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Supply Chain-Based Coral Conservation: The Case of Mozuku Seaweed Farming in Onna Village, Okinawa

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Abstract: Blue foods, including seaweed, have been overlooked in food systems analysis and policy-making due to a lack of available data. However, seaweed cultivation is gaining attention as a restorative aquaculture that could contribute to ocean health by serving as blue carbon or nurturing seagrass beds. Commercial restorative aquaculture may provide market-based solutions for improving ocean health. The Onna Village Fisheries Cooperative producers have been restoring corals, knowing empirically that when the coral weakens, the yield of Mozuku seaweed drops. Furthermore, measures taken to reduce red soil run-off prevent the reduction in Mozuku quality and quantity and protect seagrass beds, since Mozuku cultivators have continued to use them as an important nursery. The fishery cooperative and the seaweed processing company, Igeta Takeuchi Co., Ltd., have jointly developed high-quality Mozuku that is resistant to climate change and extreme weather conditions through strain selection. Based on this case, this paper examines the following questions: (1) What quality assurance technique is necessary to continue restorative aquaculture as a market-based solution over the long term? (2) What social platforms and communication channels are available to stakeholders to maintain restorative aquaculture in the long run? To answer these questions, Japanese consumer cooperatives that established "the Mozuku Fund" are also examined. This case study of Mozuku highlights how the sustainability and quality of marine products are maintained throughout the whole supply chain, focusing on the power of the Japanese consumers' cooperative.

Keywords: algae; *Cladosiphon okamuranus*; restorative aquaculture; Satoumi; Japanese consumer cooperatives; blue carbon; market-based solution

Citation: Omoto, R.; Uehara, M.; Seki, D.; Kinjo, M. Supply Chain-Based Coral Conservation: The Case of Mozuku Seaweed Farming in Onna Village, Okinawa. *Sustainability* **2024**, *16*, 2713. https://doi.org/10.3390/su16072713

Academic Editors: Giada La Scalia, Amparo Goncalves and Helena Oliveira

Received: 19 December 2023
Revised: 8 March 2024
Accepted: 11 March 2024
Published: 26 March 2024

1. Introduction

1.1. Seaweed among Other 'Blue Food'

Blue food is 'food derived from aquatic animals, plants or algae that are caught or cultivated in freshwater and marine environments' [1]. Global demand for blue food is expected to be nearly doubled by 2050 compared to the volume of 2015 [2]. Holistic analysis of the status of blue food was led by the Stockholm Resilience Centre at Stockholm University and Stanford University's Center for Ocean Solutions and Center on Food Security and the Environment in 2019 to enhance our understanding of the importance of blue food in the global food system and therefore to influence the policies and practices that will shape future food systems [1]. According to the assessment, blue foods offer greater nutritional benefits than terrestrial animal foods and have a smaller environmental footprint. Although 70% of the planet is covered by water, only 2% of our caloric intake comes from the ocean. It is expected that increasing the consumption of blue food can ensure food security in an eco-friendly way that benefits both people and the planet.

Despite their nutritional and livelihood importance, until recently, blue foods have been excluded from food systems analysis or policy-making [3], and this fails to represent the varietal diversity of blue food by overlooking aquatic plants, seaweed, and other aquatic animals [1]. A trend toward mainstreaming them has occurred since the early 2020s, including FAO's "Blue Transformation—Roadmap 2022–2030: A vision for FAO's work on aquatic food systems", published in 2022 [4]. However, fishery stock within the biologically sustainable level in 2019 was 64.6%, a fall from 90% in 1974 [5], and we cannot expect much increase in wild-caught seafood production. On the other hand, due to limited data availability, seaweed and aquatic plants are not included in the above-mentioned Naylor et al.'s [2] demand estimate, and the potential contribution has not yet been discussed.

A study comparing chicken, which is said to be the most efficient terrestrial protein produced in terms of climate footprint (i.e., greenhouse gas emissions, freshwater use, land occupation, and nitrogen and phosphorus emissions for blue foods, reported per tons of edible weight), with various blue foods found that bivalves and seaweed have the lowest environmental impact [6]. In addition, seaweed especially draws much attention since it does not require land, freshwater, or chemicals [7]. The current global market size for algae was USD 14.7 billion in 2019 (first-sale value), contributing to the livelihood of households in coastal communities [8].

