area of approximately 21.7 hectares. This includes a 4.4-hectare sandy beach and 14.0 hectares of water. Breakwaters are present on both sides and in the middle of the water area. The sandy beach extends 50 meters at high tide and 70 meters at low tide. This coast, functioning as a tourist destination and beach park, is maintained at least once a year and cleaned over 200 times annually due to heavy visitor traffic.

The 80-meter-long Fukuhamma Coast in Fukuoka City's Central Ward features substantial coastal vegetation along three-quarters of its length and is equipped with a breakwater at one end. The 150-meter-long Najima Coast in Higashi Ward has a breakwater, visible black rock at low tide, and few coastal plants, mainly *Vitex rotundifolia*, despite regular beach maintenance.

The 300-meter-long Saitozaki Coast, near Hakata Bay's innermost section in Higashi Ward, Uminonakamichi District, undergoes regular beach maintenance. Flanked by breakwaters on both sides, it has multiple small outfalls along the beach and a river outfall. The vicinity of the outfalls experiences lower water quality, and significant household waste accumulation has been noted.

2.1.3 Tsushima Island and Goto Islands

Tsushima Island, located in the Korea Strait, is Japan's largest island in this region, approximately 50 kilometers (31 miles) from the mainland of Kyushu. The island covers an area of about 709.35 square kilometers and comprises the main island of Tsushima, along with five other inhabited islands (Uni Island, Tomari Island, Aka Island, Okinoshima Island, and Shimayama Island), and 102 uninhabited islands.

Tsushima is characterized by its hilly terrain, striking coastal landscapes, and abundant greenery. The

island is subdivided into several smaller towns and villages, with Tsushima City being the largest. Its coastline, predominantly developed in a rias style, extends over a total length of 915 kilometers. Notably, the central part of the main island features Aso Bay, which penetrates the island from the west to the east, forming an intricate archipelago with bays like Miura Bay and Oroshika Bay. Aso Bay's natural coastline is renowned for being among the longest in Japan. Scattered throughout the island are numerous small bays, many of which serve as fishing ports. The island's landscape is marked by the presence of cliffs, some with height variations of up to 100 meters, offering dramatic vistas (Hand Book of Scientific Tables, 2006).

The island's watershed is primarily located to the east, with five major rivers - the Sago, Nitta, Mine, Sasu, and Se Rivers - flowing westward. The largest river flowing eastward is the Shushi River, ranking fifth in terms of area on the island. Each river's lower reaches form valley plains, yet the island overall has limited flat land suitable for cultivation, rendering land transportation generally challenging. This unique topography has significantly influenced the island's historical development and the lifestyle of its inhabitants.

Tsushima Island boasts a rich and storied history, having played a crucial role as a pivotal transit point for travelers and traders between Japan and the Korean Peninsula. This strategic position has deeply influenced the island's historical narrative. Notably, the island experienced a significant increase in tourists from Korea in recent years, reflecting its growing popularity as a renowned sea fishing destination in Japan. Korean signs and messages are commonly seen across the island, indicating its appeal to Korean visitors.

Tsushima Island holds a significant place in Japan's military history. It was the site of a Mongol invasion in the 13th century, famously repelled in the Battle of Bungyeong by samurai and local warriors. This event is emblematic of Tsushima's role in Japan's efforts to maintain sovereignty and control sea routes throughout various periods in history. Given its geographical location, Tsushima has developed a unique cultural identity, influenced by both Japanese and Korean traditions. The cultural fabric of Tsushima Island is a unique blend of Japanese and Korean influences, reflecting its geographical proximity to both nations. The island has developed its dialect, the Tsushima dialect, which is characterized by its distinctive features. Furthermore, traditional Japanese and Korean customs have been preserved in the local culture, adding to the island's rich cultural tapestry.

Tsushima Island is celebrated for its natural beauty, making it an attractive destination for eco-tourism and outdoor activities. Visitors are drawn to its lush forests, scenic hiking trails, and secluded beaches. Beyond its natural allure, the island is also renowned for historical sites, including well-preserved samurai castles and shrines that provide a window into its rich historical legacy.

The Tsushima Current, a warm current flowing through the Tsushima Strait, significantly influences the regional climate, creating a typical maritime environment that is characterized by its relative warmth and high rainfall throughout the year. In spring, the region experiences the effects of yellow

sands from the Gobi Desert, carried by monsoon winds blowing westward from the Asian continent. This phenomenon contributes to the unique seasonal weather patterns of the area. During summer, the region enjoys relatively cool and pleasant weather, with a majority of days recording temperatures not exceeding 30°C. However, this season also brings challenges, as monsoon and autumnal rain fronts tend to stagnate, leading to heavy rainfall. Although autumn generally sees lower rainfall and the average winter temperatures remain mild at around 6°C, the region is not immune to extreme weather conditions. Cold snaps originating from the mainland can cause temperatures to plummet below -5°C, and in midwinter, temperatures can even drop below freezing. The average climate of the region is comparable to that of a large city in the Pacific Belt. However, the annual occurrence of cold snaps leads to temperature drops akin to those experienced in a southern northeastern island.

This significant temperature difference is particularly notable for Tsushima Island due to its proximity to the mainland. The geographical location of the island, lying close to the mainland, plays a crucial role in these varied climatic conditions (Japan Meteorological Agency, 2020).

Fishing constitutes one of the primary industries in Tsushima. Traditional practices include line fishing for squid in the waters off Tsushima and the Sea of Japan, with dried squid being a local specialty. The island's fishermen also engage in pole and line fishing for snapper and amberjack, along with set-net fishing in coastal areas. However, due to the Japan-Korea Fisheries Agreement, which established a joint control area, the number of fishing vessels is limited. This limitation has led to a gradual decrease in catches year by year, and abalone, in particular, has been severely affected by poaching. Pearl farming, predominantly in Aso Bay, has been a notable activity since the Taisho era (Tsushima City, 2003). A growing concern around Tsushima Island is the evident decline and disappearance of seaweed beds, posing a serious ecological problem. The protection and restoration of these seaweed beds are vital not only for the maintenance of Tsushima's coastal ecosystem but also for the revival and development of the island's fisheries.

Recognizing the urgency of this issue, recent efforts by the Tsushima Fisheries Section have focused on preserving and enhancing the rocky coastal resources along Tsushima's coast. Furthermore, significant measures are being taken to protect and regenerate seaweed beds. These initiatives are crucial for safeguarding Tsushima's rich marine ecosystem and establishing a sustainable and thriving fishery sector (Tsushima City Fisheries Department, 2018).

The Tsushima Current, a significant oceanic current, flows into the Sea of Japan from the west coast of Kyushu via the Tsushima Strait. It is characterized by its high temperature, high salinity, and low nutrient content, being a surface current that mixes with the Kuroshio Current and the coastal waters of the East China Sea. This current plays a crucial role in determining the thermal and saline characteristics of the Sea of Japan. The surface layer of the Sea of Japan is broadly divided into southern and northern regions, with the demarcation line approximately at 40 degrees north latitude. In the southern surface layer, high-temperature, high-salinity water (hereafter referred to as warm

water) predominates. This warm water primarily originates from the Kuroshio, which descends the continental shelf slope in the East China Sea and passes through the Tsushima Strait.

Most of this warm water flows into the Pacific Ocean via the Tsugaru Strait, while a portion also enters the Sea of Okhotsk through the Soya Strait. This warm water forms the core of the Tsushima Warm Current, significantly influencing the Sea of Japan's hydrographic conditions. Contrastingly, the surface of the northern Sea of Japan is dominated by water with lower temperature and salinity compared to the Tsushima Warm Current, hereafter referred to as cold water. This cold water extends at depths of approximately 300 meters or deeper in the Sea of Japan. It features temperatures around 0 to 1°C and salinity levels of about 34.1, exhibiting a near-uniform composition. The southern part of the Sea of Japan's surface layer maintains high water temperatures and high salinity levels, contrasting with the colder currents. This dynamic contributes to the unique thermal and saline balance in the region, significantly affected by the Tsushima Warm Current.

The Tsushima Current, flowing northward across the Sea of Japan, traverses several key shipping lanes. This current exhibits a complex path: a portion moves along the east coast of the Korean Peninsula, forming the East Korean Warm Current (**Fig. 2.4**). The main current progresses along the west coast of the Tohoku region, particularly off Yamagata and Akita Prefectures. A significant part of the current enters the Pacific Ocean through the Tsugaru Strait, identified as the Tsugaru Warm Current. Another segment of the current flows northward along the Hokkaido Strait and crosses the Soya Strait to enter the Sea of Okhotsk, known as the Soya Warm Current. Additionally, a minor flow reaches the west coast of the Karafuto Islands (Japan Meteorological Agency, 2022). The Tsushima Warm Current markedly influences temperatures within Japan. The Japan Sea side of the Japanese archipelago generally experiences higher temperatures compared to the Pacific side, especially east of Hokkaido and in the Tohoku region (encompassing Iwate, Miyagi, and Fukushima prefectures). This climatic pattern is also observed when compared to the Korean Peninsula and the Russian Far East, located on the opposite coast at similar latitudes. Notably, many parts of the Japan Sea side of the region experience slightly warmer summers and longer sunshine hours than their Pacific counterparts at equivalent latitudes. This is particularly evident in the Hokuriku and Tohoku regions, which enjoy significantly higher temperatures and more sunshine. These areas are less prone to cold damage compared to the Pacific side at the same latitude, which is more susceptible to tidal cold waves.

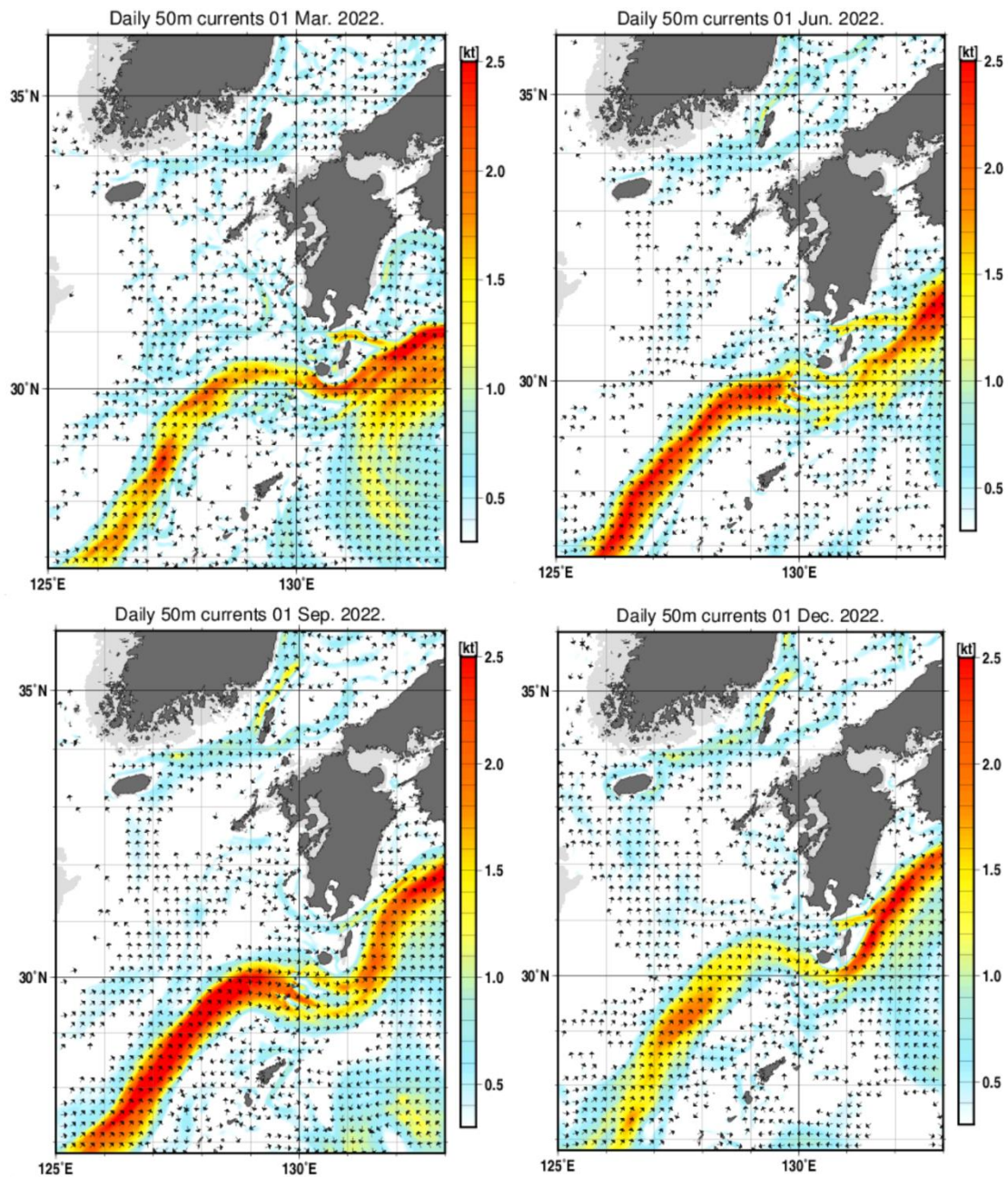


Fig. 2.4 Simulation of the movement of the Tsushima Current around Kyushu in 2022

On Tsushima Island, coastal debris sampling is conducted along five key coasts: Itangata Coast, Miuda Coast, Inokuchi Coast, Komotahama Coast, and Agami Coast. Each of these coastal areas presents unique geographical features and user statistics, which are crucial for understanding the extent and nature of coastal debris accumulation (**Fig. 2.5**).

The Inokuchi Coast, located north of Sago in Kami-ken-cho, Tsushima City, features a beach depth of 30 meters and a coastline length of approximately 300 meters. It attracts an average yearly user population of about 700, making it a significant area for debris sampling.

Renowned as one of the most popular swimming beaches in Tsushima, the Miuda Coast is situated in Nishidomari, Kamitsushima-cho. In the eighth year of the Heisei era, it was recognized as one of Japan's 100 Best Beaches. The coast is famed for its white sand beaches, formed naturally from a rare composition of microscopic shells. The sandy beaches here extend roughly 20 meters in depth and span a total of 200 meters along the coastline.

The Agami Coast, located in Izuhara Town, Shimo Tsushima, is characterized by its rocky coastline with gentle waves and breezes. Adjacent to this coast is a harbor used by fishing boats, adding to its importance for debris sampling.

In another part of Izuhara Town, the Itangata Coast is known for its accumulation of driftwood and plant stalks along the shoreline, in addition to its breakwaters. This coastline's particular features make it a relevant location for understanding the types of debris that accumulate in such environments.

The Komoda Coast, also situated in Izuhara Town, lies at the mouth of the Sasu River, Tsushima's third-largest river. This coast also features a breakwater in its marine waters, providing another diverse sampling site for coastal debris studies.

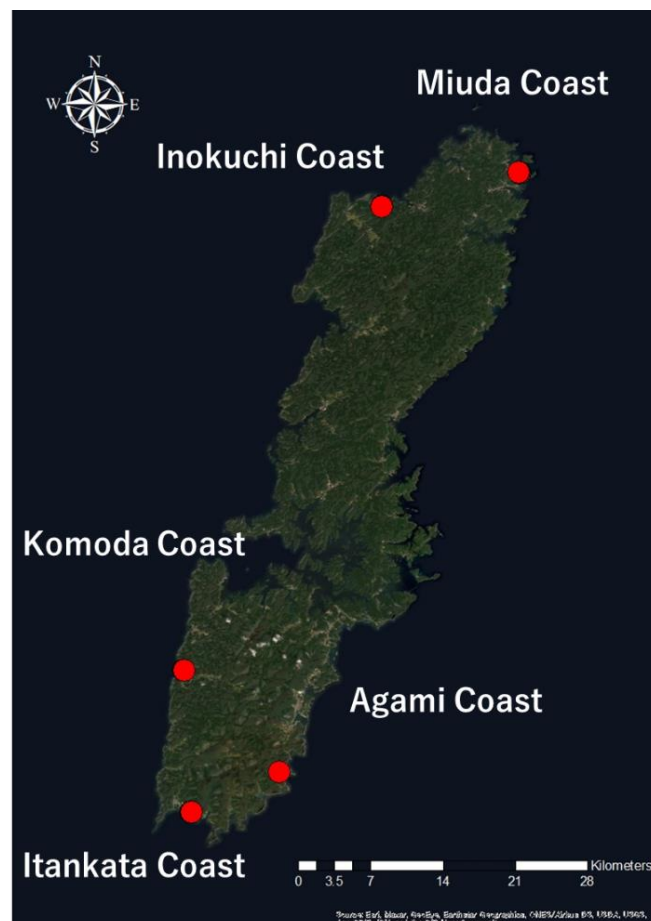


Fig. 2.5 Marine debris sampling sites on Tsushima Island

The Goto Islands, also referred to as the Goto Archipelago or simply Goto, are a picturesque group of islands located in Nagasaki Prefecture, Japan. Situated in the East China Sea, these islands lie just off the western coast of Kyushu, the southernmost of Japan's four main islands. Comprising five large islands (Nakadori, Wakamatsu, Narushima, Kuga, and Fukue) and numerous smaller islands, the Goto Archipelago extends from the northeast (**Fig. 2.6**).

Known for their natural beauty, rich historical significance, and unique cultural heritage, the Goto Islands were once part of Matsuura County and are now designated as part of Saikai National Park. The islands' landscape features a complex rias coastline characterized by mountains that descend into the sea, leaving their peaks as drowned valleys.

Due to its extensive length stretching from northeast to southwest, the Goto Archipelago is commonly divided into two main groups. The southwestern islands, centered around Fukuejima, the largest of the Goto Islands, are collectively known as "Shimo-Goto." Conversely, the northeastern islands, with Nakadorijima as the second-largest island, are referred to as "Kami-Goto." This division reflects the geographical spread and distinct characteristics of the island groups (Islands of Nagasaki Prefecture, 2020).

Within Nagasaki Prefecture, which encompasses a large number of islands, the Goto Archipelago stands out due to its cluster of islands positioned at some distance from the mainland and other islands. This grouping forms the unique collective known as the "Goto" islands, distinguishing it from other island groups within the prefecture.

The Goto Islands have a long history of human habitation, with evidence of settlement dating back to the Paleolithic period. Archaeological discoveries on the islands have uncovered a wealth of remains from both the Jomon and Yayoi periods, indicating a continuous human presence through these ancient times.

While there are various theories regarding the origins of the Japanese people, the Goto Islands' recent history includes instances of boats carrying refugees from China and Vietnam reaching its shores. Additionally, during typhoons, the islands have historically served as a sanctuary for Chinese fishing boats. These events suggest the possibility that currents from southern China could have facilitated migration to the islands.

The islands of Goto are closely clustered yet not connected by land. This geographical layout, with the sea being a constant visual presence across the archipelago, has historically been advantageous for fishing communities. The natural environment of the islands significantly influenced the livelihood and culture of its inhabitants.

Archaeological remains suggest that the lifestyle during the Jomon period on the Goto Islands was similar to that on the mainland. However, in the Yayoi period, cultural practices from the mainland were introduced to the islands with a slight delay. Notably, during the Heian period (794-1185), Goto served as the last port of call for Japanese envoys to the Tang Dynasty. Despite its distance from the

mainland, Goto's proximity to the continent meant that it remained connected with central Japanese culture and did not experience prolonged isolation.

The Goto Islands, located in Nagasaki Prefecture, Japan, are rich in historical and cultural sites that reflect their unique heritage. These islands are particularly noted for their blend of Japanese and Western cultural influences, seen in the architecture and art prevalent in the region. A key cultural site on the islands is the Goto Kanko Historical Museum, which houses a collection of artifacts detailing the islands' history. Additionally, the Goto Islands are renowned for their significant Christian (predominantly Catholic) influence. This is evident in the presence of various churches, which stand as historical testaments to the early Christian presence in the region. The islands maintain a substantial Catholic population, with over 10% of the residents identifying as Catholic. There are 51 Catholic churches spread across the Goto Islands. These churches, having long been integral to the daily life of Goto residents, are cherished as symbols of the local heritage and community. The architectural design of these churches showcases a unique fusion of Japanese and Western styles.

On January 23, 2007, the Agency for Cultural Affairs in Japan nominated the Nagasaki Churches and Christian Heritage for inclusion on the UNESCO World Heritage Tentative List. Within this nomination, four churches from the Goto Islands were selected as component properties. This recognition highlights the significant historical and cultural value of these churches, not only within Nagasaki Prefecture but also in the broader context of global heritage (Keisuke Matsui and Wataru Kawazoe, 2020).

The Goto Islands, celebrated for their pristine natural beauty, boast picturesque beaches, crystal-clear waters, and verdant greenery. Their relative remoteness from mainland Kyushu and the absence of large industrial developments have preserved their unspoiled nature, exemplified by landmarks such as the Osezaki Lighthouse and stunning sandy beaches. Historically significant, Goto served as a stopover for Japanese envoys to China during the Tang Dynasty. This rich history is encapsulated in artifacts displayed at the Tang Dynasty envoys' hometown museum on Fukue Island and another museum on Goto, reflecting the islands' cultural heritage. Goto Island also holds significance as a place visited by Kukai (Kobo Daishi) during his journey to and from Tang Dynasty China. With the impending registration of Christian churches as a World Heritage site, there is a burgeoning initiative among locals to preserve these churches and leverage them for tourism purposes.

Onidake, a landmark visible from downtown Goto, features a gently curving summit and is a popular grassy park, drawing numerous families throughout the year, except in winter. The islands' location amidst the open sea makes them abundant in marine products, attracting both individual and tour fishermen from the Kyushu mainland. The Goto Islands offer various fishing spots and beaches, such as Takahama Beach on Fukue Island, which lure tourists seeking seaside experiences. In addition to high-quality seafood and processed foods, the local cuisine is renowned, particularly for Goto Udon. This specialty noodle is characterized by its hand-pulled kneading in camellia oil, imparting a strong

texture and resistance to stretching after boiling. Other local delicacies include kankoromochi (rice cakes) and camellia oil, known for their high quality and favored as tourist souvenirs (Tourism Association of GOTO, 2020).

Fishing has been a cornerstone of the Goto Islands' economy, with the islands renowned for their delectable fresh seafood. Among the notable catches are saba (mackerel) and umi-budo (sea grapes), which are highly prized for their quality and freshness. The Goto Islands, with their intricate coastline, provide an ideal environment for various forms of aquaculture. Abalones from Goto, for instance, are so esteemed that they continue to be regarded as the finest in China to this day. The islands' aquaculture industry is diverse, encompassing not only seafood but also the cultivation of high-end yellowtail and tuna. Additionally, the farming of Akoya oysters and pearls thrives in the region, contributing significantly to the local economy. Tourism plays a pivotal role in the economic landscape of the Goto Islands. Visitors are drawn to the islands for their rich history, unique culture, and stunning natural beauty. This sector is vital for the islands' economic sustainability, leveraging their historical and natural assets to attract tourists from across Japan and beyond.

The Goto Islands feature six coasts designated as marine debris sampling sites: Masahiko Coast, Enohama Coast, Takaitabi Coast, Ohama Coast, Maruko Coast, and Tondomari Coast. Each of these coasts possesses unique geographical and ecological characteristics, making them important for environmental studies.

Located in Soneigo, ShinkamiGoto-Cho, the Masahiko Coast is adjacent to Masahiko Shrine. This coast, composed of variously sized rocks and accessible by steps, is informally named after the nearby shrine. The oceanfront on this coast resembles a spoon in shape, contributing to its distinctive appearance.

In Enohama Town, ShinkamiGoto-Cho, the Enohama Coast serves both as a shoreline and a fishing harbor. The beach is backed by scattered coastal plants, including *Carex kobomugi* and *Oenothera laciniata*. Spanning approximately 140 meters, this coastline features a sandy beach with a gentle slope and fine sand.

The Takaitabi Coast, located in Naraogo, ShinkamiGoto-Cho, is a sandy beach coast shaped by the concavity of the surrounding mountains. Its shoreline extends for about 650 meters, with a maximum depth of around 60 meters, providing a unique beach environment.

Accessible from Prefectural Route 49, the Ohama Coast in Hama-Cho, Goto City, reveals a large sandy beach when the tide recedes, contrasting with the picturesque sandy beaches on the opposite side. The coast features diverse coral reefs amidst its scattered debris.

At 3881 Nagamine, Tomie-cho, Goto City, the Maruko Coast is characterized by grayish-brown stones with rounded edges, shaped by consistent winds and waves. The beach covers an area of 0.14 square kilometers, with a 350-meter-long coastline marked by tiered sections resulting from wave erosion.

The Tondomari Coast, in Tamanoura-cho, Goto City, is a triangular-shaped beach bordered by inland mountains. The clear, nearly transparent waters near the shore provide a serene environment, offering views of lush green mountains and crystalline waters.