"Seaweed as a nature-based climate solution-vision statement", published by the United Nations Global Compact in 2021 [9], states that seaweed is a highly scalable nature-based solution that allows for both decarbonization of the economy and carbon sequestration from the ocean surface and recommends further expansion of seaweed cultivation and increased investment into seaweed-based products. The nature-based solution is defined as "actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges" (p. xii), and the societal challenges include climate change, food security, water security, disaster risk, human health, and economic and social development [10].

Blue bonds were first issued in the Seychelles in 2018. From then until 2022, 26 blue bond transactions totaling USD 5.0 billion took place [11]. Bosmans et al. [11] raise concerns about bonds without impact metrics and suggest blue carbon as one of the measurable indicators for the effective growth of the blue economy. "Blue carbon" has gained attention recently as a global trend as we strive to build a carbon-neutral society. The word characterizes the carbon taken up by the ocean because of the actions of marine or coastal organisms, but it is not generally known that marine ecosystems absorb carbon dioxide at a rate equal to or greater than land ecosystems [12]. The United Nations Global Compact report recommends implementing "Blue carbon payment systems" to reward seaweed farmers for their carbon sequestration contributions, and businesses should communicate the climate benefits of seaweed accurately and consistently to mitigate climate change. Shallow coastal ecosystems, which cover less than 0.5% of the ocean area, sequester over half of the carbon stored in the ocean [12]. Shallow coastal waters have a strong capacity to sequester carbon, making them a subject of interest in recent years [13], and many studies have worked on accurately estimating the CO_2 sequestration capacity of aquatic plants found in shallow water, including seagrass [12–14]. It is said that seaweeds have a higher carbon sequestration capacity than land plants [15] and hold great promise not only for use as a food resource but also for reducing CO_2 emissions [16]. Algae farms are also expected to play an important role as blue carbon [17], and support for expanding seaweed cultivation is growing worldwide.

While seaweed can contribute to mitigating climate change, there are also concerns about the negative impact climate change will have on algae farming. A study measuring the impact of climate change on blue foods, including algae, has found that algae are relatively less affected compared to other blue foods [18]. Although the impact is small, the impact of severe weather on algae is relatively large compared to the other impacts, including diseases and chemicals. Additionally, the same study lists Japan as the country most affected by severe weather in terms of marine production quality.

Seaweed Farming in the World Now and in the Future

Algae can be defined as 'A highly diverse group of mainly aquatic, autotrophic, photosynthesizing organisms ranging from microscopic single-cell forms to multicellular forms, distinguished from vascular plants by the absence of structures such as true roots, stems, leaves and flowers' (p. 224). This includes multicellular macroalgae (e.g., seaweeds), unicellular microalgae (e.g., *Chlorella* spp.), and Cyanobacteria, which are not true algae but are informally known as "blue-green algae" (e.g., *Spirulina* spp.)" [4].

Globally, algae production has increased rapidly in recent years [7]. By wet weight, algae (including seaweeds and microalgae) contribute almost 30 percent of the world's aquaculture production volume [8]. Regarding brown seaweed, the production volume increased by 10.9% annually between 1950 and 2019 [8].

Due to cultural reasons, current seaweed production is concentrated in Asian countries, accounting for more than 97% [8]. A study that estimates the potential area for marine algae farming in the world using species distribution models shows that about 20.8 million km^2 of ocean (up to 13.8% of the economic exclusive zones) is suitable for algae farming [19]. Of the top five countries with high potential—Australia, Indonesia, Russia, Canada, and the United States—all but Indonesia currently produce less than one percent of global seaweed [19]. Farming seaweed is being explored in various regions across the globe, such as Europe and North America [20,21]. However, there are some obstacles, like regulatory, technical, and market-related barriers, that need to be addressed [22]. Global seaweed production is anticipated to rise, which may impact the environment, economy, and society.

To realize this degree of (positive) effect at successive scales of influence, it is necessary to pay attention to both technical and policy components of managing aquaculture and the importance of each concerning market and non-market drivers. The market can reward industries that adopt sustainable and innovative approaches that can encourage further innovation, and there is an opportunity to monetize the industry's effectiveness in supporting broader ecosystem function and repair through the continued growth of market value [23].

1.2. Restorative Aquaculture—The Market-Based Solution

A specific type of aquaculture in the ocean similar to regenerative agriculture on land—"Restorative aquaculture"—is attracting attention. Restorative aquaculture has been receiving increasing attention in the industry [24], providing substantial ecosystem services and socio-economic benefits [8]. Restorative aquaculture occurs when aquaculture provides direct ecological benefits, potentially generating net-positive environmental outcomes [23]. There are similar concepts and terms for restorative aquaculture, including conservation aquaculture [25], ecological aquaculture [26], and ecosystem approach to aquaculture [27], among others.

The Nature Conservancy first developed the principles of restorative aquaculture in 2021 (Table 1). Alleway et al. [28] added the data availability in recognition of the fact that the benefit of restorative aquaculture is largely influenced by data, showing the context in which the benefit is generated.

The greatest amount of knowledge exists about the environmental benefits of bivalve and seaweed farming in the ocean, including improving water quality, providing habitat, and mitigating climate change [28]. However, given that seaweed farming is still only practiced in small areas around the world, and that seaweed species vary by region, its true environmental benefits are still unknown. In addition, investments in such nature-positive aquaculture have often been hindered by cumbersome bureaucratic licensing processes and a lack of recognition of the real ecosystem service value provided by seaweed farming activities [4].

In addition to sole restorative aquaculture practice, the Nature Conservancy [24] points out that commercial restorative aquaculture can offer "market-based solutions" (p. 11) to ocean health. Given the rapid increase in aquaculture over a short period, and the even shorter period for seaweed expansion, it is very important to share not only the concept of sustainability but also its specific sustainable techniques of seaweed production [28], processing, and distribution. Furthermore, it is even important that the seaweed supply chain including consumers comprehend the concept and the challenges and contribute back to restorative seaweed farming. The Mozuku farming case from Onna village, Okinawa provides insights into how the sustainability and quality of marine products are realized by whole supply chain stakeholders, emphasizing the power of a significant number of Japanese consumer cooperative members rather than an unspecified number of consumers at conventional retailers.

Table 1. The definition of restorative aquaculture by the Nature Conservancy [24] and Alleway et al. [28].

	Nature Conservancy (2021) [24]	Alleway et al. (2023) [28]
Principle 1	Site farms where environmental benefits can be generated.	Site farms where environmental benefits can be generated.
Principle 2	Culture species that can provide the environmental benefits intended.	Farm species that can provide the environmental benefits intended.
Principle 3	Prioritize farming equipment that enhances the delivery of environmental benefits.	Prioritize farming equipment that enhances the delivery of environmental benefits.
Principle 4	Adopt farming management practices that can enhance local environmental benefits.	Adopt farming management practices that can enhance local environmental benefits.
Principle 5	Strive to farm at an intensity or scale that can enhance ecosystem outcomes.	Strive to farm at an intensity or scale that can enhance ecosystem outcomes.
Principle 6	Recognize the social and economic value of the environmental benefits provided.	Contribute data, information, knowledge, and technical capacity to enable quantification and recognition of environmental, social, and economic benefits.

Many studies have highlighted the importance of restorative aquaculture and its potential as a market-based solution. However, few papers provide details on the market structure, supply chain relationships, and financial flow necessary to realize the positive impact of certain types of aquacultures. In addition, it is also important to consider the cultural uniqueness of seaweed as food in the context of restorative aquaculture. The objective of this paper is to explore the role the supply chain, including consumers, plays in restorative aquaculture. The research question to be answered are the following: (1) What quality assurance technique is necessary to continue restorative aquaculture as a market-based solution over the long term? (2) What social platforms and communication channels are available to stakeholders to maintain restorative aquaculture in the long run? The hypothesis of this paper is that for restorative aquaculture to be viable as a market-based solution in the long term, it must involve not only economic incentives but also other socio-economic platform(s).

2. Materials and Methods

2.1. Methods

This paper uses data analysis, literature reviews, interviews, and observations. Data provided by Onna Village Fisheries Cooperative and Igeta Takeuchi Co., Ltd. were analyzed together with seaweed production statistics of Okinawa, which are publicly available. A series of interviews with members of Onna Village Fisheries Cooperative and managers of consumer cooperatives were conducted between 2018 and 2023. Observations were conducted on boats and in the water at seaweed farming grounds. Also, the seaweed processing factory was visited in July 2023.

2.2. The Case Study—Onna Village Fisheries Cooperative

Okinawa's subtropical climate allows cultivating crops that cannot be grown on Japan's main island. The largest industry in Okinawa is commerce, specifically tourism. In Okinawa, the fishery industry centers on the coral reef ecosystem, a tourist resource. As a result, their coexistence and sustainable use are of great concern. The value of fishery production in Okinawa Prefecture in 2019 was JPY 21.047 billion, of which JPY 9.147 billion was from marine aquaculture. Furthermore, about half of the marine aquaculture industry's output, JPY 4363 million, is accounted for by Mozuku [29], which is the subject of this paper. In this way, Mozuku is extremely important as a fishery industry in Okinawa Prefecture. Additionally, areas for marine activities such as snorkeling often overlap with areas used for Mozuku cultivation.