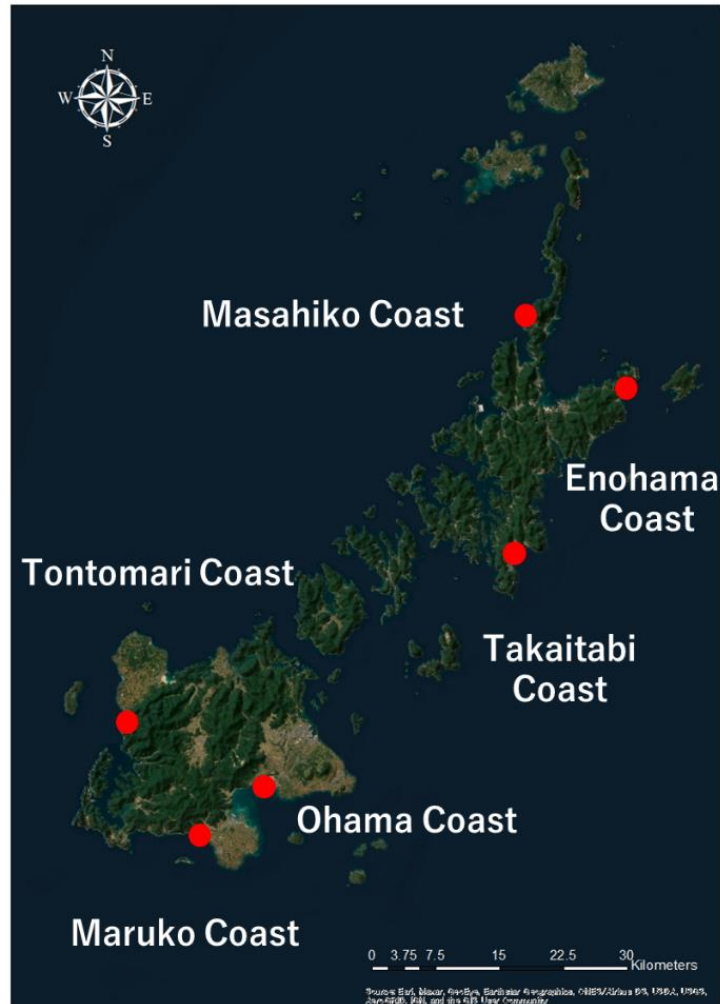


Fig. 2.6 Marine debris sampling sites on Goto Islands

2.2 Primary analysis of marine debris samples

The initial phase in the preliminary examination of marine debris samples involves determining the presence of any distinguishing features such as words, patterns, codes, or other unique markings. These identifiers are critical for tracing the geographical origin of the litter, which may include commonly found items like plastic bottles and fishing floats. This analysis helps ascertain whether the debris is domestic waste originating from Japan or transboundary litter from international sources.

In cases where such identifiable information is absent, the litter undergoes a more detailed examination. This involves categorizing the items based on their original product category, size, and material composition. The product categories are generally bifurcated into household goods and fishery-related products. Household goods are further subdivided into daily necessities and leisure goods, while

fishery-related items are classified into fishing tackle and gear.

For size classification, marine debris is categorized into three distinct groups: macro marine debris (larger than 2.5 cm), meso-marine debris (ranging between 0.5 and 2.5 cm), and micro marine debris (less than 0.5 cm). Unidentifiable fragments undergo additional analysis to determine their composition. The material of the litter is typically categorized into two main types: plastic and non-plastic debris. Plastic debris is further classified into foam, plastic film, and hard plastic fragments. Non-plastic waste commonly includes materials like glass and metal, among others.

Although this preliminary analysis is not highly sophisticated, it effectively gathers essential data from the majority of the samples. This methodology can be integrated into standard beach litter cleanup operations to facilitate the identification and categorization of marine debris, thereby contributing to more informed and effective environmental management practices.

2.3 Geographic information processing software— Arc Map 10.3

ArcGIS represents a comprehensive system for the collection, management, organization, analysis, communication, and dissemination of geographic information. It stands as the world's leading platform for creating and utilizing geographic data, widely employed across various sectors including media, government, business, academia, and scientific research.

ArcMap, a key component of the ArcGIS suite, enables users to create detailed map layouts suitable for printing or digital publication. It offers robust functionalities for symbol assignment, as well as the exploration and analysis of GIS datasets specific to a research area. Additionally, ArcMap facilitates the creation and editing of databases, making it an indispensable tool in geographic data management. Despite the advent of ArcGIS Pro, a newer and more advanced next-generation desktop GIS application, ArcMap continues to be a preferred choice for many users. This preference can be attributed to its traditional interface and established functionality (A. Tilahun and B. Teferie, 2015).

In the context of this study, the geographic data collected from the survey site were processed using ArcMap. This application was instrumental in integrating the gathered data with existing background geographic information, thereby enhancing the comprehensibility and tangibility of the study's results. The utilization of ArcMap in this research underscores its continued relevance and effectiveness in geographic data analysis and representation.

2.4 Experimental analytical methods for microplastics

The analysis of microplastic samples was primarily conducted using two sophisticated analytical techniques: Scanning Electron Microscopy coupled with Energy Dispersive X-ray Analysis (SEM·EDX) and Fourier-Transform Infrared Spectroscopy (FT/IR). The specific models employed were the SU3500 from Hitachi High-Tech Corporation for SEM·EDX and the FT/IR-4700 from JASCO Corporation for FT/IR.

2.4.1 SEM-EDX(SU3500) analysis

The Scanning Electron Microscope (SEM) is an advanced tool designed for observing the surface morphology and microstructure of various samples with high resolution. Unlike Transmission Electron Microscopy (TEM), SEM is adept at imaging regardless of the sample's thickness and shape. This capability stems from its focus on electrons that interact with the sample's surface, as opposed to electrons that pass through the sample, as is the case with TEM.

In the SEM process, an electron beam, generated by an electron gun, is accelerated and precisely focused onto the sample's surface using an electromagnetic lens. This high-speed electron beam engages with the atoms and molecules present on the sample's surface, resulting in the emission of secondary electrons and reflected electrons. These emitted electrons are then captured by dedicated detectors, processed, and subsequently translated into detailed images. The resulting high-resolution, high-magnification, high-sensitivity, and high-contrast images allow for in-depth analysis of the sample's surface shape and texture. Consequently, SEM finds extensive application in fields such as microfabrication and surface treatment, where detailed surface analysis is crucial.

The fundamental principle of SEM centers around the irradiation of a high-speed, accelerated electron beam onto a sample surface. The electrons that are reflected and scattered back from the sample surface are then detected, enabling the observation of the sample's morphology and microstructure. The high energy of the electron beam creates an electron cloud upon striking the sample surface. This interaction can excite atoms and molecules within the cloud, potentially triggering various reactions. This interaction forms the basis of SEM's ability to provide detailed surface imaging (AZ Science, 2023).

Energy-dispersive X-ray Spectroscopy (EDX) is a technique used for elemental and compositional analysis of materials. It functions by detecting characteristic X-rays that are emitted from a sample when it is irradiated with electron beams. These X-rays are analyzed in terms of their energy spectra. Since the energy of characteristic X-rays is unique to each element, it enables the identification of the elements composing the sample. Additionally, the intensity of these X-rays provides quantitative information about the sample's composition.

The underlying mechanism of EDX involves the excitation of inner-shell electrons out of an atom when irradiated with electron beams. This excitation creates vacancies in the inner shell, leading to an energetically unstable state. To stabilize, electrons from outer shells transition to the inner shell, emitting characteristic X-rays that correspond to the energy difference between the initial and final states. By measuring these X-rays, elemental analysis is conducted, as each element produces X-rays of specific energy.

Energy Dispersive X-ray Spectroscopy (EDS) is another term for this technique. It offers the capability to simultaneously measure all energies within the range of elements from Boron (B) to Uranium (U) in a relatively short duration. EDS boasts excellent detection efficiency, allowing measurements with minimal probe current. For most samples, no special pretreatment is required, enabling straightforward

analysis. Additionally, EDS can perform measurements in frozen and cooled states using a Cryo-holder, making it particularly useful for analyzing unknown samples (Foundation for Promotion of Material Science and Technology of Japan, 2023).

In this study, the SU3500 model was utilized, which offers various observation modes. It allows the observation of non-conductive samples in a high vacuum with conductive treatment, as well as low-vacuum observation without pretreatment, and low acceleration high vacuum observation. The low-vacuum mode is particularly effective for obtaining images of diverse samples such as soil, rocks, plants, and food. The device's camera navigation function enables automatic stage movement by clicking on a pre-captured sample image, facilitating the observation of multiple samples placed on the sample table. An integral component of the SU3500 is its energy-dispersive X-ray analyzer, which allows for simultaneous elemental analysis (detecting elements from Beryllium (Be) to Americium (Am)) and sample observation. The resolution of the SU3500 is 3 nm (at 30 kV), with an acceleration voltage range of 0.3 to 30 kV. It can accommodate samples up to 130 mm in diameter, enabling full-area observation. The electron gun utilized in this model is a pre-centered tungsten hairpin filament (Center of Advanced Instrumental Analysis, Kyushu University, 2015).

In this study, representative microplastic samples were selected from research sites located in Hakata Bay. Due to the limited area of the sample stage on the analytical equipment, each microplastic sample required precise preparation. These samples were affixed to a circular carbon tape plane, with a diameter of merely 1 cm, to ensure they remained secure during the analysis process. To prevent the microplastic debris from dislodging, the samples were prepared with a flat surface for effective adhesion to the tape. The sample stage is designed to process up to 12 samples simultaneously, with the number of batches and samples adjustable depending on the analysis requirements.

Given that the plastic samples were directly collected from the coastal environment, a control group was established to account for potential environmental influences. This control group included various natural elements such as driftwood, coastal vegetation, shells, animal remains (like crab shells), as well as sand and rocks from each coast. By comparing the elemental composition of the microplastics to that of the control group, it is possible to accurately identify elements unique to the plastic surfaces. Before proceeding to testing in the vacuum chamber, it is crucial to verify the height of the entire stage, ensuring all samples are securely fixed. The observation area for the samples on the stage is defined by adjusting the objective distance (OD) after entering the stage image using the Digital LUPE system. Each sample is then individually captured by a high-definition camera using Scanning Electron Microscopy (SEM), focusing particularly on the traces of surface degradation. When examining a sample with Energy-Dispersive X-ray Spectroscopy (EDX), the elemental composition at the degradation marks is also documented.

One notable limitation of this process is that most samples become non-recyclable post-assessment due to the strong adherence to the carbon tape. Therefore, when selecting representative samples for

analysis, it is advisable to either prepare additional sets of identical samples for backup or to conduct the SEM-EDX analysis as the final step in the experimental investigation. This approach ensures comprehensive analysis without compromising the integrity of the samples.

2.4.2 FT/IR-4700 analysis

Fourier Transform Infrared Spectroscopy (FT/IR) is an advanced analytical instrument predominantly used for the qualitative structural estimation of organic compounds. Unlike traditional methods that irradiate samples with infrared light at varying wavelengths, FT/IR involves irradiating the sample with continuous light. This process enables the acquisition of absorption spectra corresponding to molecular structures by Fourier transforming the interference patterns created by the light. The use of continuous light allows for the simultaneous measurement of the entire wavenumber range, facilitating high-sensitivity measurements in a relatively short timeframe.

Key features of FT/IR include:

Nondestructive Measurement: The technique does not damage the sample, allowing for further analysis if needed.

Measurement Under Vacuum: Performing measurements in a vacuum eliminates interference from atmospheric components like CO₂ and H₂O.

Microscopic Measurement: FT/IR can measure areas as small as several tens of micrometers square, enabling detailed analysis of tiny sample areas.

Versatility in Sample Types: The technique is adaptable for various sample shapes and states, utilizing methods such as transmission, reflection, and Attenuated Total Reflectance (ATR).

FT/IR is widely applied in numerous areas, including the qualitative analysis of foreign matter, evaluation of organic film materials, assessment of the state of SiO₂ films, determination of resin hardening degrees, evaluation of the imidization rate of polyimide, analysis of plastic degradation, and component analysis of adhesives.

The principle of infrared spectroscopy operates in the infrared light region, ranging from 0.8 to 1000 micrometers (μm). The most commonly utilized region is the mid-infrared (2.5 to 25 μm), where absorption spectra, also known as vibrational spectra, are observed due to molecular vibrations involving changes in dipole moments. When a molecule is irradiated with infrared light, absorption occurs if the vibrational frequency of the light coincides with that of the molecule's atoms. This absorption shifts the atoms or atomic groups from the ground state to an excited state and is detectable in the infrared spectrum. Since atoms vibrate in patterns unique to their molecular structure, analyzing these spectra provides valuable insights into the molecular structure of the sample (Foundation for Promotion of Material Science and Technology of Japan, 2023).

The FT/IR-4700 used in this study is a general-purpose instrument suitable for routine analysis, but its performance and functions have the performance to be used in research and development. However,

atmosphere control is not possible (atmospheric measurements only). The accessories (ATR, etc.) of the existing FT/IR-620 instrument can be used. Measurement wavenumber range: 7800 to 350 cm^{-1} , maximum resolution: 0.4 cm^{-1} , S/N ratio: 35000:1 (Center of Advanced Instrumental Analysis, Kyushu University, 2015).

The sample attachment table area in the FT/IR sample chamber is limited, and for proper monitoring, the sample's size and shape must be modified before analysis and the detector must come into direct contact with the sample for detection. Following detection, the data saved in the computer needs to be appropriately processed. The composition of the samples is ascertained by fitting the absorption peak morphologies of the infrared spectra that exhibit the highest degree of similarity after the infrared spectrum acquired from the detection is rectified and compared with the composition data recorded in the database. Considering that plastic samples sometimes contain several severely deteriorated fragments, sample loss during analysis may occur from parts of the sample breaking apart due to the detector's proximity to the sample.

The FT/IR-4700 instrument employed in this study is a versatile, general-purpose tool primarily designed for routine analysis. However, its advanced performance and functionalities also render it suitable for research and development applications. One limitation to note is that the FT/IR-4700 does not allow for atmosphere control, and therefore, measurements are conducted only under atmospheric conditions. Conveniently, the accessories (such as Attenuated Total Reflectance (ATR), etc.) from the existing FT/IR-620 instrument are compatible with this model. The FT/IR-4700 boasts a measurement wavenumber range from 7800 to 350 cm^{-1} , a maximum resolution of 0.4 cm^{-1} , and an impressive Signal-to-Noise (S/N) ratio of 35000:1 (Center of Advanced Instrumental Analysis, Kyushu University, 2015).

Within the FT/IR sample chamber, the space for attaching samples is limited. To ensure accurate monitoring, it is essential to modify the size and shape of the sample before analysis. Additionally, direct contact between the detector and the sample is required for effective detection. Once the detection is complete, the data stored in the computer must be meticulously processed for accurate analysis.

The compositional analysis of the samples involves a detailed comparison of the absorption peak morphologies in the infrared spectra. After rectifying the infrared spectrum obtained from detection, it is compared against the composition data recorded in the database to identify the closest matches. This process helps in determining the exact composition of the samples.

A particular challenge encountered during analysis is the fragility of plastic samples, especially those containing severely deteriorated fragments. There is a risk of sample loss during analysis, as parts of the sample may break apart due to the proximity of the detector to the sample. This aspect necessitates careful handling and preparation of samples to minimize potential damage and ensure the integrity of the analysis.

Chapter 3 Characteristics of the distribution of marine debris on the Itoshima Peninsula

3.1 Overview of the monitoring area on Nagahama Coast and Niginohama Coast

In the study conducted on the Itoshima Peninsula, five distinct groups of monitoring areas were established at each survey site. The selection of these monitoring areas was meticulously strategized, taking into account the unique coastal topography and geographic location of each site, factors that significantly influence the distribution of marine debris along the coastline. The selection process for these monitoring areas was informed by preliminary fieldwork conducted before the main survey. This preparatory phase was crucial in identifying the most appropriate sites for monitoring based on various environmental and anthropogenic factors.

Figure 3.1 in the study documentation provides a comprehensive overview of the monitoring sites along the Nagahama Coast. This section of the coast was chosen for monitoring due to several key factors: the distribution range of the foreshore plant community and the presence of human-made structures and activities such as parking lots, fences, artificial revetments, and access points. These elements play a significant role in the accumulation and movement of marine debris, making them important considerations in the selection of monitoring areas.

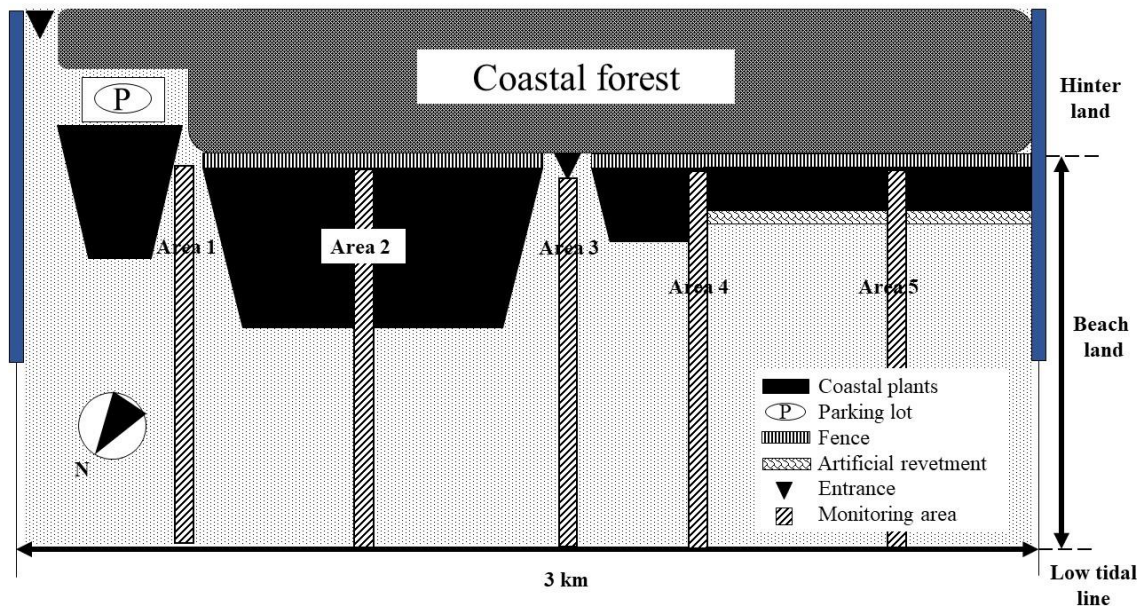


Fig. 3.1 Overview of the monitoring area on Nagahama Coast

Similarly, **Figure 3.2** details the monitoring zones established along the Niginohama Coast. Unlike the Nagahama Coast, the Niginohama Coast lacks parking facilities but features a river outflow, which can be a significant factor in debris distribution. The monitoring area for this location extends from

the low tide line to the backshore, encompassing a critical zone for observing the accumulation and impact of marine debris.

Overall, the strategic selection of these monitoring areas ensured a thorough and representative assessment of marine debris distribution along different parts of the Itoshima Peninsula's coastline, providing valuable insights into the dynamics of coastal pollution.

The study conducted at the two survey sites included a preliminary assessment of the plant species present, with a focus on understanding the distribution of the coastal plant community (**Fig. 3.3**). Six vegetation types were identified as being particularly representative of the area: *Carex kobomugi*, *Artemisia capillaris*, *Zoysia*, *Calystegia soldanella* (L.) Roem, *Ixeris repens*, and *Glehnia littoralis*.

Carex kobomugi, commonly known in Japanese as Koboumugi, is a perennial herbaceous plant belonging to the family *Cyperaceae*, often found in sandy coastal environments. It typically reaches a height of 10 to 30 cm and is native to East Asia's beaches. This species is known for forming sporadic colonies on dunes. The plant features thick leaves with smooth surfaces and slightly serrated edges. *Carex kobomugi* is a dioecious plant, meaning it has separate male and female plants. It propagates through underground stems, with new plants emerging from nodes. The plant's reproductive structure includes small white flowers, with green ears indicating female flowers and brown ears signifying male flowers. In some instances, the female part of the flower is located below the male part. The root base of *Carex kobomugi* contains brush-like fibers, and its berries are said to resemble wheat grains, which is the origin of its name (Norio Tanaka et al., 2002).

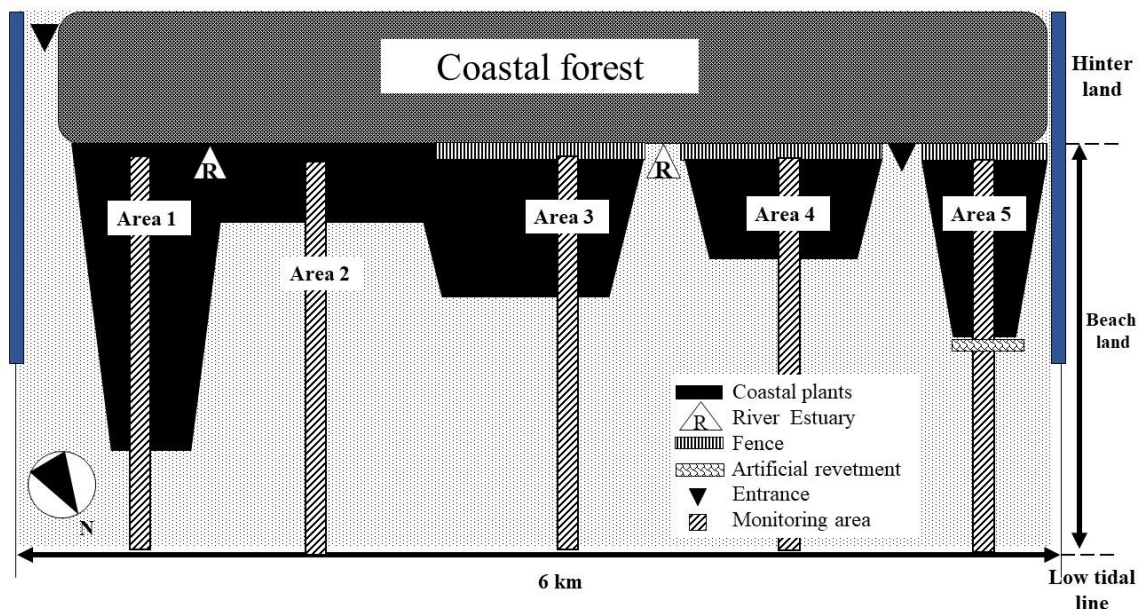


Fig. 3.2 Overview of the monitoring area on Niginohama Coast

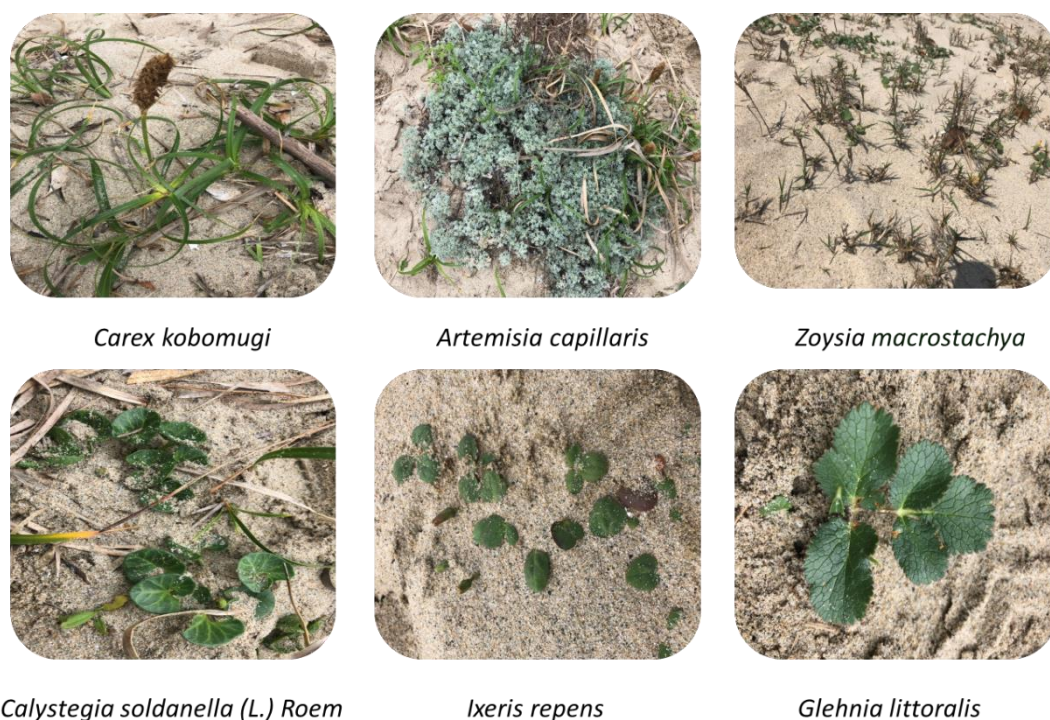


Fig. 3.3 Representative coastal plants on the surveyed coast

Within the family Asteraceae, the perennial herb *Artemisia capillaris*, commonly known in Japan as kawarayomogi, is a notable species. This plant has a widespread distribution, extending from Honshu in Japan to regions like Nepal, China, and the Korean Peninsula. *Artemisia capillaris* typically thrives in semi-arid fields and sandy environments such as seashores and riverbanks. Its growth habit has earned it the classification of a "subshrub" due to the woody, shrub-like characteristics of its lower stem. In spring, the plant exhibits silvery-green foliage, characterized by rosette-shaped leaves with short petioles and slender lobes. These leaves are densely covered with silky, grayish-white hairs. The plant's tall stems feature sessile, pinnately lobed leaves, each with two filiform lobes measuring 8–12 mm in length and 0.3–0.5 mm in width. A distinct scent is released when the plant is touched or rubbed (Yonekura Koji, 2003).