The Ryukyu Archipelago is in the southwestern area of Japan's mainland and extends about 1200 km southwest between the southern mainland of Japan and northwestern Taiwan. The archipelago defines the boundary between the East China Sea and the Pacific Ocean and consists of three islands: the Satsunan Islands (Tanegashima Island to Yoron Island), the Okinawa Islands (Okinawa Island and adjacent small islands), and the Sakishima Islands (Miyako, Ishigaki, Iriomote, Yonaguni Island, and small adjacent islands). The Kuroshio current, known as a warm current, moves northward from the east of the Philippines to the coastline of Japan and gives the Okinawan region (Okinawa Islands and Sakishima Islands) its subtropical ocean climate. In Okinawa, which is surrounded by coral reefs, there is a food culture that eats macroalgae, and Mozuku is said to be one of the foods that has been supporting Okinawans in longevity [30]. Unless they are particularly distinguished, the term Mozuku in this paper refers to both the genus *Cladosiphon* and *Nemacystus* as it is the common name for both species.

Cladosiphone okamuranus is an endemic species to the Ryukyu Archipelago [31]. Naturally found Mozuku has been traditionally used as an ingredient in home cooking and court cuisine since the Ryukyu Kingdom era (established in 1429 and destroyed in 1879) [32,33]. *Nemacystus decipiens* is distributed from mainland Japan (the southern coast on the Sea of Japan side and the central and southern coast on the Pacific side) to the Okinawa Islands [34], with Okinawa Island and Kume Island being the southern limit of its distribution [35]. For a long time, wild *Nemacystus decipiens* was harvested and used raw or salted in areas where it was produced, but due to limited production areas, the species was not eaten nationwide [36]. Although the farming of this species had been established, it is still not widely distributed or well known among consumers due to its small production. It has been confirmed that the species occurs in several places on Okinawa Island, but there seems to be no evidence that Okinawans actively used it as food before the 1970s [35]. The morphological characteristics of sporophyte *N. decipiens* include a filamentous, thin body with many branches and a high mucilage richness compared to *C. okamuranus*. Both species are significant sources of fucoidan, which is a general term for sulfated polysaccharides found in the bodies of brown algae [37,38] and is a so-called functional component effective for human bodies.

2.3. "Mozuku" Production in Okinawa and Onna Village Fisheries Cooperative

Okinawa accounts for more than 99% of the nation's Mozuku production. The annual production volume and the production value are shown in Table 2 [39]. The unit price, which is obtained by dividing the amount by the quantity, is also displayed, and it fluctuates considerably. In addition, many fishery cooperatives sometimes must adjust production or stop harvesting due to overstock or unpredictable price drops.

Onna village is located along the northwestern coast of Okinawa Island, and the long and narrow shape of the village has approximately 46 km of coastline. Extensive coral reefs adorn its shores. The village boasts 3000 hectares of shallow waters less than 50 m deep protected by coral reefs. The coastline has all been designated as the Okinawa Coast Quasi-National Park, positioning it as one of the leading marine resort areas in Japan. The population of the village is about 11,000; however, a total of 2.94 million tourists stay overnight in Onna each year.

Established in 1970, the Onna Village Fisheries Cooperative (OVFC) consisted mainly of local fishermen from Onna Village. Fishery cooperatives (gyogyo-kyodo-kumiai) in Japan are established with fishermen as members based on the Fisheries Cooperative Act (Act No. 242 of 1942). Fishing rights have been established in most of Japan's coastal waters based on the Fishery Act (Act No. 267 of 15 December 1949). A fishery right refers to a fixed gear fishery right, a demarcated fishery right, or a common fishery right. Fishing rights are granted to each fishery cooperative, and by belonging to that fishing cooperative, fishermen can use the fishing ground. For this reason, fishery cooperatives form the basis of the management of Japan's coastal fisheries ground and resources.

Table 2. The annual production volume and the production value of Mozuku seaweed in Okinawa (USD 1 = JPY 109, the average exchange rate in 2019).

	2006	2007	2008	2009	2010	2011	2012
Volume (10 ton)	2161	2233	1560	1181	801	1305	1616
Value (million yen)	4131	2566	1295	992	801	1580	2134
Price/kg (yen)	233	114	83	84	100	121	132
(Price/kg USD)	(2.13)	(1.04)	(0.76)	(0.77)	(0.91)	(1.11)	(1.21)
	2013	2014	2015	2016	2017	2018	2019
Volume (10 ton)	1533	1930	1445	1511	1925	2186	1640
Value (million yen)	2116	2645	2080	2463	3271	3630	4363
Price/kg (yen)	138	137	144	163	169	166	266
(Price/kg USD)	(1.26)	(1.25)	(1.32)	(1.49)	(1.55)	(1.52)	(2.44)

As of 2023, the cooperative has 224 union members, of which 100 are regular members, and oversees the No. 6 demarcated fishery right, which is set for the coastal waters of Onna Village. Most of these regular members are involved in seaweed cultivation and coastal fishery. In fiscal year 2022, the production volume was 1126 metric tons, with a substantial value of JPY 360.66 million (approximately USD 2.4 million). In particular, brown algae "Mozuku" cultivation accounts for approximately 90% of this volume and contributes 50% of the total production value (Figure 1).

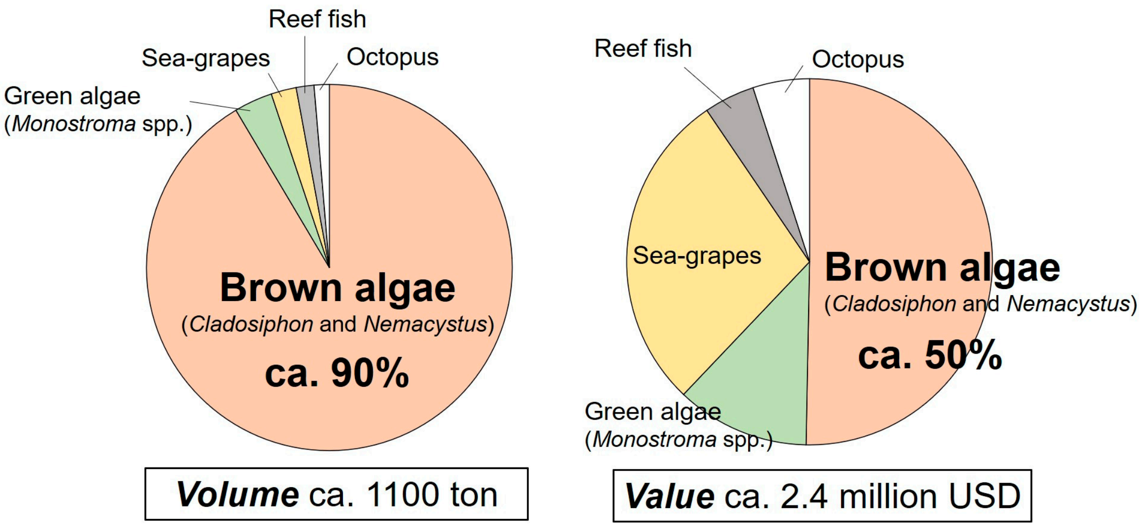

Figure 1. Catch volume and value at Onna Village Fisheries Cooperative in fiscal year 2022.

The major cultured brown algae "Mozuku" in Okinawa includes the genus *Cladosiphon* and *Nemacystus*. All of the types of Mozuku farmed at the OVFC are *Cladosiphon okamuranus* ("Hon-/Futo-Mozuku" in Japanese), *Nemacystus decipiens* ("Ito-/Hoso-Mozuku" in Japanese), and *Nemacystus decipiens*, the Onna-1 strain ("Onna-Mozuku" in Japanese) (Figure 2).