Zoysia macrostachya, belonging to the *Poaceae* family and known as Onishiba in Japan, is a perennial grass species. It is a naturally occurring wildflower in sandy coastal areas, typically reaching heights of 10 to 20 cm. This grass is characterized by long, creeping rhizomes from which short, stiff culms emerge vertically, resembling wire. Flower stalks, ranging from 5 to 20 cm in height, sprout from the nodes. Its geographical distribution includes areas from Okinawa to the Korean Peninsula, central and eastern China, and southwest Hokkaido.

Calystegia soldanella (L.) Roem. et Schult., commonly referred to as Hamahirugao, is a perennial

plant within the Hirugao family, known for its growth in clusters on sandy coastal soils. The plant features heart-shaped leaves that are rounded at the tips and deeply indented at the base. Its flowers, about 5 cm in diameter, bear a resemblance to morning glories. The leaves are equipped with transparent cuticles that reduce water evaporation. *Calystegia soldanella* plays a crucial role in coastal ecosystems, particularly on the severely eroded Chigasaki shore. Its underground branches, which spread widely in the sand and resemble vines, have robust roots that effectively prevent sand erosion. The plant typically blooms in early summer, from May to June (Hiroki Nakanishi, 2013).

Ixeris repens, commonly known as Hamanigana, is a perennial herb belonging to the family Asteraceae. It is characterized by its long underground stems and tends to grow in clumps along coastal shores. The plant's leaves are attached to long stems and typically have three to five lobes with a dense, meaty texture. *Ixeris repens* flowers from April through October, featuring a crown flower 2 to 3 cm in diameter composed of 15 to 20 yellow, tongue-shaped petals. It has a distinctive blooming cycle, flowering twice a year in both spring and fall. The name "Hamanigana" translates to "bitter greens of the beach," a reference to the white, bitter liquid that exudes from the stems and leaves when they are plucked (Yonekura Koji, 2003).

Glehnia littoralis, belonging to the genus Hamabofu in the family *Seriaceae*, is also known as "Hamabofu." This perennial herb is not only used in Chinese herbal medicine and folk remedies but is also consumed as a wild vegetable. It thrives in sandy coastal environments. The leaves of *Glehnia littoralis* are glossy and thick, with reddish-purple stems. The three-lobed, pinnately compound leaves have lobes that are elliptic to ovate, with firm walls and fine serrations. The plant's stems are relatively short, measuring 5 to 10 cm in length. It bears tiny, white to light purple flowers in compound spikelets, blooming from June to July. The fruit is oval-shaped and covered with long, delicate hairs. The seeds, resembling cork, are adept at spreading by either drifting on water or being dispersed along beaches, contributing to the plant's wide distribution. *Glehnia littoralis* has a bittersweet taste and a unique scent. Interestingly, when the stem is cut open, submerged in water, and punctured with a needle, it forms an anchor shape. This plant's distribution ranges from Hokkaido to Kyushu and Okinawa in Japan, extending to Sakhalin, Ussuri, the Sea of Okhotsk, China, Korea, and Taiwan (Yonekura Koji, 2010; Oba Hideaki, 2010).

3.2 Mapping data of the number of marine debris and the coverage of coastal plants

The distribution of marine debris on Nagahama Coast locations on the coast is significantly influenced by the environmental characteristics of each area. Areas 1 and 2 are distinguished by a higher proportion of backshore waterfront plant cover. In these regions, marine debris tends to accumulate near the low tidal line and within the boundaries of the coastal plant community. This pattern indicates a correlation between plant cover and debris deposition (**Fig. 3.4**).

In contrast, Areas 4 and 5 have undergone modifications due to the construction of artificial revetments

and embankments. These developments have not only elevated the land from the artificial revetment to the fence but have also impacted the natural growth of plants. Consequently, the accumulation of debris at the low tide line in these areas is limited. The human intervention in these areas appears to have altered both the vegetation dynamics and the patterns of debris accumulation.

Area 3, which serves as the entrance to Nagahama Coast, presents a different scenario. This area is characterized by a scarcity of plant life, likely due to its role as a primary access point to the beach. The distribution pattern of litter debris in Area 3 is distinct from the other areas, with debris being dispersed across both the foreshore and the backshore. Frequent human activity in this area, including prolonged trampling, has led to the dune elevation becoming lower and forming a concave "U" shape. This altered landscape affects the way debris is distributed, indicating the significant impact of human activity on environmental dynamics along the coast.

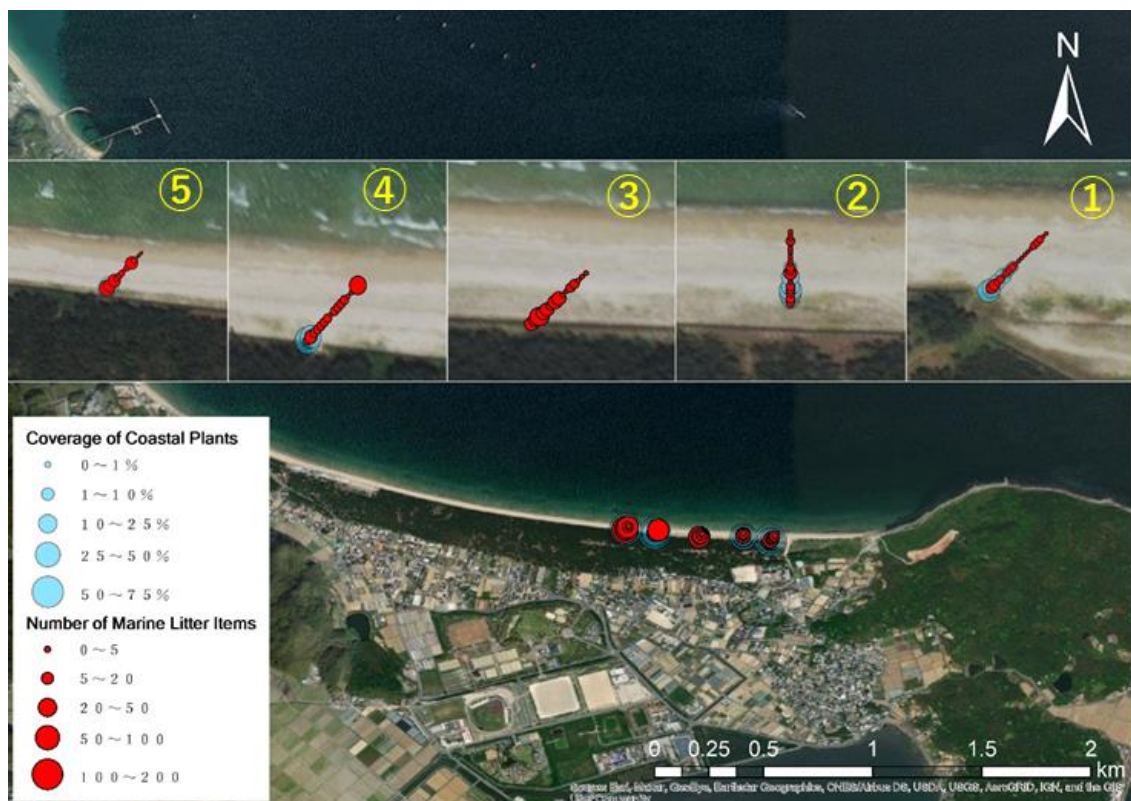


Fig. 3.4 Distribution of marine debris and coastal plants on Nagahama Coast

Monitoring Area 1 along the Niginnohama Coast boasts the largest expanse of sandy beach, primarily due to the long-term accumulation of sand from a nearby estuary. This process has significantly enriched the beach area. During low tide, the width of the beach can extend up to 70 meters. Vegetation covers up to 90% of this area's width, and a notable observation is that the majority of marine debris is concentrated within this plant community (Fig. 3.5).

In Area 2, there is a unique ecological transition zone where the backshore seamlessly connects with

the adjacent hill. This intersection serves as a habitat for a diverse array of both inland and seaside plant species. Notably, there is a significant accumulation of debris near this connection area, highlighting the interplay between different ecosystems and debris distribution.

Adjacent to Area 3, there is a river outflow, which plays a crucial role in the debris dynamics of this area. It is hypothesized that a portion of the debris found here may have been transported by the river. The predominant locations for marine debris in this area include within the plant community and near the low tide line, indicating the influence of riverine and tidal forces on debris dispersal.

In Area 4, the majority of litter debris was observed within the plant community. This pattern suggests a correlation between vegetation cover and debris accumulation, potentially due to the trapping and retention capabilities of the plants.

Area 5 is situated next to the coastal entrance and is characterized by the presence of a coastal tetrapod near the high tide line. This structural feature, particularly the gaps in the breakwater, contributes to a substantial accumulation of marine debris. The location of Area 5 at the coastal entrance, coupled with the influence of the tetrapod structure, appears to play a significant role in the concentration and retention of marine debris in this region.



Fig. 3.5 Distribution of marine debris and coastal plants on Niginohama Coast

3.3 Seasonal distribution of marine debris and coastal plants along the coastal section of Nagahama Coast and Niginohama Coast

In the Nagahama Coast, Areas 4 and 5, which feature artificial revetment, exhibit a notable transformation in the inclination of the dunes, transitioning from steep to gentle slopes. This observation is based on a comparative analysis of the cross-sectional topography across different monitoring areas. The presence of artificial structures has led to a constrained growth of vegetation due to alterations in the coastal topography. However, these revetments also act as barriers against wind movement, effectively preventing wind-carried debris from moving inland and accumulating in these areas (**Fig. 3.6**).

Adjacent to Area 1 is a developed parking lot, which significantly reduces the vegetation coverage compared to Area 2. Despite the reduced vegetation, Area 1 still experiences a substantial amount of litter accumulation, particularly noticeable during winter data collection. This suggests that factors other than vegetation, possibly human activity related to the parking lot, contribute to the debris accumulation in this area. Area 2 has retained much of its natural coastal features, including extensive plant communities covering most of the backshore. This vegetative cover correlates with the accumulation of debris within these communities, indicating the role of vegetation in trapping and retaining marine debris.

Area 3, being more heavily influenced by human activities, displays a more complex pattern of litter distribution. During summer, it is challenging to establish a definitive pattern due to the variability in human usage and activities. However, in winter, the majority of the garbage tends to concentrate on the backshore. This seasonal trend is likely influenced by prevailing winds. The absence of substantial plant communities in this area suggests that the debris is more prone to being carried along the inlet and moving directly inland, unimpeded by vegetation barriers. This analysis underscores the intricate interplay between human activities, natural vegetation, and seasonal factors in shaping the distribution of marine debris along the coast.

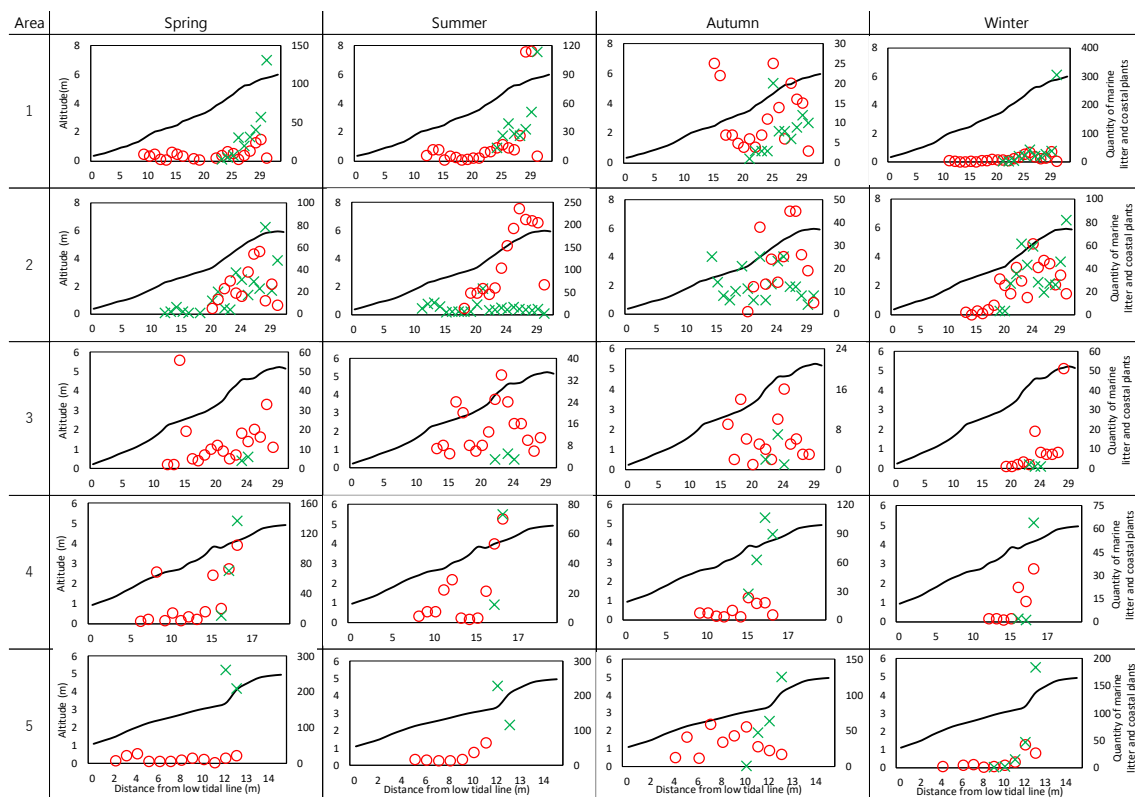
Coastal plants play a crucial role in preserving the topography of coastal dunes due to their ability to mitigate wind effects and stabilize sand. This ecological function is particularly evident when comparing the Niginohama and Nagahama Coasts. The Niginohama Coast maintains a higher degree of natural integrity, especially in terms of beach area, compared to the Nagahama Coast.

In the monitoring area of the Niginohama Coast, vegetation predominantly covers the backshore, with Area 1 showcasing extensive vegetation coverage. This large plant community acts as an effective barrier against marine debris, leading to a significant accumulation of litter within the interior of the community. The interdependence between dune topography and plant communities is a key aspect of this coastal region.

Area 2, characterized by a higher sectional height, forms a natural transition from the backshore to the hills. The plant community here not only serves as a barrier to wind but is complemented by the hills,

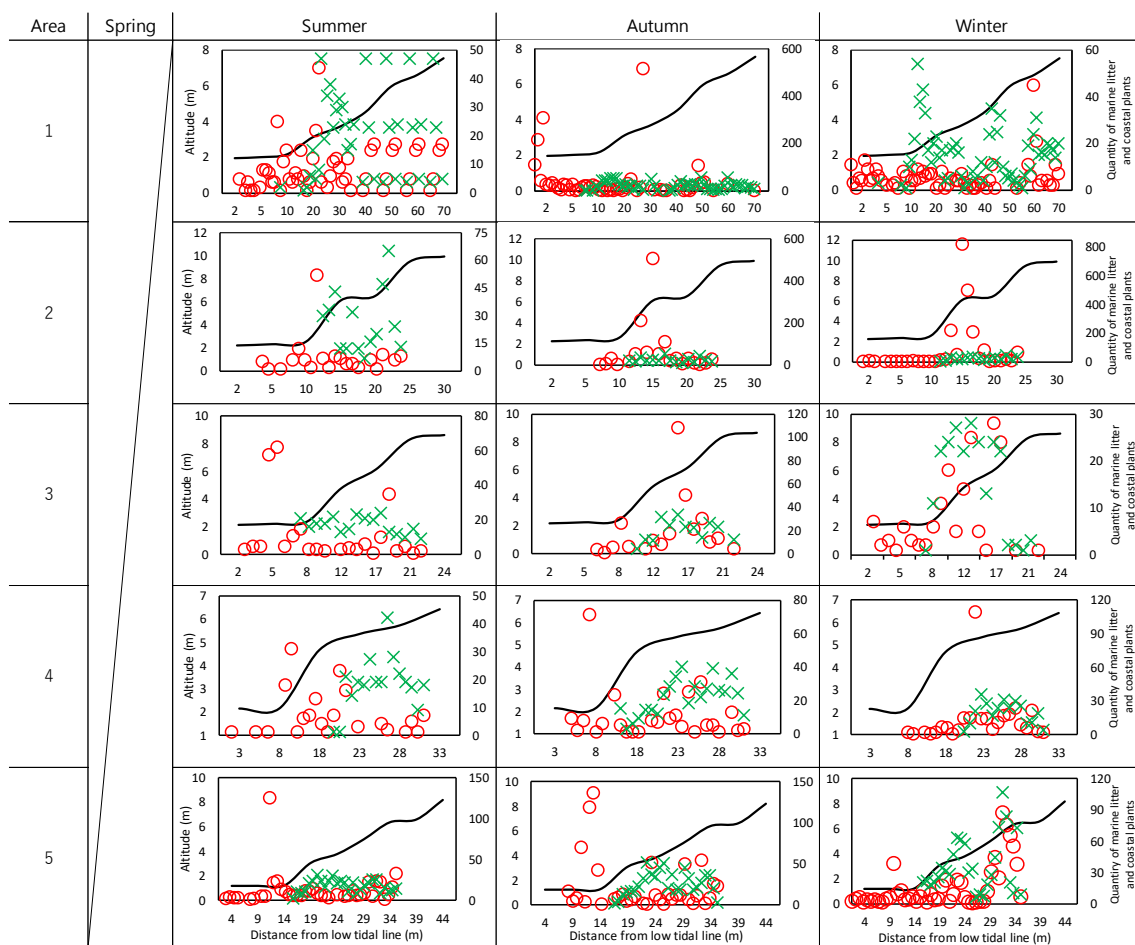
which act as an even more robust 'wind-blocking board.' This natural structure proves particularly effective against the seasonal winds common in winter, preventing litter debris from penetrating inland and resulting in most debris accumulation along the beach.

In Areas 3 and 4, debris is commonly found within the plant community and along the tide line, with Area 3 experiencing a higher overall litter presence. The influence of human activity is more pronounced in Area 5, located near the coastal entry. This area sees an increased accumulation of debris, particularly around the coastal breakwater, where a modest peak in litter concentration is observed. This pattern underscores the impact of human interaction with the coastal environment and its influence on debris distribution.



○ The number of marine debris; x The cover of coastal plants.

Fig. 3.6 Seasonal distribution of marine debris and coastal plants along the coastal section of Nagahama Coast



○ The number of marine debris; x The cover of coastal plants.

Fig. 3.7 Seasonal distribution of marine debris and coastal plants along the coastal section of Niginohama Coast

Coastal plants, predominantly perennial and herbaceous, exhibit relatively stable coverage throughout the seasons, largely unaffected by seasonal changes. Their well-developed and robust root systems are instrumental in maintaining dune topography. In contrast, terrestrial plants often undergo significant seasonal changes, such as leaf fading and considerable fluctuations in coverage. However, it is important to note that the study only conducted a single measurement of coastal topography. In reality, the topography of coastal regions is subject to local variations influenced by both climatic conditions and human activities.

For instance, seasonal wind movements, often intensified by near-shore currents, can elevate the high tide line, while long-term coastal erosion plays a crucial role in shaping shoreline topography. During the investigation on the Niginohama Coast, it was observed that some backshore areas were undergoing construction during the fall survey period (**Fig. 3.7**). This construction, which included the installation of fencing, resulted in significant alterations to both the coastal topography and vegetation

due to the inherently unstable nature of the sandy terrain.

Furthermore, development activities in the backshore areas were noted both before and after the fall survey date, indicating ongoing human impact on the coastal environment. Additionally, the topographic survey conducted on the Niginohama Coast involved fewer survey points compared to the Nagahama Coast, leading to unnatural variations in slope measurements. This discrepancy highlights the importance of comprehensive and consistent data collection in accurately assessing and understanding the dynamic nature of coastal topographies.

3.4 Composition of marine debris on Nagahama Coast and Niginohama Coast

At both survey locations, foam debris emerged as the predominant type of litter, followed closely by hard plastic and plastic packaging debris. Additionally, two main categories of litter were identified: those related to fishing activities and domestic waste (**Fig. 3.8**). Notably, the Niginohama Coast exhibited a higher percentage and quantity of litter associated with fishing compared to the Nagahama Coast. Specific types of fishing-related debris, such as fishing ropes and oyster culture tubes, were frequently found. The prevalence of oyster culture tubes can be attributed to inadequate management of waste from nearby oyster farms.

In contrast, the Nagahama Coast, which is in proximity to recreational facilities, showed a seasonal variation in litter quantity. There was a noticeable increase in litter during the summer months, likely correlated with the influx of visitors. Conversely, the Niginohama Coast experienced a significant rise in marine debris during the winter, possibly linked to seasonal wind movements that transport debris to the shore.

If these two sites are representative of the wider Itoshima Peninsula, it can be inferred that over 95% of the debris is composed of plastic materials. However, this part of the data presents several challenges. Collecting and counting litter on-site during field surveys is not only labor-intensive and time-consuming but also requires meticulous evaluation of the data's accuracy. This is particularly true for small-sized debris, where the impact of various unforeseen factors can significantly influence the results. Therefore, while the findings provide valuable insights into the types and quantities of litter present, they also highlight the need for cautious interpretation and validation of the data, considering the complexity and variability of environmental factors.

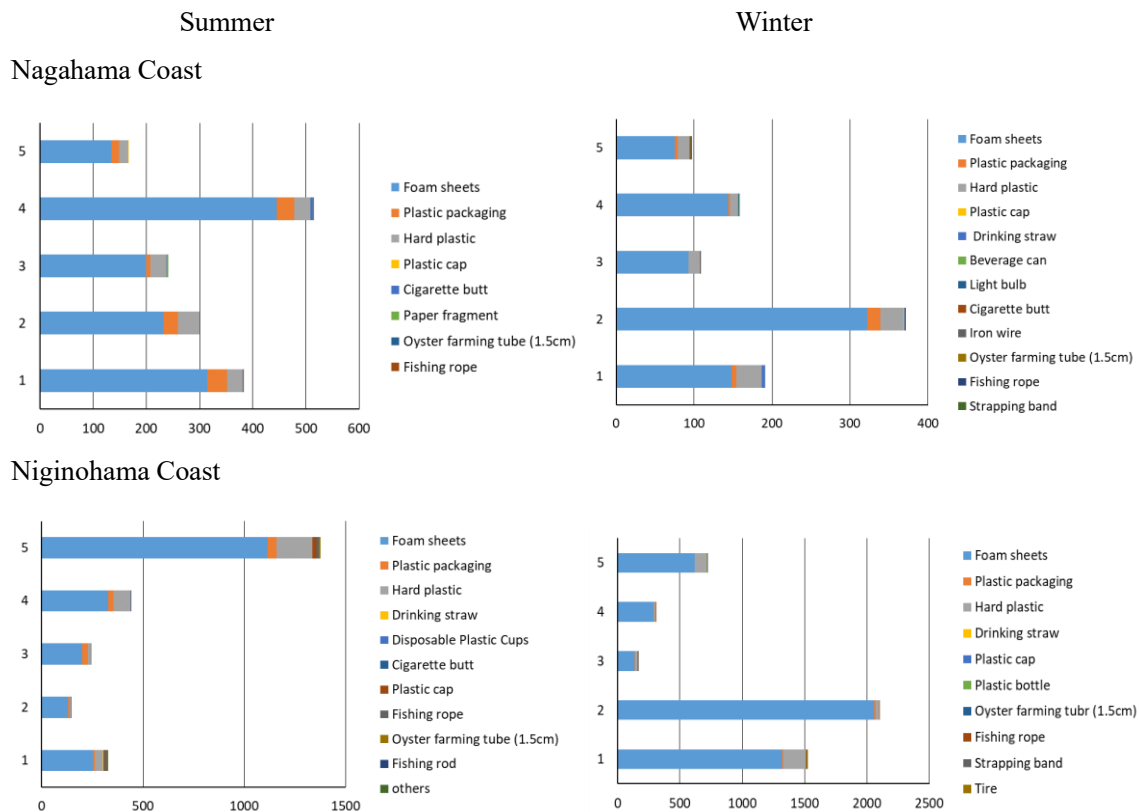


Fig. 3.8 Composition of marine debris on Nagahama Coast and Niginohama Coast

3.5 Summary

The coasts of Niginohama and Nagahama, while naturally formed, have experienced varying degrees of impact from human activities. The majority of these anthropogenic activities, aimed at benefiting human society, have inadvertently caused damage to the ecosystem and landscape. This damage includes the construction of artificial infrastructures and the physical trampling of the coast. The survey conducted across all seasons, with a particular focus on summer and winter, provided a comprehensive understanding of how litter distribution and plant life vary seasonally. This seasonal approach to data collection enriched the study, offering clearer insights into the dynamic interplay between natural and human-induced changes along the coast.

Given the diverse array of coastal plant species on the Itoshima Peninsula and their differing influences on dune topography and debris distribution, a focused examination of a few dominant plant populations could yield more controlled and insightful results. By narrowing the scope to these key populations, the study could more effectively isolate and analyze the specific effects of various plant species on the coastal environment.

Plastic remains the predominant form of debris, originating from both household waste and fishing-related activities. To enhance the understanding of coastal litter, future research could delve into the

sources of litter accumulation along the coast and the specific composition of plastic litter. Such an investigation would provide valuable data for devising more effective strategies for managing and mitigating the impact of coastal litter, particularly plastic, on the environment. This approach aligns with the broader objective of understanding and preserving the delicate balance of coastal ecosystems amidst ongoing human activities.