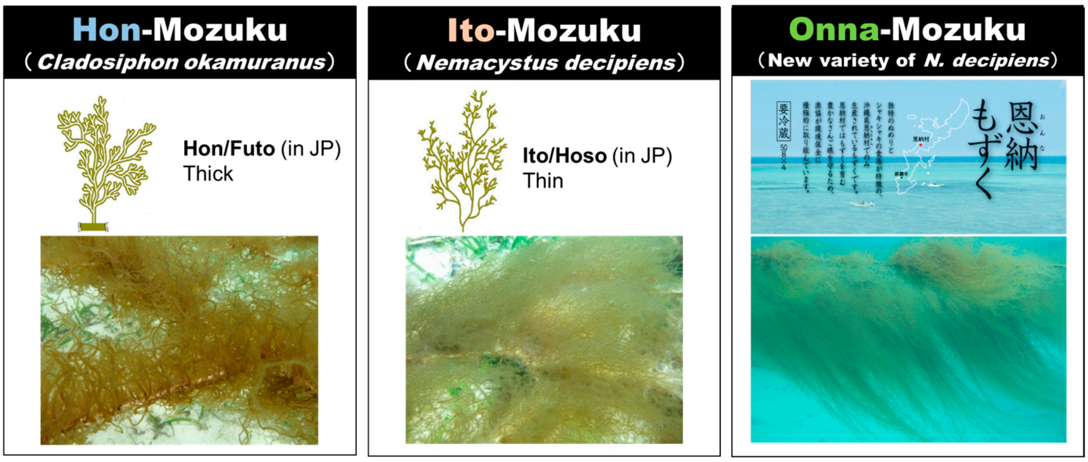

Figure 2. All types of Mozuku farmed at OVFC: *Cladosiphon okamuranus* ("Hon-/Futo-Mozuku" in Japanese), *Nemacystus decipiens* ("Ito-/Hoso-Mozuku" in Japanese), and *Nemacystus decipiens, Onna-1 strain* ("Onna-Mozuku" in Japanese with the package design explaining its unique texture as this is a new product at market place).

The cultivation method of Mozuku, which requires an intermediate nursery on seagrass beds and the setting of cultivation nets just above the beds, was discovered by a member of the Mozuku study group at the OVFC, and in 1977 it was the first cultivation success for the species in Okinawa Prefecture. Since its cultivation success, the species has been actively cultivated all over the prefecture as the demand for this seaweed as a healthy, low-calorie, high-fiber food has increased.

Over the past four decades, three different local strains of *Cladosiphon okamuranus* have been mainly cultivated on Okinawa Island: the K-strain (the initial letter of discovery location), which has thicker and more robust lateral branches, originated from the Katsuren coast; the O-strain, which is characterized by its compact, smaller lateral branches, collected from the Onna coast; and the C-strain, which strikes a balance between intermediate-sized and slender lateral branches, from the Chinen coast [40–42]. Using genome analysis, Nishitsuji et al. [42] suggested that these uniquely morphed strains were indeed different at the sub-species level. In addition, the result of a yield test for K- and O-strains shows that the biomass yield of the former species was higher than that of the latter species [43]. In the future, the quality of each strain, including sliminess and texture, will be revealed, and these genetic and breeding results may be more useful for selecting superior strains and developing new strains.

Although the OVFC succeeded in developing the farming method of *C. okamuranus*, its location on the west coast made it more susceptible to northwesterly winter winds than production areas on the east coast of the Okinawa main island, limiting production. In addition, the production methods for *C. okamuranus* were transmitted in different parts of the prefecture, and the price began to fluctuate according to overall production volume. Therefore, the OVFC changed its policy to survive on quality rather than quantity and began to cultivate *N. decipiens* in the early 1980s, which was considered technically difficult at that time. The OVFC has been working on the stable production of *N. decipiens*, but in Okinawa, the southern limit of its distribution, it was essential to develop a variety that was tolerant to high temperatures and less gristly. A turning point was reached in 1993. Okinawa Prefectural Fisheries Experiment Station and Okinawa Prefectural Fisheries Extension Office (now Okinawa Prefectural Fisheries Research and Extension Center) established a seeding production method for a free-living concoelis of *N. decipiens* (see [44]). This method made it easier to manage its seedings than the conventional method and enabled a more efficient expansion culture before seeding, thus saving labor in the production process of its mother plant. This technique could also be used to cross strains with useful traits.

2.4. The Supply Chain Approach and the Case Study

The alternative food supply chain, also known as the short food supply chain, is a movement that aims to establish a direct relationship between producers and consumers. It seeks to move away from long-distance, industrialized, and uniform food commodities and instead focus on creating new quality recognition associated with locality, environmental conservation, and new forms of production–consumption networks [45]. There are three types of short food supply chains: (1) face-to-face, in which consumers buy a product directly from the producer or processor through a face-to-face transaction and authenticity and trust are secured in person; (2) spatial proximity, in which products to be purchased are made within a specific region within that region, valuing locality; and (3) spatially extended, in which the value and meaningful information about the place of production and the people involved in producing the food are transmitted to consumers who are not located in the region where the food is produced. These consumers may have no personal experience of the region where the food is produced.