Chapter 4 Estimation of the origin of marine debris accumulated on the coast: Morphological, elemental, and compositional analysis of debris samples collected on the western coast of Kyushu, Japan

4.1 Introduction

Addressing the issue of marine debris necessitates a focus on reducing debris formation at its source. Understanding the origins of marine debris is crucial and can be broadly categorized into geographical sources and human-induced causes. For larger fragments of marine debris, identifying the original product and its source is relatively straightforward. However, the task becomes more challenging with micro-debris, which often lacks visible surface characteristics that could aid in source identification. Foam debris, particularly prevalent along Japan's coast, poses a significant environmental burden. According to 2015 data, 140,000 tons of foamed products were produced, with 127,000 tons undergoing recycling. Despite these efforts, approximately 10% of foamed waste remains unrecycled in the environment. Due to its loose and porous structure, foamed litter easily breaks down into granular debris under environmental conditions, a process known as weathering. Common sources of this debris include insulated fisheries shipping containers, food containers, and packaging materials for domestic products.

In this study, a combination of morphological and compositional methodologies was employed to analyze the debris, with a particular focus on hard plastic shards. These shards pose a unique challenge as their original items are often difficult to ascertain. By utilizing these methodologies, the study aimed to provide a more comprehensive understanding of the composition and potential sources of these hard plastic fragments, thereby contributing to more effective strategies for managing and mitigating marine debris.

The utilization of an energy-dispersive X-ray analyzer is pivotal in determining the elemental composition of sample surfaces, thereby facilitating the identification of inorganic additives present on plastic surfaces. This tool aids in speculating about the constituents of the plastics, which can be crucial for understanding their environmental impact. Additionally, the morphological method employs a low-vacuum, high-sensitivity scanning electron microscope to assess the degree of weathering on the sample surfaces. This method provides high-resolution images that reveal the extent of degradation and surface changes the samples have undergone.

Furthermore, the compositional approach involves the use of a Fourier Transform Infrared Spectrophotometer. This instrument compares the spectra generated by the chemical bonds within the polymer to standard sample spectra, effectively determining the polymer's composition. This technique is essential for identifying the specific types of plastics and understanding their potential environmental effects.

Marine debris, influenced by ocean currents and wind movement, accumulates along shorelines,

including areas such as the Goto Islands, Tsushima Island, and Hakata Bay. This accumulation results in pollution that adversely affects the natural environment and reduces the appeal of coastal areas for tourism and sightseeing. Over time, long-term weathering causes marine debris to break down into smaller fragments, leading to secondary pollution. This fragmentation not only complicates the cleaning and recycling efforts of coastal debris but also releases toxic inorganic substances. These substances pose a significant threat to the health of coastal ecosystems and organisms, highlighting the urgent need for effective management and mitigation strategies to address the issue of marine debris.

4.2 Marine debris sampling methods for various types of coasts

Marine debris sampling across the coasts in the Kyushu region employs a variety of techniques, tailored to the specific types of coastlines encountered. To effectively conduct these samplings, understanding the nature of each coastline is essential. Generally, the coastlines in this region can be categorized into two primary types: artificial and natural. Additionally, these coastlines are further characterized by their composition, which includes gravelly, pebble, and sandy beaches.



Fig. 4.1 Marine debris sampling on the foreshore (left) and backshore (right)

The methodology for marine debris sampling varies significantly between artificial and natural sandy coasts due to their differing ecological and physical characteristics. Artificial sandy coasts: On artificial sandy coasts, where plant growth is often hindered by regular coastal maintenance, sampling points are specifically set at the foreshore low tidal line and the backshore zone (**Fig. 4.1**). These areas are targeted as they are likely to accumulate litter due to human activities and natural tidal movements.

Natural sandy coasts: Conversely, natural sandy coasts, characterized by finer grain sizes (less than 2 mm), typically feature plant communities in the backshore zone. The coastal slope on these beaches is divided into high and low slopes. Litter concentration is frequently observed at the low tidal line of the foreshore, along the boundary of plant growth in the backshore zone, and within the internal areas of these plant communities.

Beaches composed of gravel and pebbles, with grain sizes larger than 2 mm, develop distinct slopes due to wave action. However, as marine debris on these beaches tends to be more dispersed, sampling points are randomized to capture a representative distribution of litter. When a large quantity of litter is found, samples are sorted, and photographed, and large garbage items exceeding 10 cm are immediately recorded. The remaining debris is collected for laboratory analysis (**Fig. 4.2**). For samples containing smaller quantities of garbage, all material, including surface sand, is taken back to the laboratory for examination. To ensure accurate documentation, sampling bags are meticulously labeled with the date, location, and sample number. This rigorous approach ensures that the data collected is both comprehensive and reliable, facilitating a thorough understanding of marine debris distribution along these coasts.



Fig. 4.2 Gathering samples of marine debris and beach sand at the surface

4.3 Distribution of marine debris in Hakata Bay, Tsushima Island, and Goto Islands

To investigate the composition and sources of marine debris along Hakata Bay, Tsushima Island, and the Goto Islands, a comprehensive study was conducted involving the visual categorization and

analysis of the surface morphology, elemental composition, and overall composition of marine debris. This study encompassed a total of eighteen shorelines across these three areas, with data collection taking place in September 2021 and during June/July 2022.

The timing of the sample collection at each site was strategically determined based on several factors. These included the local knowledge from Tsushima Island and the Goto Islands, where there is a high incidence of marine debris during the summer months. Additionally, the climatic patterns of the Fukuoka area, particularly its vulnerability to typhoons around September, were taken into account. The insights gained from a pre-survey conducted on the Itoshima Peninsula also informed the timing of the sample collection.

The sampling locations were carefully chosen to represent areas where floating debris is most likely to accumulate. Samples were collected along the low tidal line, a typical gathering point for floating debris. Additionally, areas at the intersection of coastal plant communities and within the communities themselves along each coast were sampled, in response to the findings from the Itoshima Peninsula research.

Figure 4.3 in the study provides a detailed illustration of the Tsushima Current flow near Tsushima Island and the Goto Islands. It also depicts the direction of seasonal wind movement near Hakata Bay. This visual representation aids in understanding the potential pathways and accumulation zones of marine debris, offering valuable insights into the dynamics of marine debris distribution in these coastal regions.

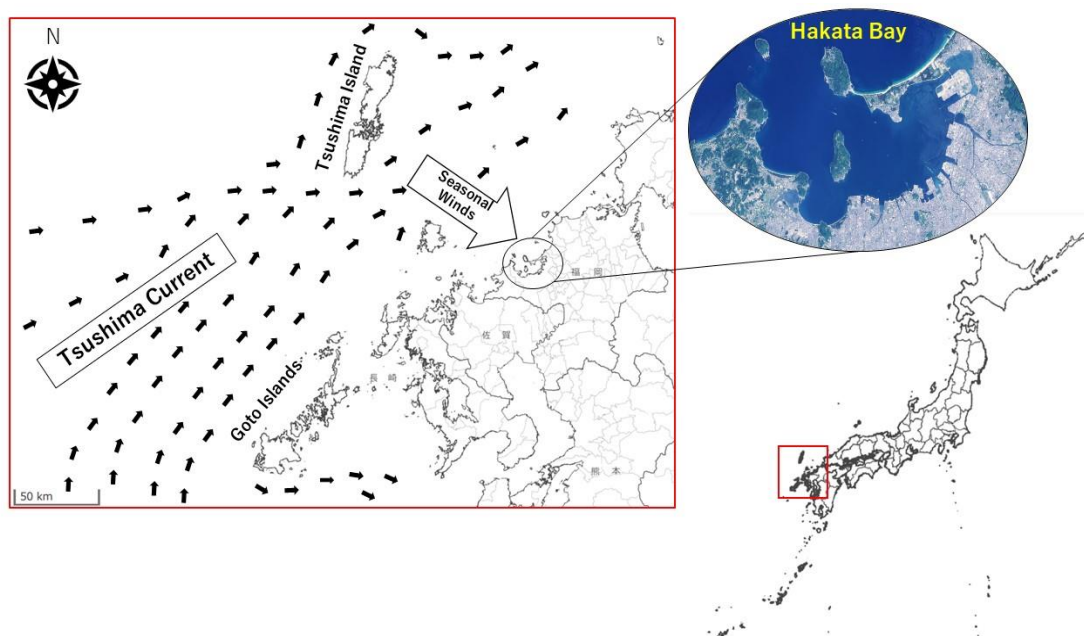


Fig. 4.3 Sampling sites of Hakata Bay, Tsushima Island, and Goto Islands

A comparative analysis of data from artificial coasts (locations S2, S4, S6, S7) and natural coasts (locations S1, S3) highlighted that the frequency of cleaning efforts on artificial coasts played a significant role in the amount of litter accumulation. This suggests that human intervention in the form of regular cleanups can effectively reduce marine debris in these areas.

In terms of debris composition, there was a higher percentage of foam-type fishery-related garbage near the mouth of the bay. This increase could be attributed to several factors, including the possibility of waste input from overseas, the concentration of fishing vessel docking areas in the surrounding fishing ports, and other related activities.

Conversely, in the inner bay near the metropolitan region, where there is a dense population and a high level of urban development, household garbage was more prevalent (**Fig. 4.6**). This type of debris is likely carried to the shore by rivers or left behind directly at the location. The significant presence of hard plastic debris at locations S4, S6, and S7 could be attributed to a combination of factors: the presence of small particles that are difficult to recycle, residual sand from beach maintenance activities, and potential plastic material leakage during maritime transit. These findings underscore the complex interplay of environmental, geographical, and human factors in the distribution and composition of marine debris in Hakata Bay.

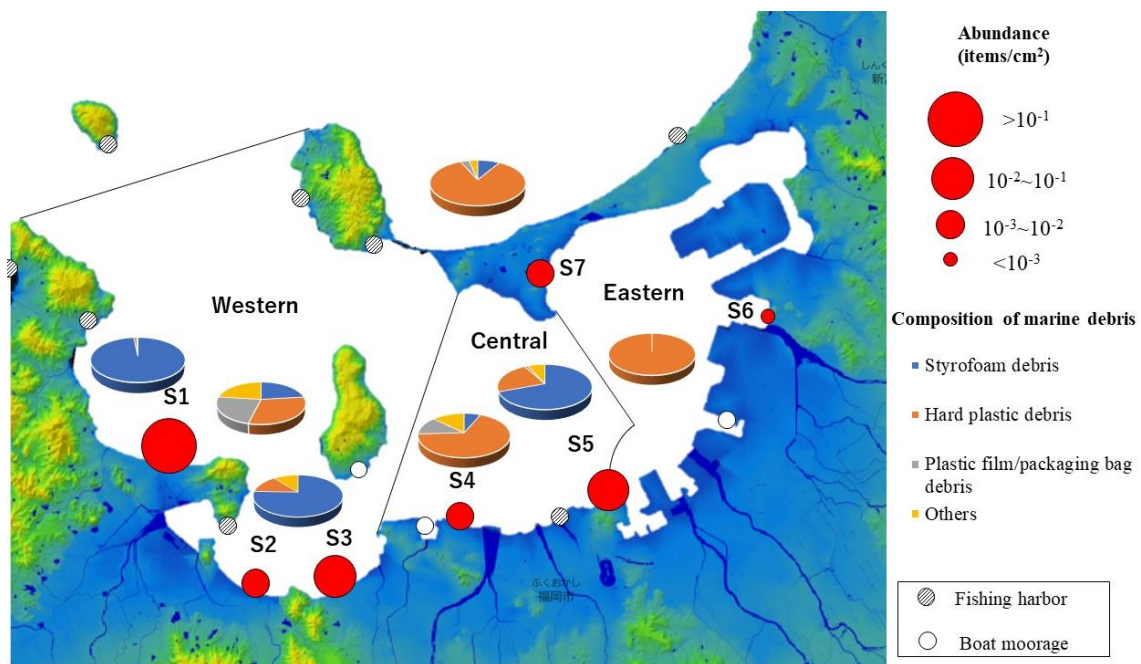


Fig. 4.5 Distribution of marine debris along Hakata Bay

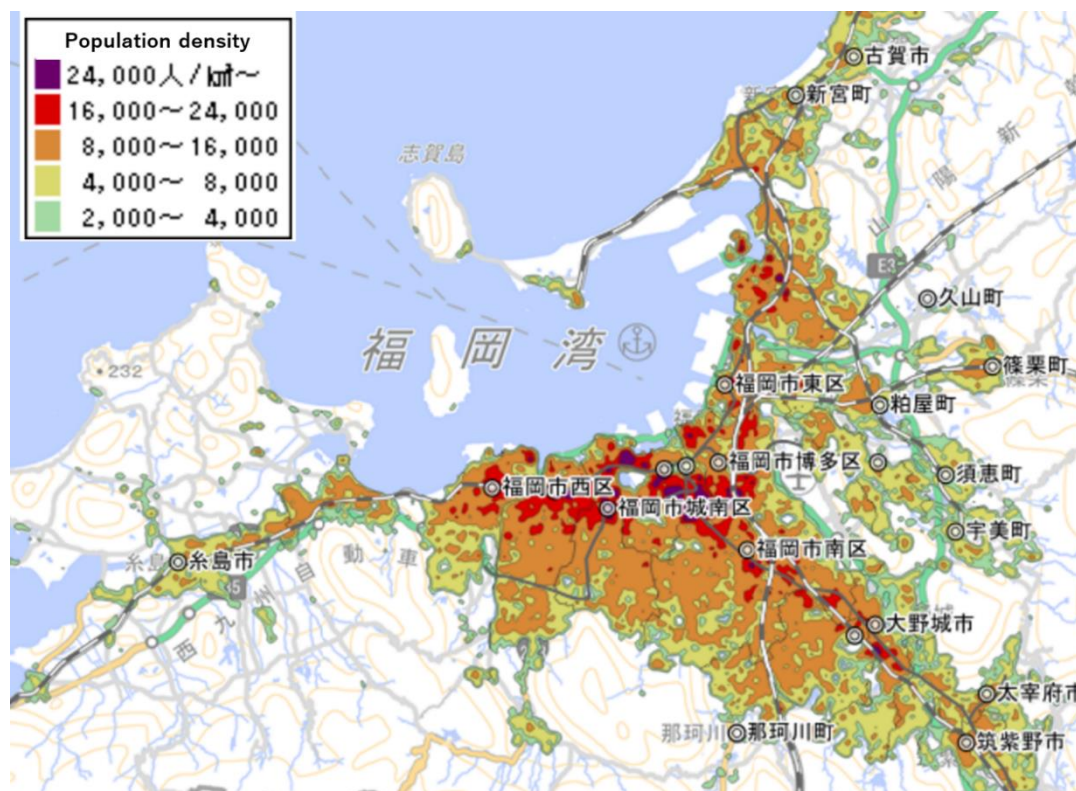


Fig. 4.6 Population density distribution along Hakata Bay

The distribution of marine debris along Tsushima Island's coastline exhibited a marked disparity in debris abundance between the northern (S1, S2) and southern ends (S3, S4, S5), with notably higher quantities observed in the north. Additionally, the proportion of foam debris was exceptionally high in these northern areas. The considerable accumulation of debris at location S2 could be attributed to the formation of current eddies influenced by the Tsushima Current, which flows through this region. The patterns observed in the distribution of marine debris are detailed in **Figure 4.7** of the study.

The movement path of the Tsushima Current plays a significant role in debris accumulation, particularly influencing the type of litter that gathers along the coast. Consequently, the proportion of fishery-related garbage was found to be higher on the western side of Tsushima Island compared to the eastern side. In contrast, the southern area exhibited a higher proportion of domestic debris than the northern part. These variations in debris abundance and composition between the north and south of the island may be linked to the level of urban development and the distribution of population density, as depicted in **Figure 4.9**.

An intriguing aspect of the study was the identification of the origins of some of the fishery-related debris. A considerable portion of the floats collected in S1, S4, and S5 were traced back to the Zhejiang (blue) and Guangdong (orange) regions of China. Furthermore, a significant number of large plastic drums, likely ship's oil drums from South Korea, were discovered along the coast of S5. This finding

suggests that a substantial amount of the fishery-related debris is cross-border marine debris, as illustrated in Figure 4.7. These insights highlight the transboundary nature of marine pollution and underscore the need for international cooperation in addressing the issue of marine debris.

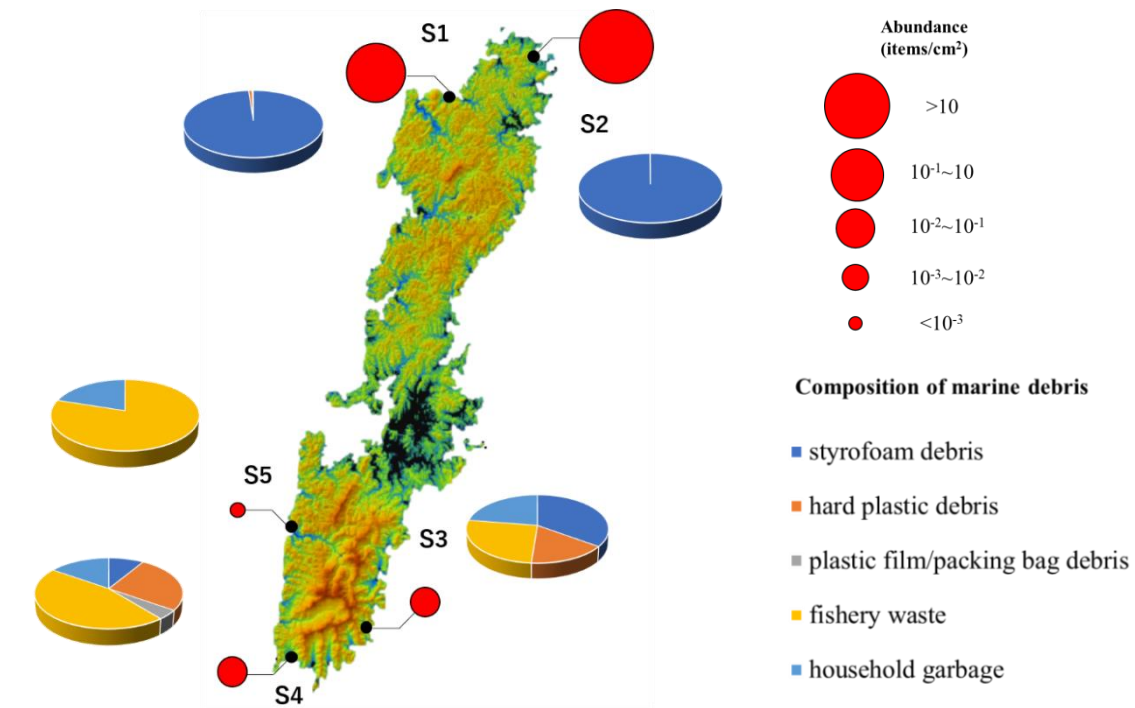


Fig. 4.7 Distribution of marine debris on Tsushima Island

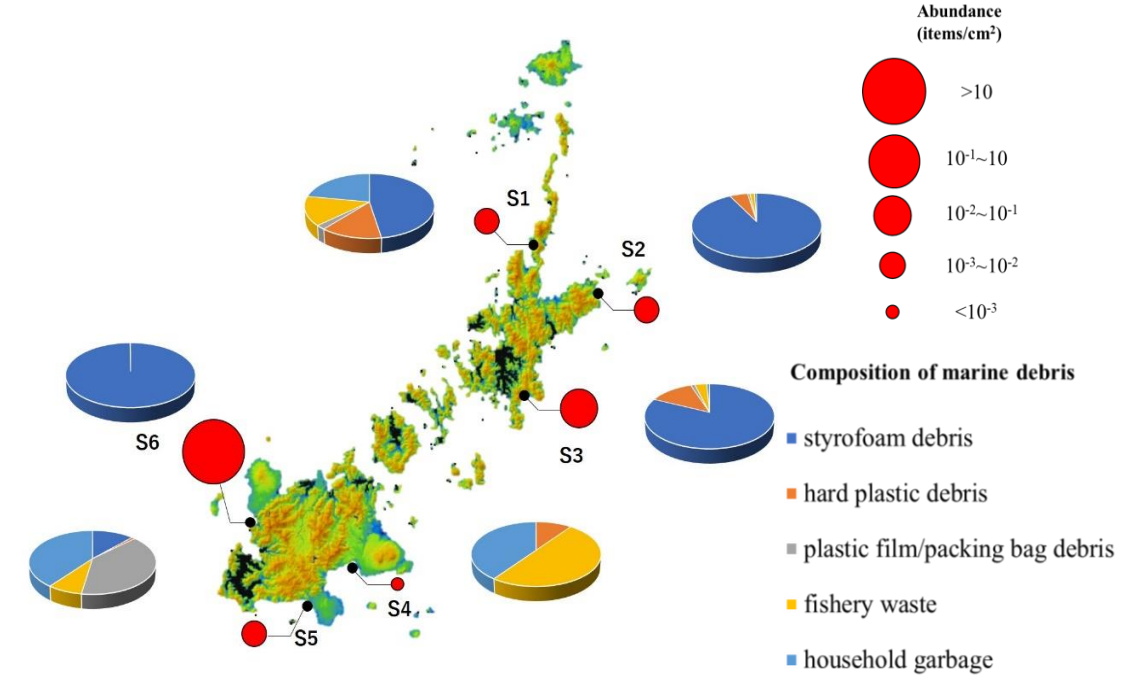


Fig. 4.8 Distribution of marine debris on Goto Islands

The accumulation patterns of marine debris along the shores of the Goto Islands indicated distinct spatial variations. Specifically, S6, situated directly in the path of current movement, experienced a higher likelihood of marine debris accumulation compared to S4, which recorded the lowest abundance of debris. This distribution pattern is detailed in the data gathered from the sampled shores of the Goto Islands (**Fig. 4.8**).

A notable observation was the high percentage of foamy debris at S2 and S3. Coupled with the results of the litter composition analysis, this suggests that the fishery litter in this area might be attributed to cross-border litter or potentially inadequate waste management practices at coastal fisheries farms located across the continental divide. The prevalence of household litter at S4 and S5 was also noteworthy and could be linked to the increased distribution of population density in these areas.

Another significant finding was the origin of many of the floats found at S1 and S6. The majority of these floats were identified as originating from the Zhejiang and Guangdong provinces of China. This evidence, combined with the statistical data on the floats used for fishing on the two islands, points to a substantial likelihood of cross-border litter from these Chinese provinces entering Japan. The root cause of this issue may stem from inadequate waste management practices in these regions. This hypothesis is supported by the data and is visually represented in Figure 4.8 of the study. These findings highlight the transnational challenges of marine debris management and underscore the need for collaborative efforts in addressing marine pollution across borders.

In addition to foamed debris, a detailed analysis of various types of domestic and fishery-related waste collected from the shores of Tsushima Island and the Goto Islands revealed a notable pattern. Fishing ropes were a predominant component in the fishery waste category, consistently found in significant quantities on all the studied beaches. This prevalence of fishing ropes in marine debris underscores their common usage and potential for disposal in these coastal regions.

Furthermore, the study found that food containers and plastic packaging constituted the majority of domestic waste. The predominance of these items can be attributed to their relatively short lifespan and frequent use in household settings. The disposable nature of such items, coupled with their widespread usage, contributes to their significant presence in the marine debris composition. This finding is visually illustrated and further elaborated in **Figure 4.10** of the study.

These insights into the composition of marine debris on Tsushima Island and the Goto Islands highlight the specific types of waste that contribute most to the marine debris problem. Understanding the composition of marine debris is crucial for developing targeted strategies for waste management and reduction, particularly in coastal and marine environments.

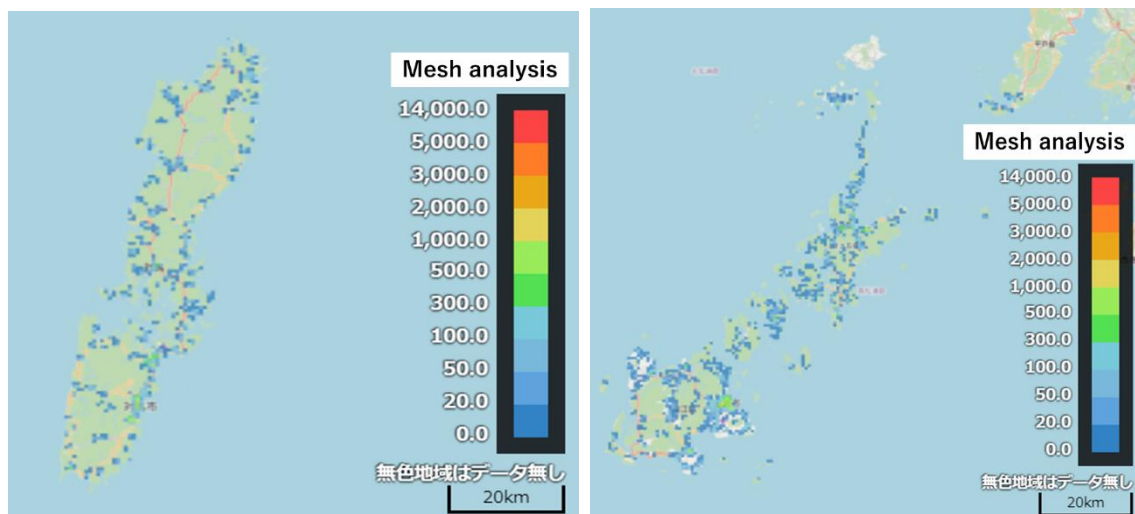


Fig. 4.9 Population density distribution on Tsushima Island (left) and Goto Islands (right).

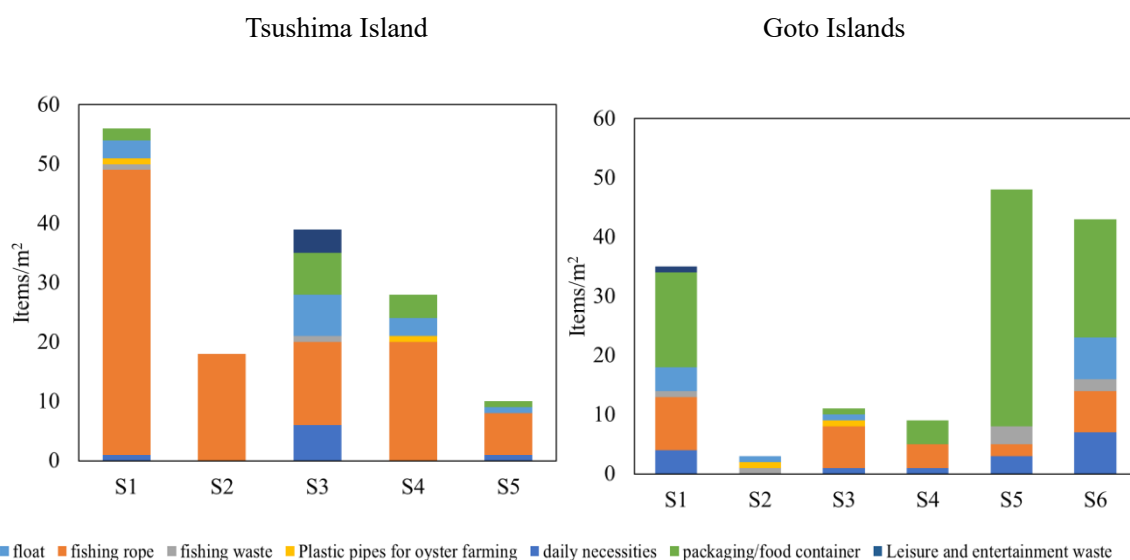


Fig. 4.10 Sub-segmentation of fishery-related waste and domestic items composition

An extensive geographic origin investigation of PET bottles was conducted on the beaches of Tsushima Island and the Goto Islands, areas noted for a significant accumulation of such debris. The majority of the collected PET bottles retained their original product information, including labels with words, codes, barcodes, QR codes, etc. The recycling labels on plastic bottles in Japan and other countries are essential elements of their respective recycling frameworks, yet they demonstrate distinct characteristics. In Japan, the labeling system is meticulously detailed, featuring the 'PET bottle' designation and a triangle of arrows encompassing the number '1', signifying the bottle is made of polyethylene terephthalate (PET). These labels are accompanied by comprehensive instructions, including directives for label and cap removal, underpinned by an organized collection infrastructure

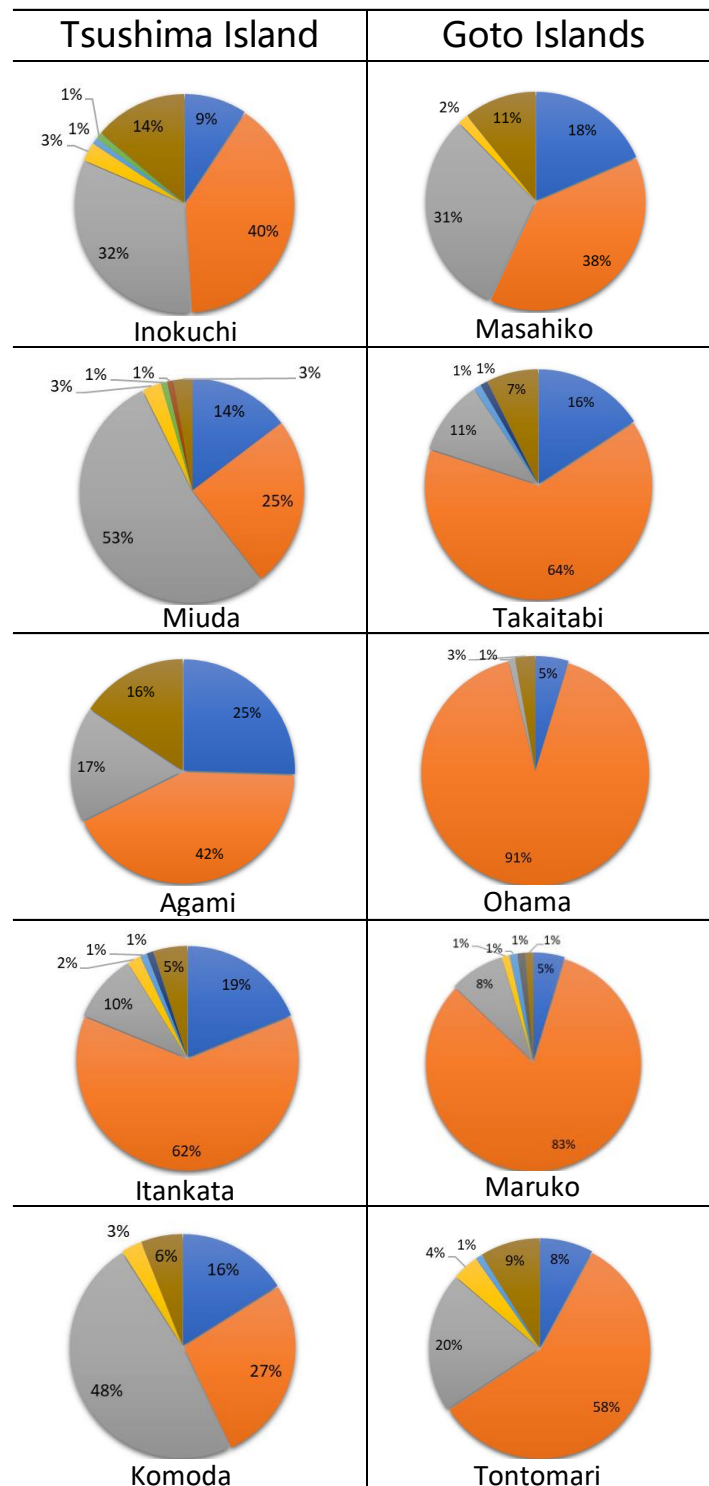
and robust legal regulations, fostering active consumer engagement and a strong commitment to environmental conservation. Conversely, in various other countries, the predominant labeling feature is the Resin Identification Code (RIC), which classifies the type of plastic by a numeral within the recycling symbol. The extent of recycling instructions and the nature of collection systems differ markedly, ranging from minimal to elaborate guidance and from color-coded bin systems to single-stream recycling approaches. These labels are pivotal in guiding populace behaviors towards effective recycling practices, reflecting each country's unique infrastructure and environmental policy frameworks. This information proved crucial in tracing the geographic origins of the products. For this part of the survey, approximately 100 samples were collected from each coast, with the country of origin being meticulously recorded for each sample (Fig. 4.11).

In cases where samples fell into the "other" category, their origins could not be determined due to insufficient or unclear labeling information. The analysis revealed that the primary sources of cross-border marine debris, in this case, are South Korea and China. Given the geographic proximity and the Korea Strait being the only physical separation, Tsushima Island exhibited a higher proportion of plastic bottles originating from South Korea compared to the Goto Islands. Conversely, the Goto Islands had the highest percentage of PET bottles traced back to China (Fig. 4.12).

Countries in Southeast Asia, particularly Vietnam, represented a smaller but significant portion of the origins of these PET bottles. Intriguingly, the study also considered the improbability of plastic bottles from South Africa and Russia reaching Japan's coastlines solely through global ocean currents, given the distance and prevailing oceanic flows. Instead, these bottles were more likely discarded by ships traveling the seas before arriving in Japan. This hypothesis suggests a different pathway for marine debris, emphasizing the role of maritime activities in the global spread of plastic pollution.



Fig. 4.11 Traceability investigation method of PET bottle production country



■ Japan ■ China ■ Republic of Korea ■ Vietnam ■ Malaysia ■ Indonesia ■ Philippines ■ Russia ■ South Africa ■ Others

Fig. 4.12 Country-specific composition of PET bottles in Tsushima Island and Goto Islands

4.3 SEM-EDX analysis results

The analysis of microplastic samples revealed the presence of spherical plastic microbeads, predominantly in white or transparent hues, commonly employed in the production of plastic products (Fig. 4.13). These primary-source plastics exhibit signs of degradation, with certain microbeads displaying yellow discoloration. Microscopic examination of these microbeads reveals a rough surface morphology, characterized by an array of features including holes, fissures, and other irregularities. Additionally, a small fraction of these microbeads are dark green, though their specific purpose remains indeterminate.

Further investigation using high-definition electron microscopy uncovered a variety of degradation morphologies in other hard plastic samples. These include the presence of holes, fractures, bulges, and grooves. Moreover, foamed plastic samples were observed to undergo weathering processes, evidenced by dents and splits, and display unique morphologies resembling fish scales and honeycombs (Fig. 4.14, 4.15).

The sample set also included plastic layer casings, typically utilized in agricultural layer fertilizers. These casings play a crucial role in the gradual dissolution of fertilizer components. For example, the application of coated fertilizers during spring obviates the need for summer fertilization, thereby reducing labor. However, once utilized, these coating casings can migrate from agricultural fields into marine ecosystems, thus contributing to environmental pollution. Conversely, the efficient release of fertilizer as crops grow minimizes the total amount of fertilizer required. This controlled dissolution significantly mitigates the leaching of nutrients into groundwater and other water bodies, thereby diminishing the environmental impact. This dual aspect of coated fertilizers highlights both their utility in agricultural efficiency and their potential role as environmental pollutants.

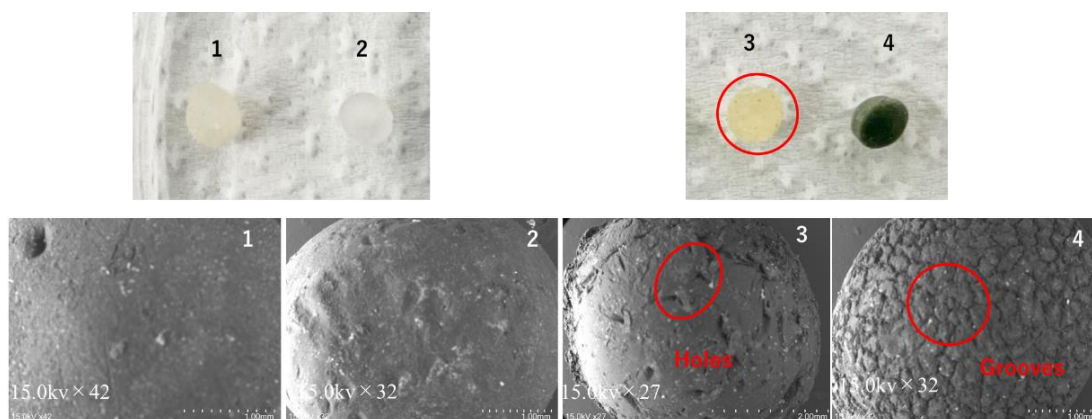


Fig. 4.13 Primary source of microplastics- Raw material for plastic products (pellets)

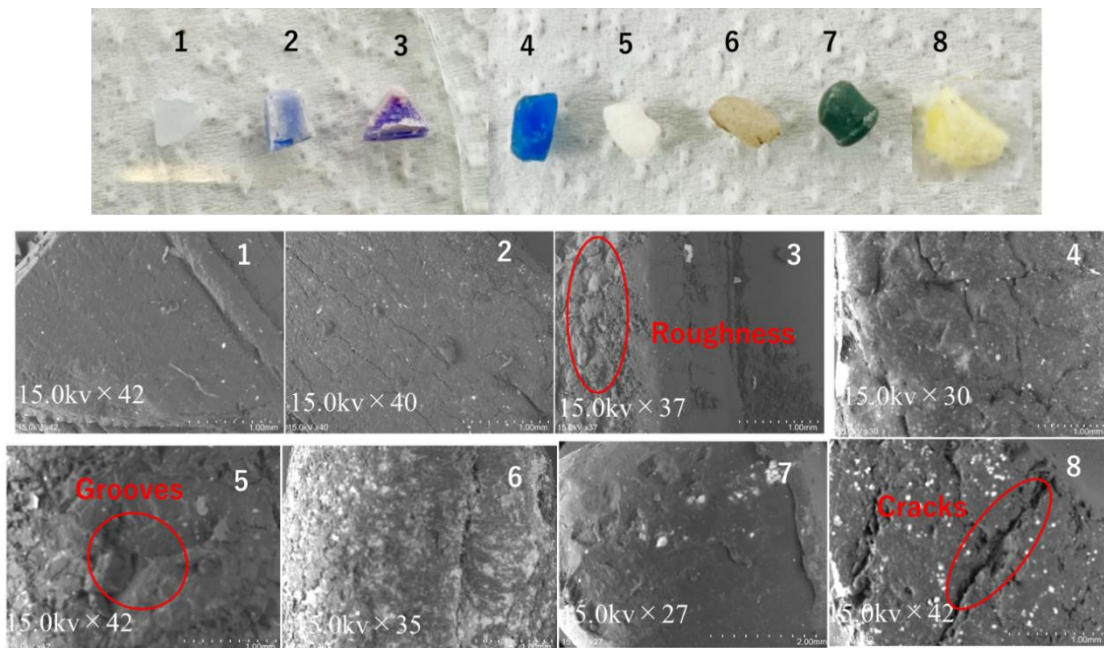


Fig. 4.14 Secondary source of microplastics– Physical fragmentation of hard plastic debris

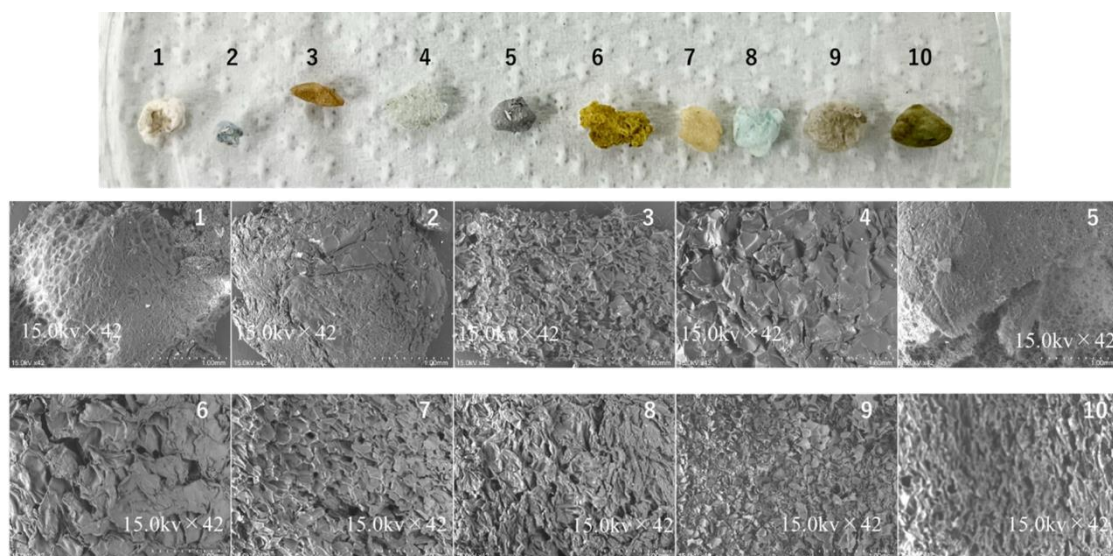


Fig. 4.15 Secondary source of microplastics– Physical fragmentation of foam debris

The sample under study also encompassed a variety of everyday items, both plastic and non-plastic. This assortment included items such as fragments of glass, cigarette filters, rubber bands, plastic label fasteners, plastic films, and plastic sheets commonly used as separators in lunch boxes. Over an extended period, these items are subject to considerable weathering and deterioration. This process leads to their fragmentation into minute particles, which can be termed 'micro-garbage.' These particles, significantly reduced in size and altered in appearance, become unrecognizable compared to their original forms. This transformation poses a substantial challenge in the realm of recycling and

waste management (**Fig. 4.16**).

As these fragments lose their identifiable features, they complicate the recycling process. Their small size and altered state make it difficult to classify and process them effectively as recyclable materials. This issue emphasizes the need for advanced and more sophisticated approaches in waste management, especially tailored to address the recycling of products that degrade into micro-garbage. Such approaches are crucial in mitigating the environmental impact of waste and improving recycling efficacy.

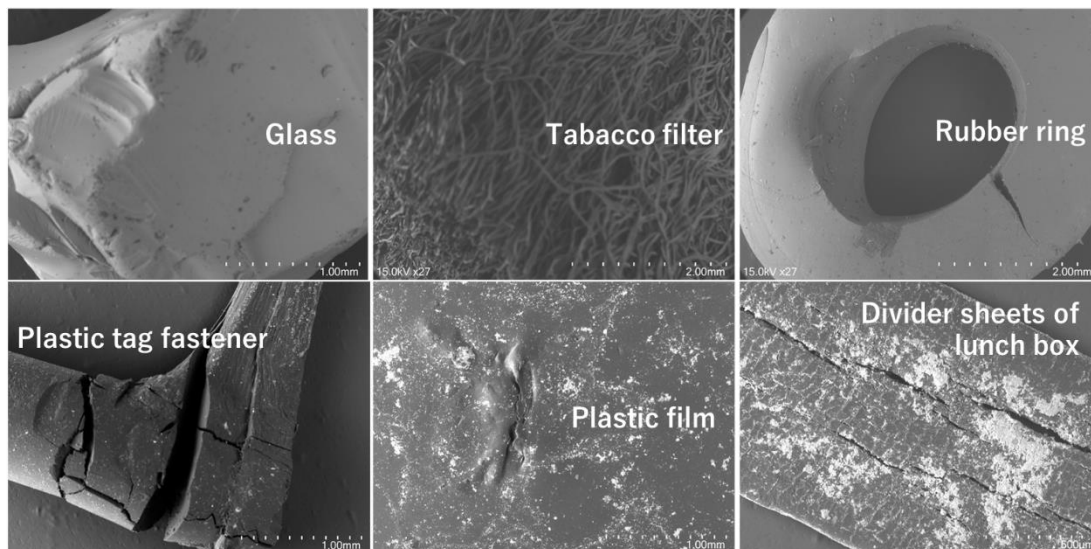


Fig. 4.16 Secondary source of microplastics– Physical fragmentation of domestic debris

The elemental analysis of the experimental samples often encountered interference from multiple environmental elements, primarily because the plastic samples underwent no pretreatment other than drying. To mitigate this issue, various groups of environmental background factors were established as controls to differentiate between these interfering elemental classes, as detailed in **Table 4.1**.

In addition to the sand collected from each shore, the samples included other environmental components such as driftwood, seaside plants, shells, and animal remains like crab pincers. The analysis of the control group revealed that the presence of carbon (C) and oxygen (O) elements is often attributable to organic matter, such as oil and grease, commonly found in the air. These substances can easily adsorb onto the surface of the samples, leading to contamination. Consequently, absorption peaks for C and O elements are frequently identified in the samples.

The use of carbon tape to stabilize the samples in the sample stage also contributes to the absorption peaks of C elements. Similarly, the use of an aluminum (Al) sample stage or glass substrate in Scanning Electron Microscopy (SEM) introduces a substrate signal for Al and silicon (Si) in the thinner portions of the sweep spectrum. The equipment itself may artificially produce a trace amount of corresponding energy regions for these elements.

Detecting rare elements, including lanthanides and actinides, is challenging due to the stronger noise

in their peak regions. The presence of copper (Cu) and chromium (Cr) in the sample detection components is typically attributed to trace elements found in the sample rod or chamber material. Extensive movement of the sample during the sweep or heating of the sample can enhance susceptibility to these absorption peaks. In some cases, a sudden increase in resolution results in a distinct peak for boron (B).

Overall, these findings highlight the complexity of elemental analysis in environmental samples, particularly when dealing with diverse materials and potential contaminants. Understanding these interferences is crucial for accurate interpretation of the results and for distinguishing between naturally occurring elements and those introduced through environmental contamination or the analysis process itself.

Table 4.1 Groups of environmental background factors

Coasts	Elements	C	O	Ce	Na	Mg	Al	Si	P	S	Cl	K	Bk	Ca	Fe
Naga	Blank sand	0	0		0	0	0	0				0		0	0
	Blank impurity(floated tree)	0	0		0	0	0	0		0	0	0		0	0
Tare	Blank sand	0	0		0	0	0	0				0		0	0
	Blank impurity(stone grain)	0	0		0	0	0	0		0	0	0		0	0
Iki	Blank sand	0	0		0	0	0	0			0	0		0	0
	Blank impurity(crab claw)	0	0	0	0	0	0	0	0	0	0		0	0	
Ata	Blank sand	0	0		0	0	0	0			0	0		0	0
	Blank impurity(shell fragment)	0	0		0	0	0	0	0	0	0			0	
Fuku	Blank sand	0	0		0	0	0	0			0	0		0	0
	Blank impurity(plant stem)	0	0		0	0	0	0	0	0	0			0	
Naji	Blank sand	0	0		0	0	0	0			0	0		0	0
	Blank impurity(shell fragment)	0	0		0	0	0	0	0	0	0		0	0	
Saito	Blank sand	0	0		0	0	0	0			0	0		0	0
	Blank impurity(plant leaf)	0	0		0	0	0	0		0	0		0	0	

A significant observation emerged from the comparison between the elemental composition of the blank control group and the interfering elements detected in the experimental environment. Specifically, titanium (Ti) was frequently identified in the surface elemental composition of various plastic debris collected from different shores of Hakata Bay (**Fig. 4.17**). The presence of titanium is likely attributable to titanium dioxide nanoparticles (TiO₂-NPs), commonly added to plastics during manufacturing. TiO₂-NPs serve as a white pigment and an ultraviolet-blocking agent, enhancing the degradation efficiency of plastics in natural environments.

However, there are environmental concerns associated with the breakdown of polymer composites containing TiO₂. As these composites degrade, they may release TiO₂-NPs into the environment. Such particles pose potential hazards to aquatic life, including fish, bacteria, algae, and invertebrates. Moreover, titanium dioxide is classified as a class 2B substance, which means it is possibly carcinogenic. The environmental impact of these nanoparticles is a critical consideration, especially given the high rate of degradation of plastics containing TiO₂.

Despite the advantages of using TiO₂-NPs in plastics for increased degradation efficiency, their potential to harm aquatic ecosystems and their classification as potentially carcinogenic substances

raise concerns about their widespread use. This dilemma underscores the need for careful consideration of the materials used in plastic production and the importance of assessing their long-term environmental impacts.

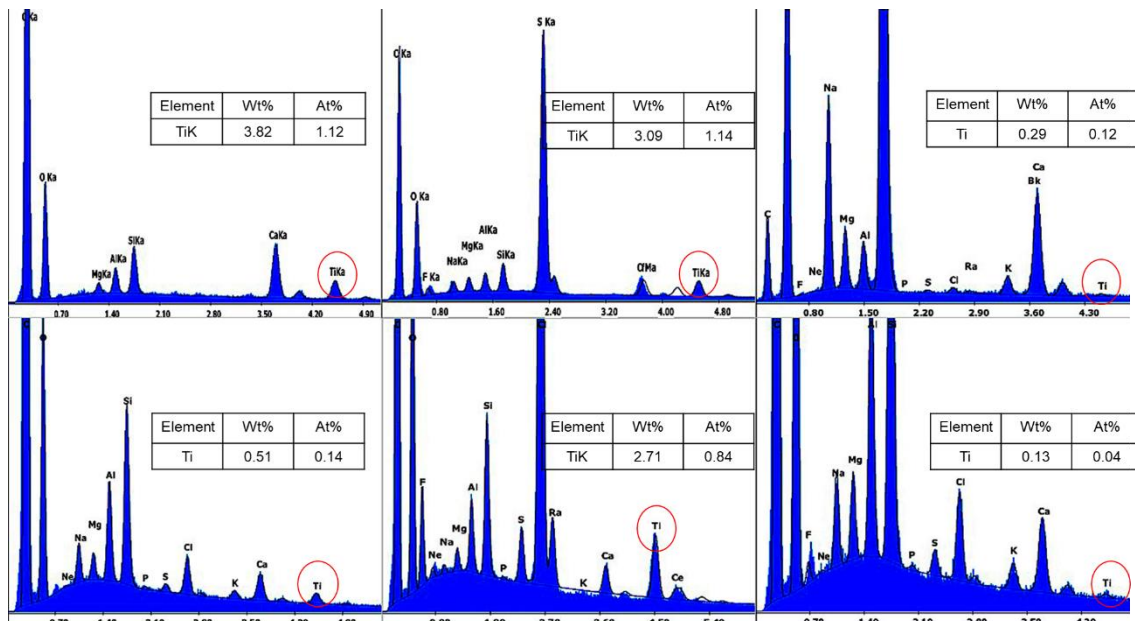


Fig. 4.17 Frequent presence of Ti in the surface elemental composition of plastic debris from various coasts

4.4 FT/IR analysis results

Fourier Transform Infrared Spectrophotometry (FT/IR) analysis of micro-plastic debris samples identified the primary constituents as polypropylene, high-density polyethylene (HDPE), and low-density polyethylene (LDPE), with polypropylene and HDPE being predominant (**Fig. 4.18**). The HDPE samples exhibited characteristic polyethylene absorption peaks in their infrared spectra. These peaks were observed at wavenumbers ranging from 2800–3000 cm^{-1} , 1400–1500 cm^{-1} , and approximately 700 cm^{-1} . Notably, a distinct absorption peak in the range of 1000–1100 cm^{-1} was identified, alongside a broader peak in the region of 3300–3400 cm^{-1} , which is indicative of the hydroxyl (-OH) functional group's absorption peak. Furthermore, an absorption peak associated with the carbonyl (C=O) functional group was identified near the wavenumbers of 1600–1700 cm^{-1} (**Fig. 4.19**).