The Mozuku supply chain in Onna begins with individual producers growing Mozuku, harvesting it, and landing it on the OVFC's primary storage facilities. The landed Mozuku is weighed by OVFC staff, and after initial cleaning, it is salted at a specified saltiness to keep the quality of the algae body. The salted Mozuku is then transported to Igeta Takeuchi, Co., Ltd., a manufacturing company in Tottori, for processing. This paper presents an example of restorative aquaculture based on algae cultivation using the Mozuku farming case in Okinawa and also examines what types of seaweed distribution forms and schemes can support market-based restorative aquaculture.

3. Results

3.1. Mozuku Production as the Creation of Satoumi

Coral reefs are the center of the productive activities for producers of the OVFC and are home to a variety of organisms, which are distributed in a zonal distribution roughly parallel to the shore. Such distribution is formed by a gradient of various physical and chemical environmental parameters from shore to offshore where the coral reefs are. Producers use the shore-side tidal flats as a cultivating area for the green algae "Hitoe-gusa" (*Monostroma nitidum*), seagrass beds as an intermediate nursery for Mozuku, and lagoons as a final cultivating area for Mozuku, giant clams (*Tridacna* spp.), and corals (mainly *Acroporidae*). The OVFC has a concept that fishery/seaweed farming activities are a part of coral reef ecosystems. Coral reefs as fishing grounds are sensitive to climate change and land-based pollution, and algae cultivation also requires clean seawater and bottom sediments [46]. The Satoumi concept is defined as the coastal sea with high biodiversity and productivity with active human intervention [47,48] allied with restorative aquaculture.

The production volume of *C. okamuranus* at the OVFC has shown an increasing trend since 1977 and has fluctuated repeatedly since 2000, generally remaining between 300 and 1000 tons (Figure 3). The production of *N. decipiens* has been gradually increasing since 1986, when its aquaculture began in Onna Village, and has shown an increasing trend with repeated fluctuations since 1993, when the cultivation method for a free-living concoelis was established (Figure 3). The OVFC began the mass production of *N. decipiens* in 1995, and since then the OVFC has selected and bred strains that are tolerant to high water temperatures and less sinewy and has repeatedly tested their cultivability with producers. In 2007, it accounted for more than half of the prefectural total production, making the OVFC one of the leading producers in the prefecture. There were no landings in 2010, 2011, and 2015 because no production took place due to assertive inventory adjustments. In addition, there was an El Niño in 1998, 2016, and 2019, and the winters tended to be warmer.