According to the research by Brandon et al. (2016), the presence of carbonyl bonding is indicative of the interaction between oxygen molecules and the hydrocarbon chains within the polymer matrix. This interaction leads to a gradual oxidation process within the polymer's internal structure, culminating in the formation of oxidized groups as the plastic debris ages in environmental conditions. The detection of functional groups such as -OH, C=O, and C-O in the analyzed samples signifies that the polymer

has undergone significant oxidation. Similar absorption peaks were also detected in the FTIR analysis of polypropylene and LDPE samples, as documented in **Figures 4.20 and 4.21**.

Upon examining high-definition images depicting the deterioration of various sample surfaces, it becomes evident that the intensity of absorption peaks corresponding to weathering groups varies with the degree of deterioration in different materials. Analysis of Scanning Electron Microscope (SEM) images indicates that the extent of deterioration and the intensity of the absorption peaks of oxidized groups do not exhibit a consistent correlation. Nonetheless, this observation leads to a preliminary hypothesis regarding the photooxidation process in high-density polyethylene (HDPE) samples, which appears to occur in two distinct stages. The first stage is characterized by uneven coloring and the presence of scratches, while the second stage is marked by the emergence of cracks and surface roughness.

The collected environmental garbage samples demonstrate varying accumulation times. These differences in accumulation durations can be tentatively estimated based on the intensity of the oxidation group absorption peaks and the observed surface weathering characteristics. Further quantitative analysis could potentially reveal a linear relationship between the duration of accumulation and the extent of photooxidation, as indicated by the correlation of these two factors. This hypothesis suggests that a systematic and detailed analysis could yield significant insights into the aging process of plastic debris in environmental settings.

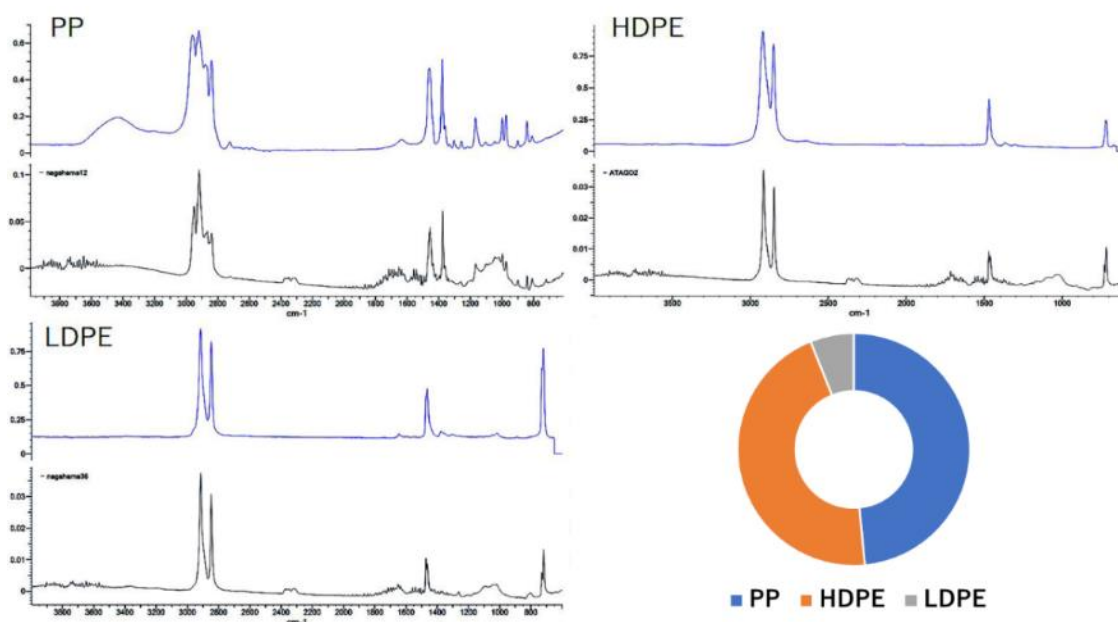


Fig. 4.14 The main components found in the micro-plastic debris samples

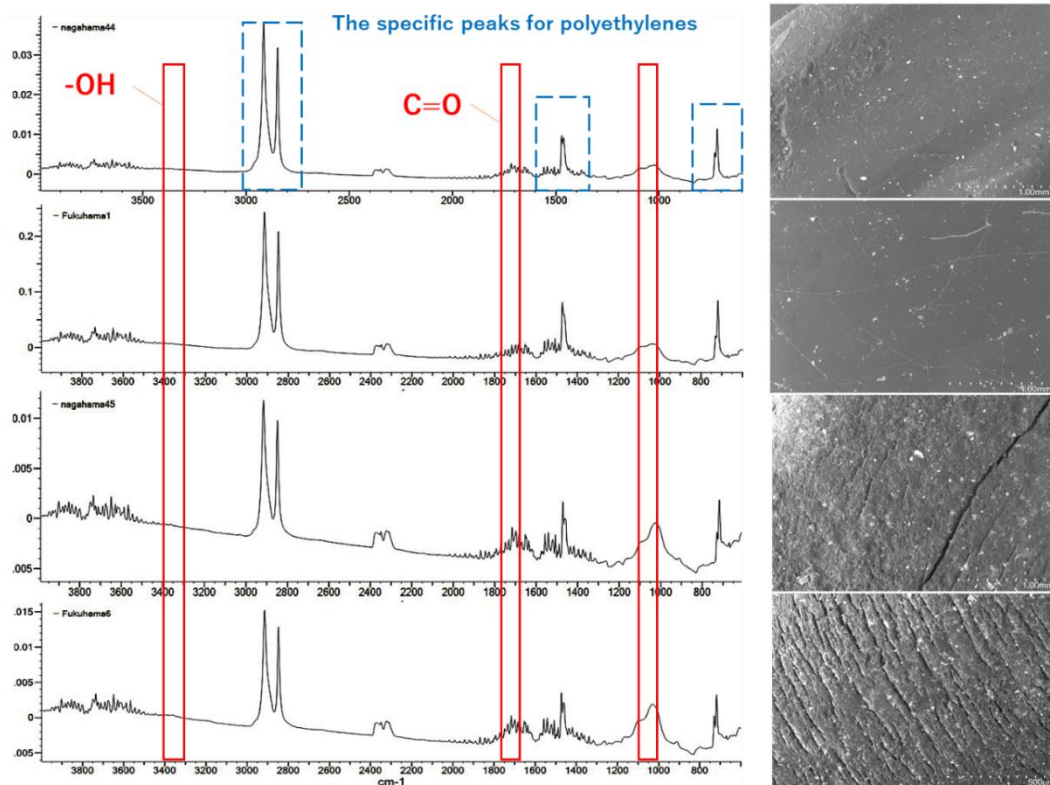


Fig. 4.19 HDPE's infrared spectra and the accompanying surface weathering morphology

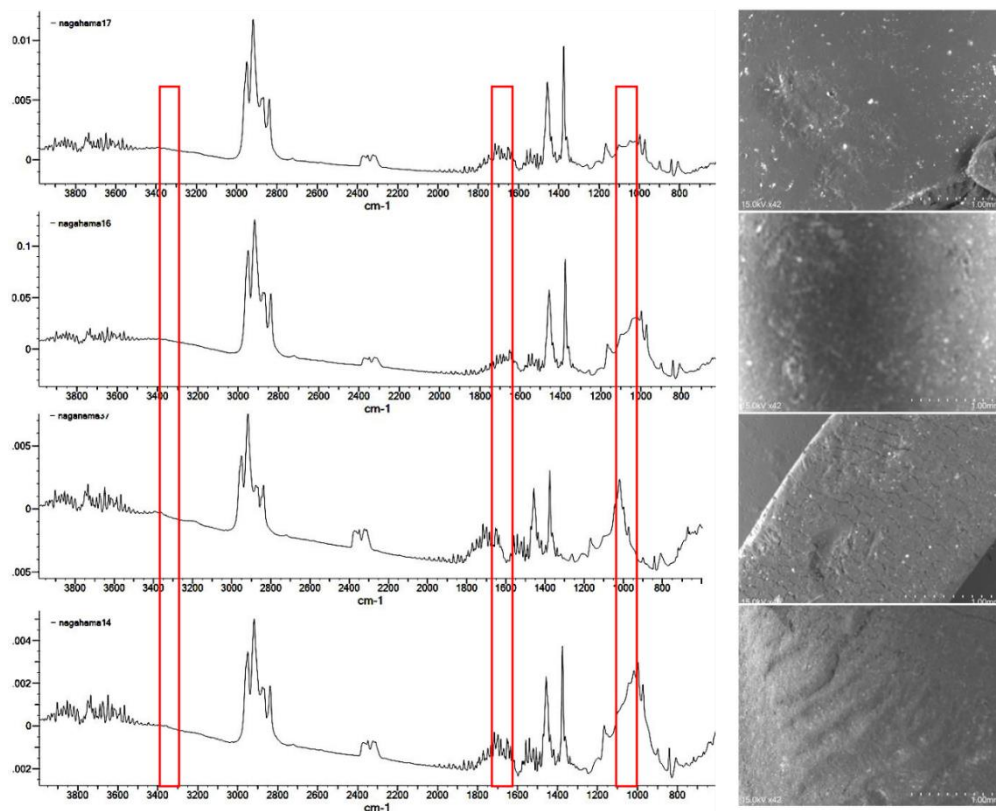


Fig. 4.20 PP's infrared spectra and the accompanying surface weathering morphology

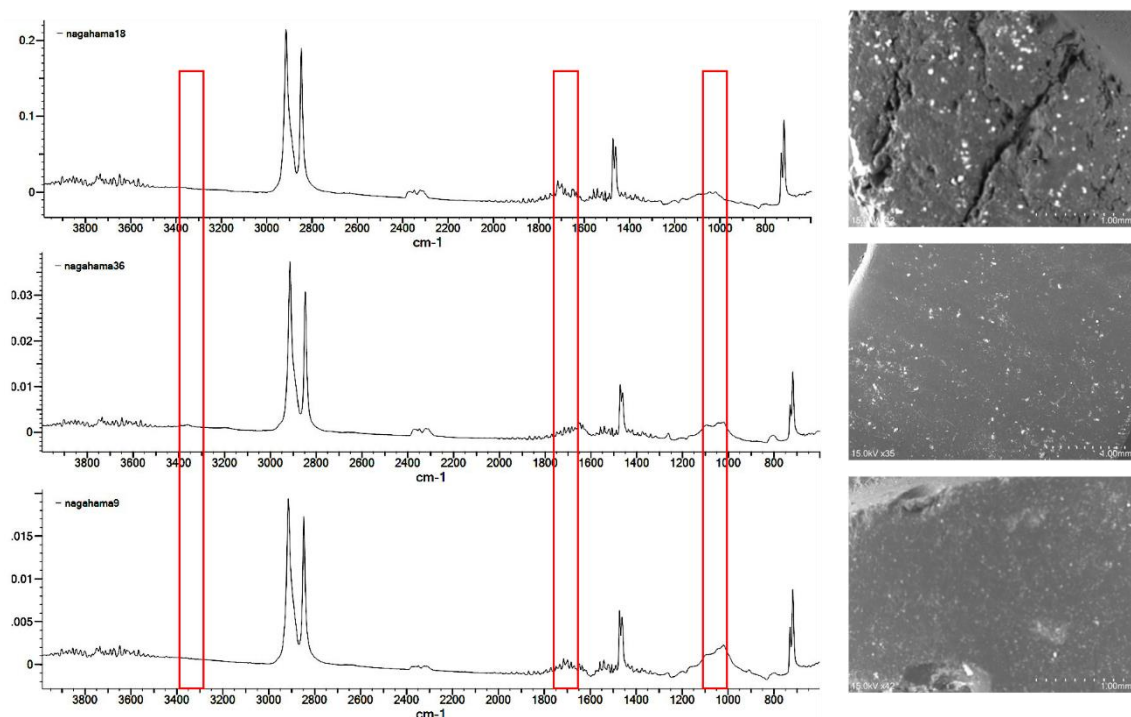


Fig. 4.21 LDPE's infrared spectra and the accompanying surface weathering morphology

4.5 Summary

In the coastal region off the western coast of Kyushu, Japan, a significant accumulation of marine debris has been observed. This area encompasses the enclosed sea regions around Tsushima, Hakata Bay, and five other islands. The origins of the debris in these areas are diverse. Proximate to urban centers, in the central and eastern sections of the sea, there is a predominant presence of domestic waste. Conversely, the western section of Hakata Bay tends to accumulate waste from external sources. Debris from foreign origins is notably prevalent along the shores of Tsushima Island and the other five islands, influenced by the Tsushima Current. Here, the proportion of domestic waste is considerably lower in comparison to the non-transit zones. Notably, cross-border marine debris originating from countries such as Indonesia, Malaysia, Vietnam, Russia, and South Africa has been identified. Among these, a majority of the plastic bottles, floating objects, and oil barrels bear distinct markers that facilitate the identification of their country of origin, predominantly China and South Korea.

Addressing the challenge of marine debris conservation requires international cooperation, as local authorities alone are insufficient to manage the accumulating litter. Furthermore, the task of determining the geographic origin of marine debris presents significant difficulties. Relying solely on labels or symbols for origin identification is often biased and inadequate. This challenge is exemplified by observations made at the Goto Islands Fishing Tackle Store, where the presence of goods from Japan, China, and Korea complicates the process of pinpointing the exact origins of the debris. This complexity underscores the need for more comprehensive methods to accurately trace and manage

marine debris.

The significant proportion of marine debris attributable to fishing-related waste raises critical questions about the efficacy of current waste management systems in the fishing industry. Predominantly, marine debris comprises plastic materials, including polypropylene, high-density polyethylene (HDPE), low-density polyethylene (LDPE), and expanded polystyrene (EPS), with EPS pellets being a primary component.

The weathering process leads to the oxidation of the polymer's internal structure, resulting in surface cracks and, eventually, fragmentation. This fragmentation increases the likelihood of microplastic formation. The generation of microplastics not only complicates the determination of the plastic's anthropogenic origins but also poses significant challenges in the recycling and disposal system of marine debris. Furthermore, the presence of inorganic titanium dioxide nanoparticles (TiO₂-NPs) in marine environments poses a severe threat to marine safety, titanium dioxide is classified as 2B (possibly carcinogenic).

Given the current state of marine rubbish pollution and the challenges associated with addressing this issue, there is an urgent need to regulate the production of plastic products and the development and application of new materials. This need is accentuated by the indispensable role of plastic products in daily life and industrial production. Immediate action is required to mitigate the environmental impact of these materials and ensure the sustainability of marine ecosystems.

Chapter 5 A natural barrier on the coast: the ability of coastal plant communities to capture marine debris

5.1 Introduction

To effectively address the issue of recurring pollution caused by marine debris re-entering inland areas, it is imperative to understand the relationship between the distribution of marine debris and coastal plant communities along natural shorelines. This investigation explores the potential role of coastal regions as temporary repositories for marine debris. Specifically, it examines whether coastal plant communities can intercept and retain some of the coastal litter, thus acting as natural barriers to prevent the re-entry of marine debris into inland areas.

In the context of mangrove forests, which are known to function as sinks and traps for marine debris, there is a recommendation for future initiatives to cultivate coastal plants on both artificial coastlines and heavily damaged natural coasts. This approach aims to restore ecological balance and leverage the natural barrier properties of these plant communities. However, it is also crucial to consider the influence of other natural factors, such as wind patterns and geographical features, on the movement and deposition of marine debris along the coast.

This study highlights the often-overlooked contribution of coastal plant communities in the context of marine debris dispersion. These communities are not only vital to the stability of coastal ecosystems but also act as natural barriers, protecting inland areas from the continuous influx of marine debris. Recognizing and harnessing the role of these communities could provide an alternative and eco-friendly approach to mitigating the impact of marine debris on coastal and inland environments.

Addressing the significant yet complex knowledge gap regarding the influence of coastal plant communities on the distribution and trajectories of marine debris transit poses a critical research challenge. Existing studies, such as those by Moreno-Casasola (1986), have established a correlation between coastal topography and the dispersion of coastal plant groups. This research implies that the physical features of coastlines play a pivotal role in shaping the distribution of both plant communities and marine debris.

Additionally, research by Pham et al. (2014) has highlighted the impact of coastal topography on the spread of marine trash, further underscoring the interplay between physical geography and debris distribution. Furthermore, studies like those conducted by Yoshizaki et al. (2006) have demonstrated that coastal plant communities possess the capability to trap and accumulate airborne sand particles. This finding suggests a potential parallel function in the accumulation of marine debris.

Despite these insights, there remains a notable gap in understanding specifically how coastal plant communities contribute to the collection and retention of marine debris. This area of research is underexplored and warrants further investigation to elucidate the mechanisms through which these communities interact with and influence the deposition and movement of marine debris. Bridging this

knowledge gap is essential for developing comprehensive strategies to manage and mitigate the impact of marine debris on coastal ecosystems.

5.2 Research methods

The study on the dispersion of marine debris concentrated on three key factors due to their significant influence on the distribution characteristics of reference flysch: coastal topography, coastal plant communities, and wind movement. To capture a comprehensive understanding, data collection was conducted in both winter and summer of 2022. This approach allowed for the consideration of seasonal variations in plant characteristics and the movement of marine debris.

In the vegetation monitoring area, three prominent coastal plant groups were selected for detailed observation. Each of these groups exhibited specific features that were critical to the study (**Fig. 5.1**). The analysis of these plant groups aimed to provide insights into how their unique characteristics interact with and affect the distribution and accumulation of marine debris along the coastline. By understanding these dynamics, the study aimed to contribute valuable information towards the development of more effective strategies for managing marine debris in coastal environments.

The study closely examined the deciduous shrub *Vitex rotundifolia*, as described by Nakamura et al. (2020). This plant species is characterized by its growth pattern, with stems that sprawl across the ground and are partially embedded in the sand, often forming dense clusters in sandy coastal areas. The typical height of *Vitex rotundifolia* ranges between 15 to 20 centimeters, and it features an abundance of foliage during the summer months. However, an interesting adaptation observed in this species is that its stems continue to grow in the winter, even as the leaves wither and fall off (**Fig. 5.2**). This growth behavior of *Vitex rotundifolia*, particularly its ability to thrive in sandy coastal environments and adapt to seasonal changes, makes it a relevant subject for understanding the interaction between coastal plant communities and the distribution of marine debris. The plant's physical characteristics and growth patterns may influence how it interacts with and potentially traps or redirects marine debris along the coastline.

Imperata cylindrica, a perennial grass species, is notable for forming dense clumps, as depicted in Fig. 5.3. According to studies by Tominaga (2007) and James A. et al. (2015), this species typically reaches a height of 40 to 50 centimeters. It is characterized by its horizontally sprawling, long, white, nodding underground stems. These stems, which have few clustered leaves in certain areas, facilitate the plant's multiplication through the development of fine roots (**Fig. 5.3**).

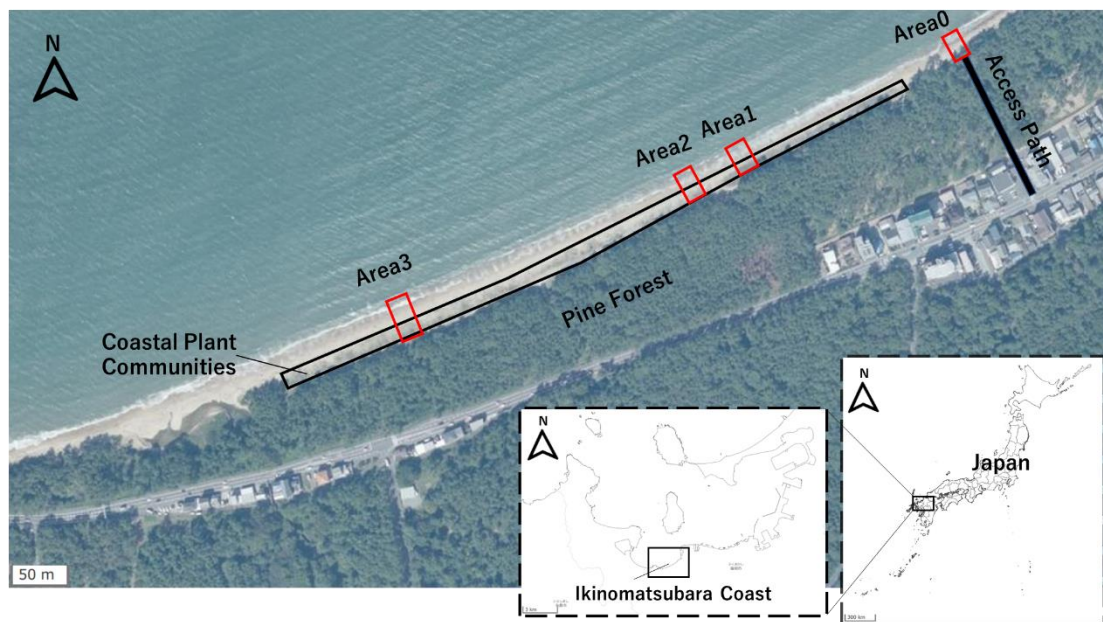


Fig. 5.1 Monitoring areas on Ikinomatsubara Coast and the surrounding area's overview.

In 2000, the International Union for Conservation of Nature (IUCN) classified *Imperata cylindrica* as one of the top 100 most dangerous invasive alien species. A significant ecological characteristic of *Imperata cylindrica* is its root system, which secretes substances that inhibit the growth of surrounding plants. Consequently, once established, *Imperata cylindrica* often creates an environment where few other plant species can thrive nearby. This trait has significant implications for local biodiversity and the ecological dynamics of the areas it invades, particularly in how it interacts with and potentially influences the distribution of marine debris in these environments.

Carex kobomugi is distinguished by its robust underground stem system, which exhibits both horizontal and vertical growth as it penetrates the sandy substrate (Fig. 5.4). According to Wootton et al. (2005), while the density of the plant cover is less pronounced compared to the other two species previously mentioned, the unique morphology of *Carex kobomugi*'s pendulous leaves is noteworthy. These leaves are adapted to the plant's proximity to the beach, enhancing its capacity to trap airborne sand and floating debris from the shoreline.

The plant's long stolons extend deep into the sand, with stems emerging at various points on the surface. This growth pattern contributes to the plant's stability and effectiveness in trapping materials. Typically, *Carex kobomugi* reaches a height of 5 to 10 centimeters. This characteristic height, combined with its specialized leaf structure and extensive stolon system, makes *Carex kobomugi* a significant species in the context of coastal ecology, particularly in its role in interacting with and potentially capturing marine debris and sand in coastal environments.



Fig. 5.2 *Vitex rotundifolia* community in monitoring area 1 and its specimens. The height of the underground rhizomes is 40 cm, while the aboveground stalks are 14 cm.



Fig. 5.3 *Imperata cylindrica* community in monitoring area 1 and its specimens. The height of the underground rhizomes is 30-50cm.

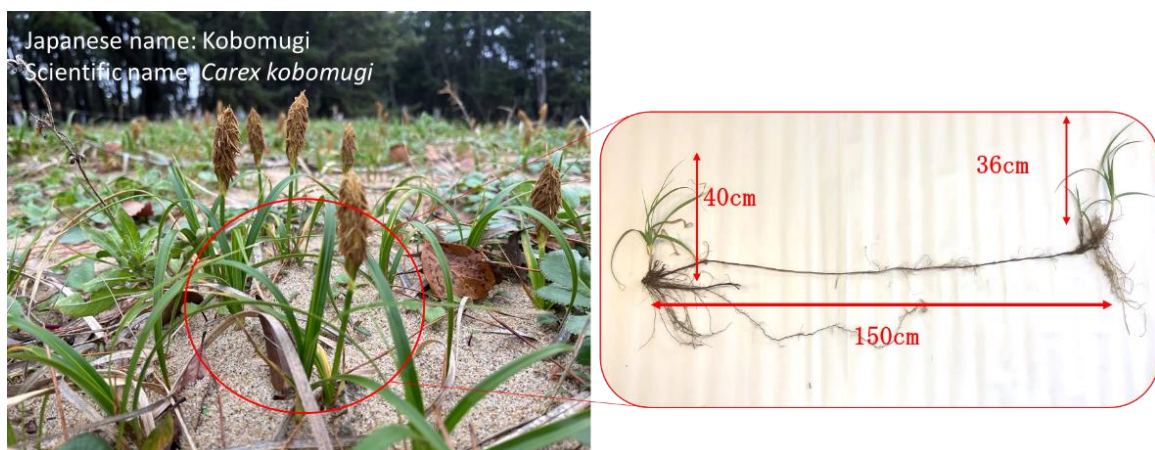


Fig. 5.4 *Carex kobomugi* community in monitoring area 1 and its specimens. The height of the underground rhizomes is 30-40cm, and underground interplanted rhizomes are about 1.5 m long.

In the study conducted along the Ikinomatsubara Coast in Fukuoka City, three distinct coastal plant community distribution sites (labeled A1, A2, and A3) were selected, along with a control region (A0) that lacked vegetation. To facilitate data collection, the four observation areas were divided into 0.5 x 0.5 m data sampling points, employing the Transect Line Analysis method, as delineated in Fig. 1. This setup extended from the inland area to the low tidal line, as documented by Balemlay, S. and Siraj, M. (2022).

The methodology employed in this study involved the use of a belt-transect method, which was characterized by a width of 50 cm, subdivided into square sample areas each measuring 50 cm on a side. This transect commenced at the termination of the backshore and extended to the limit of plant community growth, as documented by Keiko Oshida and Akiharu Kamihogi in 2004. However, it was observed that coastal plants often possess extensive root systems. Consequently, the stalks visible above ground are frequently interconnected below the surface, belonging to the same plant. This phenomenon renders simple enumeration techniques ineffective. To address this challenge, we adopted a digital photographic approach. Images were captured of the upper portion of each sample area. These images were then subjected to a process of binarization, enabling us to determine the percentage of ground coverage by vegetation. This methodological enhancement facilitated a more quantitative analysis of vegetation based on coverage percentages. Despite the advancements in calculating vegetative cover percentages, two critical considerations emerged. First, the computation of coverage percentage must be adaptable to account for seasonal variations in plant life, especially in species that exhibit significant changes in leaf and stalk coverage areas. Second, the binarization process encounters difficulties in differentiating between the yellowish foliage typical of autumn and winter seasons and the sand's color, leading to potential inaccuracies. In light of these challenges, future research will necessitate the integration of various interfering factors into the analysis of plant coverage. This will likely involve the utilization of artificial intelligence to refine research instruments and methodologies, thereby enhancing the precision and reliability of data concerning vegetative cover in coastal environments.

Each sampling point underwent a series of methodical processes:

(1) Measurement of coastal microtopography

To ascertain the precision of microtopographic slope variations along the coast, a substantial portion of the required topographic data was derived from simulated reproductions of cross-sectional slopes. These simulations were based on actual measurements obtained using the Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) at specified locations within the observation area. The measurement points were systematically arranged at one-meter intervals to ensure detailed coverage.

RTK-GNSS stands as a sophisticated technique under the umbrella of relative positioning. This method involves the reception of signals from four or more GNSS satellites using two receivers: one

situated at a reference station and the other at a mobile station. The key principle of RTK is to rectify any discrepancies in positional information between these two receivers, thereby achieving significantly enhanced positional accuracy. A notable attribute of RTK-GNSS is its ability to maintain errors within a few centimeters, a level of precision that enables the automated operation of drones, agricultural machinery, and construction equipment. This degree of accuracy was unattainable with standalone positioning systems. RTK receivers are already widely implemented as surveying tools in the civil engineering and construction sectors.

GNSS, an acronym for Global Navigation Satellite System, serves as a collective term for various satellite positioning systems, including the United States GPS, Russia's GLONASS, China's BeiDou, and Japan's QZSS. RTK-GNSS employs a dual-point observation methodology, involving a known reference point and an observation point. The reference point is a fixed reference station with a known location, while the observation point is the mobile station whose position is being measured. The positioning accuracy achieved with RTK-GNSS is remarkably high, approximately 2 to 3 centimeters horizontally and 3 to 4 centimeters vertically, far surpassing the accuracy of independent positioning methods (Eilidh Stott et al., 2020).

In the preliminary phase of the study conducted on the Peninsula coast, drones were utilized to gather geographic data and create three-dimensional terrain models. This approach significantly enhanced the efficiency of the survey. However, due to certain limitations in drone technology and application, this method did not gain widespread adoption in the broader scope of the study.

(2) Wind Speed Survey

Simplified instantaneous anemometers, which are lightweight and designed for ease of reference, were employed to estimate wind speeds along the studied coastal regions. The key tool used was a hot-wire anemometer (model DT-8880, MK Scientific Inc.), comprising a telescopic measuring probe and a control unit for the operator. This instrument facilitated precise horizontal and vertical wind speed measurements along the coast. The telescopic probe's primary role was to assess wind speeds within the plant communities. The methodical procedure involved positioning the wind speed measurement point at the center of the observation area designated for the plant cover survey. The measurement scope was then extended to the low tidal line. Wind speeds were recorded at consistent intervals, starting from the beach surface up to a height of one meter at each observation point.

Several challenges were encountered with this measurement approach. Firstly, the environmental variables at the beach were not fully controllable, marked by strong winds, rapid fluctuations in instantaneous wind speeds, and inconsistent data recording at the measurement sites. Secondly, despite the possibility of synchronizing the instrument with a computer for data storage, manual data recording was necessary. This proved to be inefficient, especially considering that the coastal environment is not conducive to prolonged exposure to standard laptop computers. Lastly, fieldwork conducted in winter presented additional difficulties. Low temperatures often resulted in unreliable performance of the

instruments, complicating the data collection process. These issues highlight the need for adaptability and robustness in both instrumentation and methodology when conducting fieldwork in dynamic and challenging coastal environments.

(3) Sand particle size analysis method

Surface sand samples were meticulously collected from the designated vegetation observation areas, penetrating to a depth of approximately 0.5 cm. These samples included any debris present. Each sample was securely placed in a labeled sample bag, with annotations indicating the date, sample number, and specific geographic position of collection.

Upon returning to the laboratory, the sand samples underwent a drying process. They were placed in a dryer, with the temperature set at 70 degrees Celsius, and left to dry for a period exceeding 12 hours. This specific temperature setting was strategically chosen to preserve the structural integrity of any plastic litter fragments within the samples, ensuring their undistorted analysis later on.

Post-drying, the samples were meticulously divided into 100-gram quadrants, ensuring that each quadrant did not exceed a total weight of 0.5 grams. These subdivided samples were then processed through a sieve machine. The sieving equipment utilized a multi-tiered mesh system, comprising eight distinct aperture classes: 2 mm, 1 mm, 500 μm , 250 μm , 150 μm , 106 μm , 75 μm , and 45 μm , as per the methodology outlined by Eilidh Stott et al., 2020.

Following the sieving process, samples from each mesh screen were extracted, accurately weighed and recorded to the nearest tenth of a percent. The sieving process was calibrated with an intensity setting of forty and a duration of twenty minutes. This meticulous procedure facilitated a comprehensive and detailed analysis of the sand samples, providing valuable insights into the composition and characteristics of the coastal sediment within the observation areas.

5.3 Coastal topographic features and coastal plant community cover

In 2022, data collection was conducted during January and August to capture the most pronounced seasonal variations in coastal plant cover, specifically comparing summer and winter conditions. This approach aimed to examine the effects of seasonal variation on coastal vegetation, which plays a crucial role in dune formation and topographical maintenance by obstructing wind and retaining sand. Notably, the majority of observed vegetation was located on the backshore, an area characterized by higher topography.

The cross-sectional topography of each monitoring area, recorded during both seasons, revealed that the vegetation-dense region in the A0 control area exhibited a lower elevation compared to areas with dense vegetation (**Fig. 5.5**). The topography of dunes in the backshore was more pronounced in the summer, reflecting the influence of seasonal changes on coastal plant groups.

The study also found that different plant species varied in their ability to stabilize sand. For instance, the deciduous shrubs in the A1 area, which underwent significant cover changes, were less effective

at maintaining topography during winter foliage dieback compared to the plant populations in the A2 and A3 areas.

A notable challenge in the study was the use of image binarization for vegetation counting. This method faced difficulties in color misclassification, particularly in winter when the color of the sand and vegetation were similar. As a result, the winter data required corrections to reflect accurate coverage. Looking forward, there is an anticipation of employing artificial intelligence recognition techniques to enhance the accuracy and efficiency of the research process, thereby optimizing data collection and analysis in future studies.

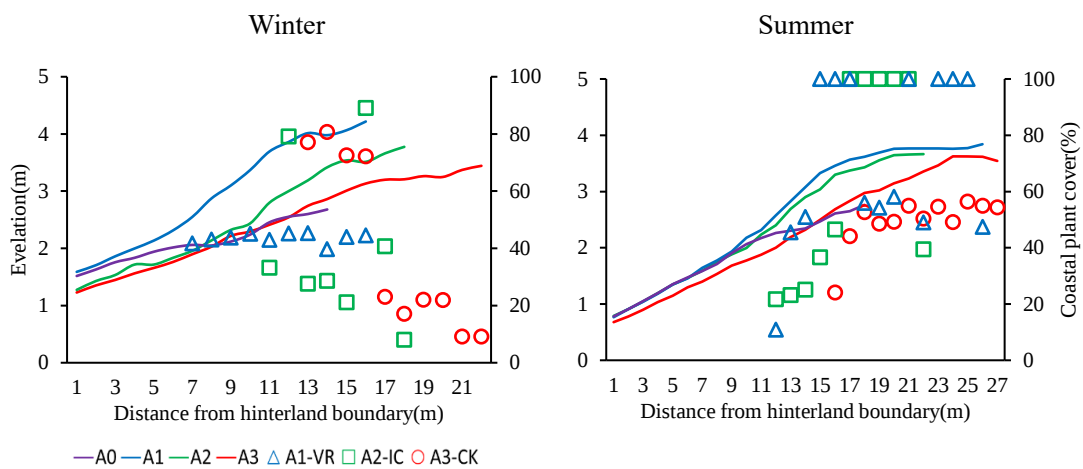


Fig. 5.5 Topographic features and the cover of the coastal plant community. VR- *Vitex rotundifolia*, IC- *Imperata cylindrica*, CK- *Carex kobomugi*.

5.4 Near-surface wind speed analysis

The concept of wind shear refers to variations in wind direction and speed, both horizontally and vertically. Wind shear can be categorized into three types: vertical wind shear, horizontal wind shear, and shear of horizontal winds. This study specifically focuses on the changes in horizontal wind speed at varying vertical heights close to the ground, as the height of coastal plants is generally lower than that of inland plants.

To illustrate the variation in horizontal wind speed at different vertical heights, the study employs wind contours of mean wind speed with height, as depicted in **Figure 5.6**. The coefficient of determination, denoted as R^2 , is used to quantify the rate of change in wind speed with height. Higher R^2 values indicate a more accurate model fit. The wind shear index, a crucial metric in this study, measures this variation. When the wind speed profile conforms to a power law equation, the wind shear index is equivalent to the power law index, indicating that wind speed increases with height in direct proportion to the wind shear index.

Surface roughness, a key dynamical factor, significantly influences the variation of wind with height in the near-surface layer. Thermal conditions are among other elements affecting wind flow. Generally, a higher wind shear index and greater surface roughness lead to more pronounced wind deceleration at near-surface heights. Seasonal changes in surface vegetation also impact the wind shear index. During the study, average plant heights were recorded as follows: in winter, A1–15 cm, A2–40 cm, A3–10 cm; in summer, A1–20 cm, A2–50 cm, A3–15 cm.

Notably, there was no significant variation in the changes in wind speeds within and outside the plant community in the other locations compared to the vertical wind speed variations in the unvegetated area A0. The study found that the change in horizontal wind speed in the vertical direction was influenced by the additional roughness introduced by the plant community to the near-surface area. This understanding of wind shear about plant communities provides valuable insights into coastal environmental dynamics.

Figure 5.7 presents the horizontal wind speed data collected from each observation area during the summer and winter seasons. However, the reliability of the summer data warrants further investigation, particularly because the data collection coincided with the typhoon season in western Kyushu, Japan. During this period, the average horizontal wind speeds were observed to be 5 to 10 times higher than those in winter, and the extent of change in wind speed was not as marked as in the winter season.

The study also contemplates a theoretical aspect, suggesting that the wind protection capacity of plant communities may have a critical threshold. Beyond this threshold, the difference in wind speeds within and outside the plant community might become indistinct, especially when the wind speeds exceed the community's protective capacity. To empirically ascertain the limits of the community's wind protection capacity, it is essential to simulate the plants' ability to shield against wind under varying wind speed conditions.

An interesting observation was made regarding the variance in wind speed data during the summer. At heights below the average height of plants in observation areas A1, A2, and A3, the magnitude of wind speed variance was significantly lower compared to measurements taken at other heights. This pattern suggests that wind speeds are generally lower inside the plant community than outside it, particularly at heights below the average plant height. This observation underscores the effectiveness of the plant community in providing wind protection, indicating its ability to attenuate wind speeds within its bounds. This finding is crucial as it highlights the role of coastal plant communities in influencing microclimatic conditions, particularly in terms of wind dynamics.

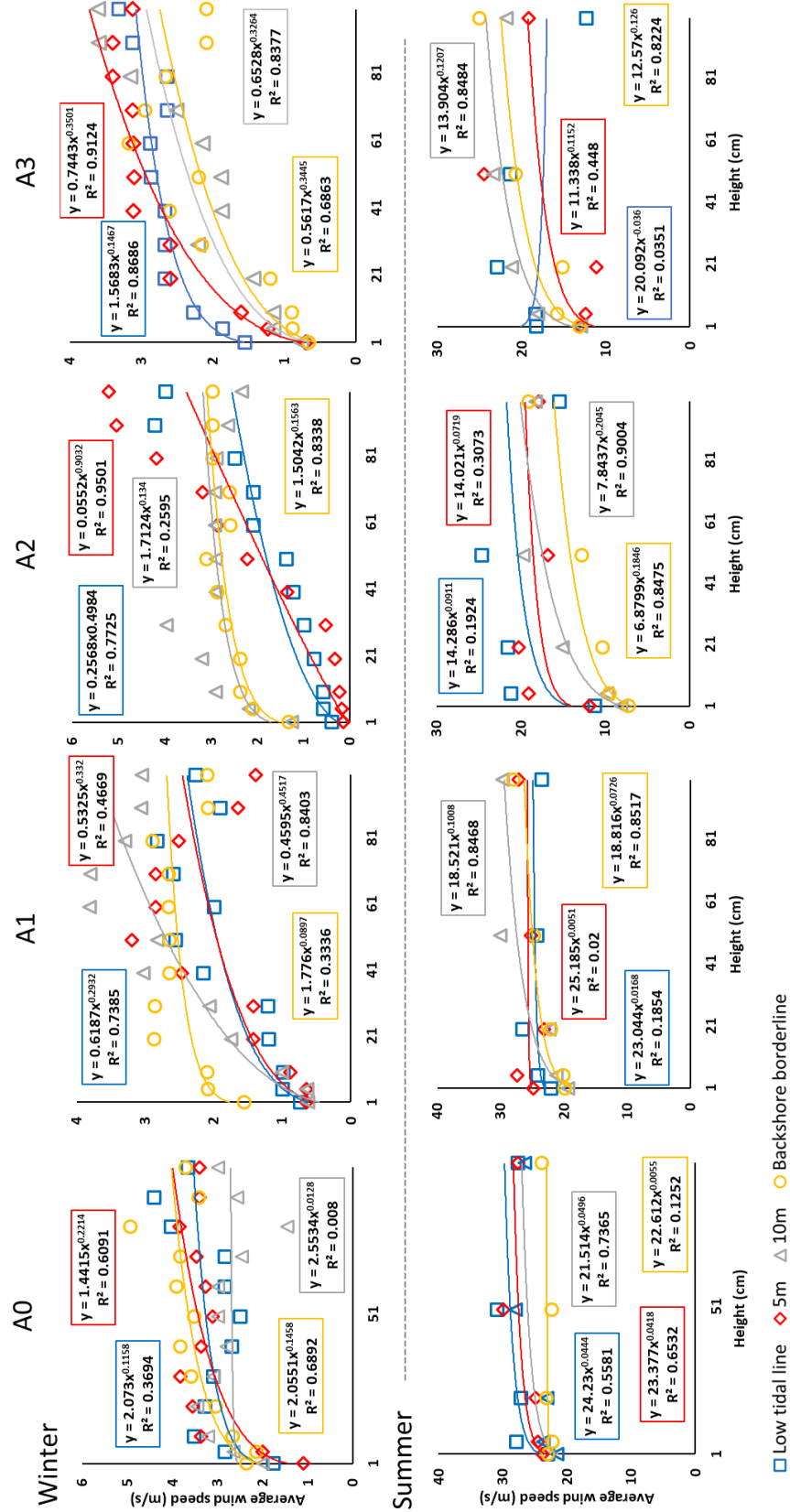


Fig. 5.6 Variations in vertical wind speed in the winter and summer at monitoring areas

The analysis of mean wind speed data, as illustrated in the box-and-line plot (**Fig. 5.8**), reveals distinct differences among the various areas studied. Notably, the control area (A0), characterized by the absence of plant distribution, exhibits the highest mean wind speed. Additionally, the variability in wind speed data in this area is substantially lower compared to the other locations.

A particularly interesting observation is made in the A2 area, where the largest fluctuation in winter wind speed data was recorded. This could be attributed to the presence of *Imperata cylindrica*, which is dispersed over a limited area and demonstrates significant changes in vegetation cover both within and outside the community. This pattern suggests that the spatial distribution and density of this plant species may play a pivotal role in influencing local wind dynamics.

Moreover, the data from the A1 area display considerable fluctuation between winter and summer, which is closely linked to the seasonal behavior of the low-leaved shrub *Vitex rotundifolia*. During winter, this plant species undergoes a significant reduction in foliage, which in turn markedly decreases its capacity to provide wind protection. This seasonal variation in *Vitex rotundifolia*'s foliage highlights the dynamic nature of plant communities in modulating wind speeds and emphasizes the importance of considering seasonal changes when assessing the environmental impact of coastal vegetation.

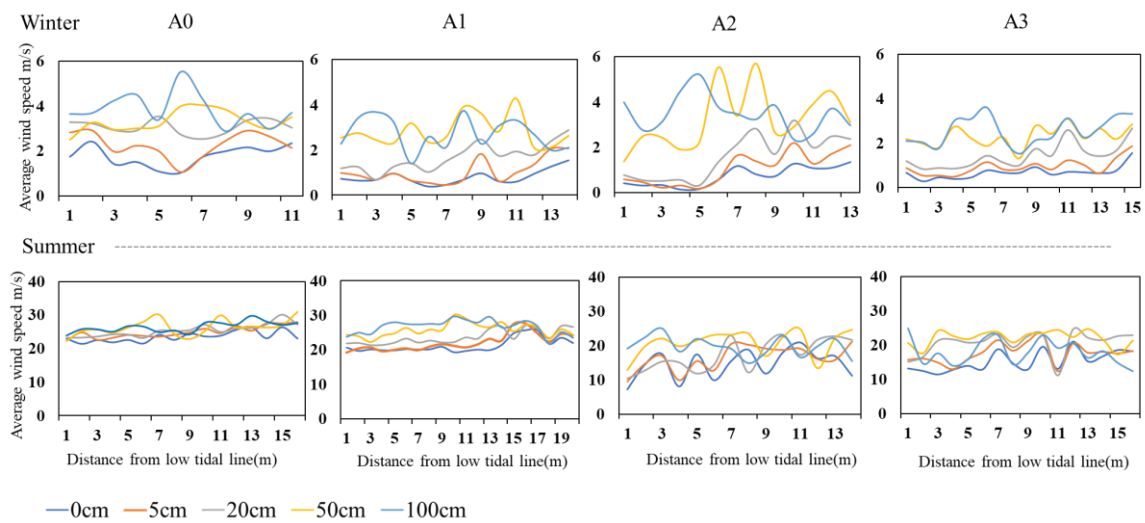


Fig. 5.7 Variations in horizontal wind speed in the winter and summer at monitoring areas

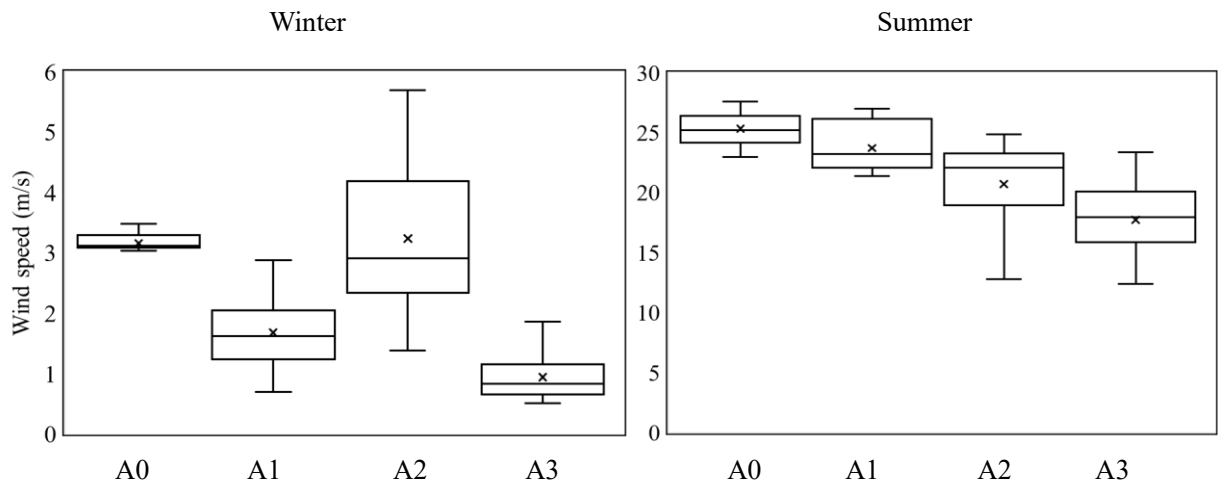


Fig. 5.8 The mean values of wind speed in each observation area

5.5 Distribution of surface sand samples

The compositional analysis of surface sand samples from each observation area, as depicted in **Figure 5.9**, reveals that coarse and medium sand predominantly constitute the surface sand along the coast. Notably, there is a discernible trend in the distribution of these sand types: the proportion of coarse sand increases moving from the low-tide line towards the plant communities, while the proportion of medium sand shows a decreasing pattern.

This variation in sand composition was more pronounced during both the winter and summer seasons. The data suggest that the presence and distribution of coastal vegetation may have a significant influence on the sedimentary characteristics of the beach.

In contrast, area A0, which is devoid of vegetation, exhibited a distinct pattern in its sand composition. This section of the beach, located in the central part, showed a higher percentage of coarse sand. Additionally, there was a clear diminishing trend in the percentage of medium sand in this area. The absence of vegetation in area A0 likely contributes to these differences in sand composition, as plant communities can play a crucial role in trapping and stabilizing different types of sand particles.

These findings underscore the intricate relationship between coastal vegetation and sediment dynamics. Understanding this relationship is essential for comprehending the ecological and geomorphological processes at play along coastlines, and for informing coastal management and conservation strategies. The data presented in **Figure 5.10** offers a detailed analysis of the two primary components of surface sand – coarse and medium sand – about their distribution within and outside the plant community areas during both winter and summer. It is observed that there is an increasing trend in the proportion of coarse sand outside the community areas, while a higher proportion of medium sand is found within the community areas in both seasons.

An important metric in this context is the median grain size, or D50, of the sand samples. The D50 is defined as the grain size at which 50% of the sample's particles are larger and 50% are smaller. This

measure holds significant physical relevance as it provides a central value for the distribution of particle sizes in the sample.

According to the findings illustrated in the figure, the median grain size within the community areas is largely associated with medium sand. In contrast, median grain sizes corresponding to coarse sand are more prevalent outside of the community areas. This distinction in grain size distributions underscores the influence of plant communities on the sedimentary characteristics of coastal areas. The presence of vegetation appears to have a stabilizing effect on the sand, influencing the accumulation and distribution of different sand types. Understanding these variations is crucial for comprehensively assessing the geomorphological and ecological dynamics of coastal regions.

This section delves into the dynamics of sand import and export along this particular coastline. Sand on natural coastlines typically has three primary sources: firstly, sand eroded from nearby hills or shores is transported to the area by currents; secondly, sand carried by nearby rivers reaches the mouth of the estuary, where tidal action brings it ashore; and thirdly, sand accumulation directly on the banks of estuaries, though this last source is less likely in the area under investigation due to the distance from the estuary, as noted by Psuty. N.P. (2008).

In the first two scenarios, the currents transport sand to the beach. From there, it is either moved inland by winds to form dunes or carried back to the sea by the winds, where it settles as seabed deposits. Research by Kita, K. et al. (2005) on the movement of flying sand along the Ninety-Nine Mile Coast highlights that wind-borne sand with grain sizes smaller than 0.11 mm is prevalent and selectively blown toward the land to form dunes. Conversely, near the shoreline, coarse-grained sand with grain sizes of at least 0.25 mm is more commonly found.

An interesting observation is that the backshore region exhibits a higher percentage of fine sand during the summer compared to the area near the low tide line. This observation is further corroborated by the statistics presented in **Figure 5.10**, which indicate a trend towards a higher percentage of fine sand within plant communities compared to outside them. In this context, the plant community acts primarily as a barrier against wind and sand. This role is crucial for assisting the accumulation of fine sand to form dunes, particularly during the summer months, and for replenishing sand in the backshore area, which typically features higher topography on the back coast. Understanding these sand dynamics is vital for comprehending the geomorphological processes at play and for informing effective coastal management strategies.

In the particle size analysis experiments, it was discovered that the smallest particles in the sand samples were mostly plant debris, not sand. This plant debris resurfaces to benefit the plant communities along the beach, as shown in **Figure 5.11**. Additionally, these small particles are a key source of nutrients for beachside plants, playing a crucial role in their survival and growth. This finding highlights the important role of plant debris in the coastal ecosystem, contributing both to the nutrient cycle and the stability of the coastal environment.

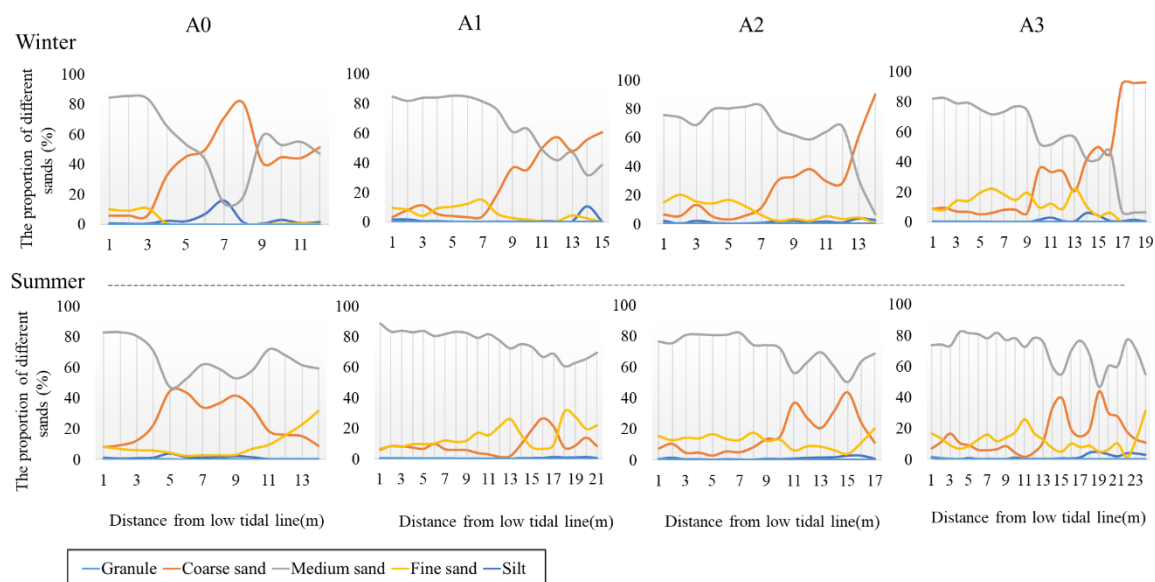


Fig. 5.9 Variation in the proportion of surface sand in the monitoring area

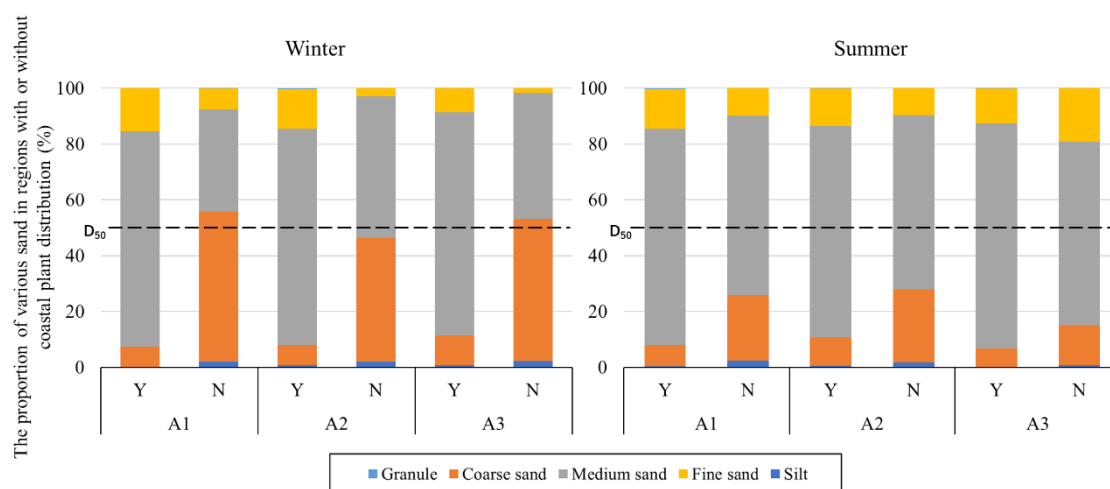


Fig. 5.10 Average proportion of various grains of sand in the observed areas of A1, A2, and A3 with and without vegetation distribution (%). The winter data are displayed on the left, and the summer data are displayed on the right. Y- the region with coastal plant distribution; N- the region without coastal plant distribution.

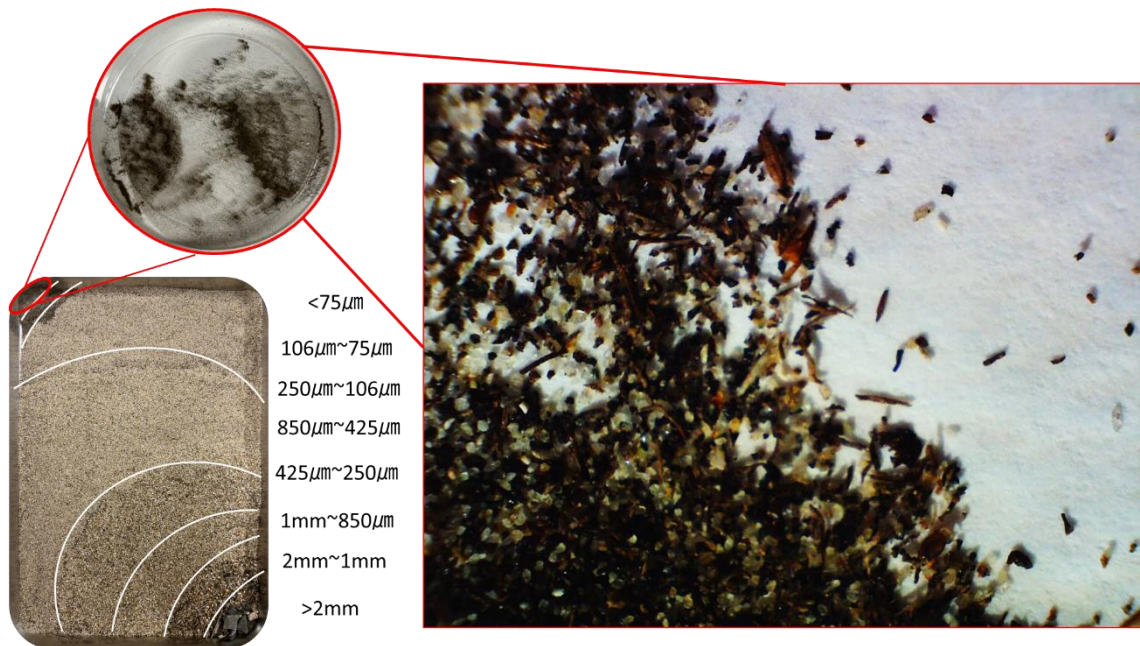


Fig. 5.11 Plant debris in sand samples below 75 microns.

5.6 Distribution of marine debris

This segment of the study focuses on three predominant types of litter found along the western coast of Kyushu: hard plastic debris, foam debris, and debris from food packaging or containers. The analysis, as illustrated in **Figure 5.12**, indicates that there was minimal variation in the total quantity of marine debris between the summer and winter seasons.

The study acknowledges that typhoons are a common occurrence in the western part of Kyushu, typically in September, coinciding with the summer survey period. Additionally, the Fukuoka area experiences the northwest monsoon during winter, particularly when a west-high-east-low pressure pattern prevails, as detailed by the Japan Meteorological Agency.

Given these climatic conditions and the data obtained from a comprehensive survey conducted in the Itoshima Peninsula in 2019, it is anticipated that the prevalence of marine debris along this coast will be consistently high throughout the year, irrespective of the season. This assertion is based on the understanding of the regional climatic influences on marine debris accumulation. The study thus provides valuable insights into the seasonal dynamics of marine debris distribution along Kyushu's western coast, underscoring the impact of local weather patterns on environmental pollution.

In the summer data from Area 1, it was observed that the highest concentration of marine debris was situated approximately 10 meters from the low tide line. This pattern suggests a possible temporary accumulation of litter at the boundary of the plant community, likely influenced by wind movement. In Areas 1, 2, and 3, the total amount of marine debris was significantly greater within the plant communities compared to the areas outside these communities.

Notably, Area 0, which lacks vegetation, showed a varied distribution of litter along the beach. However, the quantity of litter in this area was considerably lower than in the vegetated areas. The landward side of Area 0 serves as the main access point to the shore. Under normal circumstances, one would not expect substantial variations in litter abundance along the same coastline. However, the absence of a coastal plant community in Area 0 implies that the debris, subject to the same wind conditions as in other areas, could have been driven further inland, possibly into the inlet channel.

This hypothesis is further supported by photographic evidence of debris dispersion along the pathway in Area 0. The photographs depict litter scattered extensively across the area, with some debris even reaching the adjacent road (**Fig. 5.14**). This evidence suggests that in the absence of a barrier like a coastal plant community, marine debris can spread more widely inland from the coast, highlighting the critical role of vegetation in containing and mitigating marine debris accumulation.

Polystyrene foam debris is identified as having the highest abundance ratio among all types of marine debris, a finding consistent with previous observations that it tends to accumulate along the Sea of Japan coast (Fujieda et al., 2007). An analysis of the debris size distribution, as illustrated in **Figure 5.13**, reveals that the majority of the foam debris falls within size ranges of 0.1 to 0.5 cm.

The widespread use of polystyrene foam in the manufacturing of products, particularly food and fisheries containers, is attributed to its lightweight, insulating, waterproof, and easily moldable properties (Shigeru et al., 2005). However, its tendency to break down into small, lightweight plastic fragments contributes significantly to its prevalence as marine debris, commonly accumulating along coastlines.

When comparing the accumulation of polystyrene foam debris to flying sand, which is also affected by wind, it is important to consider that the individual particle densities of these materials differ by several orders of magnitude, making direct comparisons challenging. Instead, the surface roughness of the accumulation surfaces for both foam debris and flying sand is deemed a more relevant factor for analysis. This approach accounts for the differing physical characteristics of these materials and provides a more accurate understanding of how each interacts with and is influenced by environmental factors like wind.

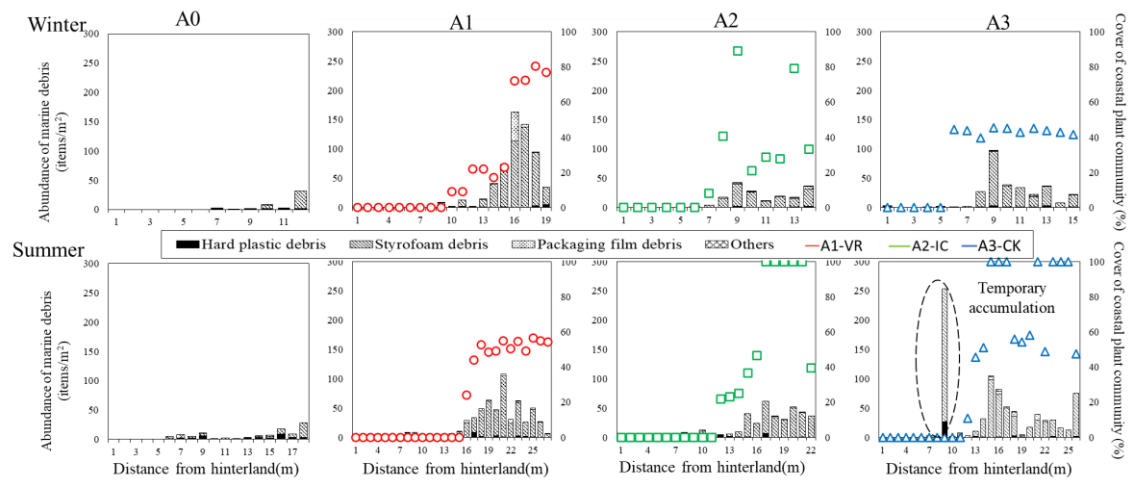


Fig. 5.12 Changes in the abundance of marine debris and the cover of coastal plant community in each observation area. Changes in the cover of the coastal plant throughout different regions are shown by scatter plots. Each sampling point's surface sand composition is displayed in the histogram.



Fig. 5.13 The proportion of different types and sizes of marine debris in each observation area. Not only are the different debris categories identified, but each type is also categorized by size.



Fig. 5.14 Litter debris scattered throughout the trail

5.7 Summary

The primary objective of this study was to ascertain the key environmental factors influencing the accumulation of marine debris along coastal areas. A significant focus was placed on determining whether plant communities can act as effective natural barriers, impeding the inland movement of litter debris. This involved comparing the impact of various environmental factors on the distribution of surface and understanding the role of vegetation in controlling debris movement.

One of the challenges encountered in the study was related to equipment limitations and the insufficient assessment of meteorological variables before and after the survey dates. As a result, the horizontal wind speed data collected inside and outside the plant communities during the summer were less informative compared to the data obtained in the winter. Despite these limitations, the data collected still provide valuable preliminary insights into the potential of the plant communities to mitigate wind effects.

Further detailed observations are necessary to accurately establish the upper and lower limits of the wind protection capacity of these plant communities. Such comprehensive data would enable a better understanding of the extent to which these communities can function as natural barriers against the movement of marine debris driven by wind. This knowledge is crucial for developing effective strategies to manage and reduce the impact of marine debris on coastal environments.

Plant communities located close to inland areas on the backshore of the coast are notably more effective at trapping flying sand particles smaller than 0.11 mm, as well as being superior in

aggregating sand to form dunes compared to unvegetated areas (Kita et al., 2005). It was observed that the volume of litter debris accumulating within these plant communities was significantly higher than that in areas without vegetation. This pattern was especially prominent in the case of foam debris, with particle sizes ranging from 0.1 to 0.5 cm.

In selecting observation areas for this study, consideration was given to the potential influence of different plant species on the accumulation of litter debris. Contrary to initial expectations regarding the barrier capabilities of *Vitex rotundifolia* communities, it was found that communities of *Carex kobomugi* were more effective in trapping litter debris. This effectiveness is attributed to the lower average height of *Carex kobomugi* and the drooping, ground-hugging nature of its leaves. The ability of plant communities to collect marine debris appears to be enhanced by the maturity of the plants.

Tussock grasses emerge as a potential target species for both artificial and natural coastal ecological structures, owing to their effectiveness in debris collection. Additionally, this study provides valuable data that can be used to address the issue of marine debris pollution, which is a growing concern for beach tourism. The findings underscore the importance of integrating ecological considerations into coastal management, particularly in the context of mitigating marine debris and preserving the attractiveness and health of beach environments.

To more accurately quantify the ability of plant communities to capture marine debris, there is a need for further in-depth simulation experiments with controlled variables. These experiments should aim to provide a quantitative measure of the capture capacity of these communities. By doing so, a more definitive understanding of how effectively various plant species and community structures can intercept and retain marine debris can be achieved. This quantitative approach is essential for enhancing the precision and reliability of our knowledge in this area, and for informing effective environmental management and conservation strategies.

Chapter 6 Summary

6.1 Main conclusions

(1) The coast serves as a temporary repository for marine debris, with human activity being a major contributor to this form of pollution. Marine debris, as an environmental contaminant, often results from the inefficient management of waste generated by human activities. Even on natural coasts, human influence varies in extent and impact. Most anthropogenic activities, whether for societal benefit or leisure, inevitably affect the coastal topography and ecological environment. This impact manifests through the construction of artificial structures and the frequent trampling of beach areas.

Although the previous study examined data across all seasons, only summer and winter data were selected for detailed analysis. This selection was made due to the more pronounced seasonal variations in the distribution of litter and coastal plants during these periods, which provided clearer insights for analysis. The seasonal pattern of marine debris distribution is influenced not only by beach tourism in summer but also by meteorological events such as typhoons and monsoons. In terms of coastal vegetation, the primary indicator of seasonal variation is the change in plant coverage.

The Itoshima Peninsula, featuring a wide variety of coastal plant species, each with unique growth characteristics, plays a critical role in shaping the morphology of the dunes and the dispersion of debris. To gain a deeper understanding of their effects, it is advantageous to focus on a few dominant plant communities and manage other variables accordingly.

Plastic, whether it originates from domestic debris or is associated with fishing operations, constitutes the bulk of marine debris. This prevalence of plastic highlights the ongoing challenges in waste management and the need for improved strategies to mitigate the impact of human activities on coastal environments.

(2) Significant quantities of marine debris accumulate along the western coast of Kyushu, Japan. The Hakata Bay area, particularly its central and eastern parts near urban centers, predominantly contains domestic waste. Conversely, the western coast of the bay tends to gather fishing-related debris, especially foam sheets. The Tsushima Island coast and the Goto Islands, influenced by the Tsushima Current, often see an accumulation of cross-border marine debris. In these transit zones, the debris is mainly transboundary, including plastic bottles from countries such as Indonesia, Malaysia, Vietnam, Russia, and South Africa. Additionally, fishing floats and oil barrels identifiable to China and South Korea are commonly found.

The management of this marine debris is a complex challenge that extends beyond local authority capacities, necessitating international cooperation for the effective preservation of the marine environment. Identifying the geographic origin of marine debris is complicated, particularly when solely relying on labels or symbols. This issue was exemplified during a visit to the Goto Island Fishing

Tackle Store, where a mixture of goods from Japan, China, and Korea made it difficult to ascertain the precise origins of litter.

A significant portion of the marine debris is associated with fishing activities, raising questions about the effectiveness of current waste management systems in the fishing industry. The predominant form of litter is plastic debris, consisting mainly of polypropylene, high-density polyethylene, low-density polyethylene, and expanded polystyrene (EPS). Weathering processes lead to the oxidation of the polymer's internal structure, resulting in surface cracks and fragmentation. This fragmentation increases the likelihood of microplastic formation, complicating the determination of the debris' anthropogenic origin and posing a significant challenge for recycling and disposal systems.

Moreover, the presence of inorganic titanium dioxide nanoparticles (TiO₂-NPs) in marine debris presents a grave threat to the marine environment. These particles are especially toxic to bacteria, vertebrates, algae, and fish, highlighting the urgent need for comprehensive strategies to manage and mitigate the impact of marine debris on coastal ecosystems.

(3) The study of evaluating the marine debris capture capacity of coastal plant communities. The primary aim was to identify key environmental factors contributing to the accumulation of marine debris along shorelines. Specifically, the research sought to demonstrate how plant communities could act as natural barriers, effectively halting the inland progression of litter debris. This was investigated by comparing the impacts of these environmental factors on the distribution of surface sand.

One of the challenges faced during the study was related to equipment limitations and the lack of a comprehensive assessment of meteorological variables both before and after the survey dates. As a result, the horizontal wind speed data collected within and outside the plant communities during the summer did not provide as much insight as the data collected in the winter.

Although the study offers initial insights into the wind protection capacity of plant communities, more detailed observations are necessary to accurately determine their full range of capabilities. This includes establishing both the upper and lower limits of their capacity to protect against wind. The preliminary data, despite its limitations, begins to shed light on how effectively these communities can respond to and potentially mitigate the impacts of wind on marine debris accumulation.

Inland-proximate coastal plant communities on the backshore are notably more effective at trapping flying sand particles smaller than 0.11 mm and are better at aggregating sand to form dunes compared to unvegetated areas. A significant observation from this study was that the volume of litter debris trapped within these plant communities exceeded that found in areas without vegetation. This was particularly evident in the accumulation of foam debris, with particle sizes ranging from 0.1 to 0.5 cm. The selection of observation areas for the study carefully considered the potential impact of different plant species on the accumulation of litter debris. Contrary to initial assumptions about the barrier capabilities of *Vitex rotundifolia* communities, it was found that communities of *Carex kobomugi* were

more effective in trapping litter debris. This efficacy is attributed to the lower average height of *Carex kobomugi* and its drooping, ground-hugging leaves. The ability of plant communities to collect marine debris appears to be enhanced by the presence of mature plants.

Tussock grasses have been identified as a potential key species for both artificial and natural coastal ecological structures due to their debris collection capabilities. This finding is significant as it provides valuable information for addressing the issue of marine debris pollution, which poses a threat to beach tourism. Understanding the role of specific plant species in trapping marine debris is crucial for developing effective strategies to mitigate the environmental impact of this pollution and preserve the health and attractiveness of beach environments.

6.2 Deficiencies in the study

This study encountered several challenges and limitations, which highlight areas for further research and improvement:

Sampling Depth: The research focused only on surface litter samples from a coast with significant marine debris accumulation. Future studies should consider sampling deeper layers of litter that have accumulated over time, as these could provide valuable insights into the weathering processes of marine debris.

Micro-litter Extraction: The methodology for extracting micro-litter was limited to basic manual techniques, targeting only debris visible to the naked eye. Advanced methods involving chemical treatment, precipitation, and filtration could potentially extract smaller and more varied sizes of litter.

Elemental Composition Analysis: The study's examination of the elemental composition of plastic samples primarily focused on the presence of titanium and its environmental impact. Further research should include a broader range of elements to gain a more comprehensive understanding of the debris' composition and sources.

Challenges with Foam Debris Analysis: Foam debris, due to its soft, porous, and fragile nature, posed challenges during analytical procedures. It often compressed or ruptured under pressure, leading to skewed results that reflected the composition of the sample-carrying table rather than the debris itself. This indicates that Fourier Transform Infrared (FT/IR) spectroscopy may not be suitable for analyzing such materials.

Determining Geographic Origin: The geographic origin of debris was primarily inferred from text, drawings, and symbols on the litter. However, most debris lacks such identifiable information, making it challenging to trace its origins. Additionally, the difficulty in identifying the original product from hard plastic fragments complicates the research into the sources of marine debris.

Plant and Beach Color Similarity: In autumn and winter, the color of the plants closely resembles the color of the beach, posing a challenge in distinguishing between the two during image color zone processing. Despite the advancement from traditional counting methods to image binarization

techniques in surveying plant coverage, the data still requires adjustments to reflect actual conditions more accurately.

Wind Speed Measurement Limitations: The instantaneous nature of wind speed, which varies rapidly over time, presented a challenge in this study. The accuracy and quantity of instruments used were limited, hindering the ability to precisely replicate a coastal wind speed cross-section map. This limitation impacts the reliability of data regarding how wind influences marine debris distribution.

Need for a Mathematical Model: To quantitatively assess the capability of coastal plant communities in trapping marine debris, a comprehensive mathematical model is necessary. Such a model would consider the interplay of various elements within the coastal environment. The current study's approach relies on inferential analysis of these factors, which may not fully capture the complexity of the interactions between plant communities and marine debris.

Overall, these limitations underscore the need for more sophisticated and diverse research methodologies to enhance our understanding of marine debris, its sources, composition, and environmental impact. Improving these aspects of research will contribute significantly to the field of marine pollution studies and aid in the development of more effective mitigation and management strategies.

6.3 Research prospects

The tracing of marine debris origins necessitates more sophisticated analytical techniques. In this study, the primary method involved collecting and analyzing litter samples from coastal areas. While it is possible to trace the geographic and anthropogenic sources of samples that contain information about the product type and its origin, most fragmented plastic debris lacks such identifiable data. The fragmentation of plastic products results from long-term weathering and deterioration influenced by various environmental factors, including UV radiation, seawater corrosion, and gravel friction.

To develop mathematical and theoretical models for plastic deterioration, representative types of plastic commodities not exposed to natural environments are subjected to weathering simulation experiments. These experiments observe the deterioration process over different time dimensions, allowing for the control of various influencing factors and the simulation of weathering conditions. This approach aims to understand how plastics with different polymer compositions break down in environmental settings.

Quantifying the pattern of action in which plant communities catch litter remains a challenge, as current research is limited to observations of established environmental situations. A fundamental method to quantify the litter debris capture capacity of plant communities involves building a mathematical model. This model would account for the litter debris abundance variable and simulate coastal environmental elements that affect this behavior, such as wind movement, vegetation cover, and dune topography.

Further research into the role of plant communities as natural barriers to marine debris transmission in coastal environments can provide valuable insights and potential solutions to the marine debris problem. Understanding and quantifying the impact of these natural barriers is crucial for developing effective strategies to mitigate marine debris pollution.

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卒業された先輩たちには、外国で勉強する旅に出たばかりの私に数え切れないほど手を差し伸べてくださり、私の悩みを解決してくださり、勉強や生活の経験を分かち合ってください、温かい仲間に誘ってください、海外に一人でいる不安を解消してくださり、それ以来一緒に過ごした大切な友人になってくださいました。特に、日本に来てから最も親密な友人となった王燦さんには感謝したいと思います。彼女の温かい人柄のおかげで、人生の苦しさから引き離され、日本社会を体験し、溶け込むことができ、人生で大きな打撃を受けた時、抱きしめて心の支えとなってくれた彼女は、5 年前に出会った時の思いと同じように、私にとって一生の宝物になると思います。

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平凡な家庭から私を懸命に引き上げてくれ、より高く広い世界を見ることができるよう支えてくれた両親に誠にありがとうございました。愛なる母を信じられないほど懐かしく思い、あなたの子供は当初の夢を実現しました。

数え切れないほどの昼と夜、笑いあり、苦しみあり、挫折あり、成功あり、私に勝てないものは、やがて私が強くなるのを見るだろう。