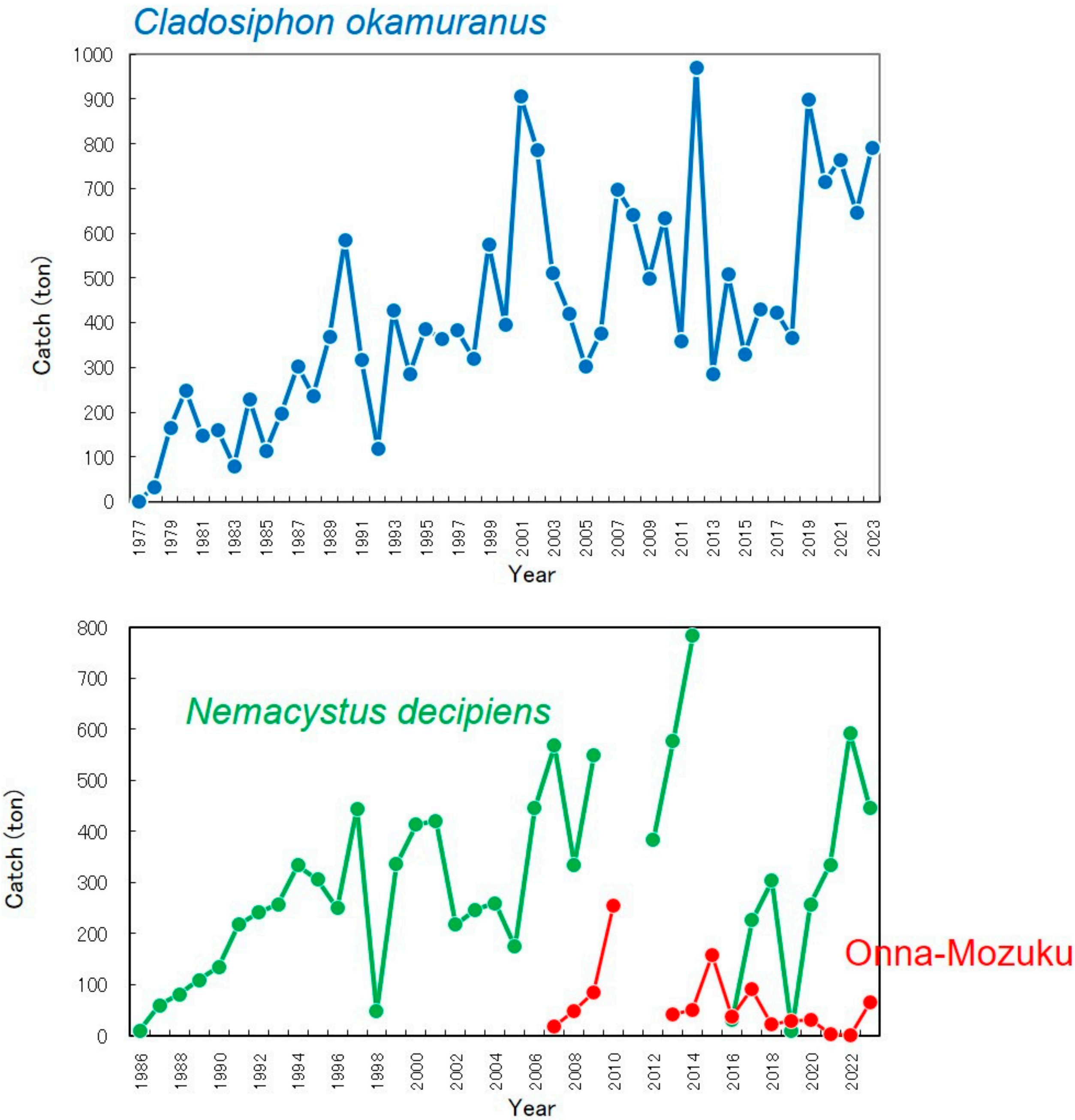

Figure 3. Yearly harvest amount of three types of Mozuku: The blue line with circle markers indicates *Cladosiphon okamuranus*. The green and red lines with circle markers also show *Nemacystus decipiens* and Onna-Mozuku, respectively.

As for *N. decipiens*, although the production volume of the Onna-1 strain (commonly "Onna-Mozuku" in Japanese) increased rapidly after experimental farming began in 2007, it has been declining since 2013, except for 2011 and 2012, when it was not produced (Figure 3). As a private brand, there are still many challenges to the stable production of Onna Mozuku, including understanding the proper timing of seeding and intermediate/main cultivation.

As a result of these efforts, the production of *N. decipiens* has been steadily increasing and has now become an established specialty of Onna Village. This long-term effort of more than 20 years has also led to developing a new strain.

Mr. Munekazu Mekaru, a Mozuku producer from the OVFC, discovered the mother plant of Onna-Mozuku in 2007. The seed-saving technique was developed by Mr. Yoshimi Higa, who worked in a leadership service division of the OVFC. Repeated trial cultivation of this species was also conducted by the OVFC and fishermen, and it became the first brown algae variety in Japan to be registered by the Ministry of Agriculture, Forestry, and Fisheries in 2011. It is still exclusively cultivated in Onna Village, making it a rare strain that accounts for only a few percent of the total Mozuku production in Okinawa Prefecture. After repeated quality evaluation by the OVFC in collaboration with the manufacturer Igeta Takeuchi, Co., Ltd., they developed the product of the new strain in 2008. Onna-Mozuku has a good texture and sliminess, which is quite different from *C. okamuranus* and *N. decipiens*. The production is unstable due to the short history of cultivation, and the technique is not yet fully established. Currently, the OVFC and fishermen are conducting experimental trials to stabilize the production of Onna-Mozuku. In addition, the genome of the Onna-1 strain has been sequenced [49].

3.2. Procedures and Techniques for Cultivating Three Types of Mozuku

It is relatively easy for producers to cultivate Mozuku adapted to the environment of Onna Village's coral reef waters, i.e., the O-strain of C. okamuranus, the original of Onna Village. However, it presents challenges due to its short main axis and high branch density, which results in a lower yield per culture net—a drawback for processing. While the O-strain shows a higher increase in functional ingredients during aquaculture compared to K- and C- strains of the species [50], its texture as a product is harder and less slimy, and it has a dry characteristic compared to these K- and C- strains. On the other hand, Onna-Mozuku has no major processing problems and is highly regarded as a product, but there are concerns about stable production. At present, efforts are being made to select a well-balanced strain of *N. decipiens* with both high productivity and a strong commercial reputation that minimizes processing problems. Therefore, the Mozuku to be cultivated must be a well-balanced variety that considers both productivity and processing characteristics and value as a commodity.

The OVFC currently determines the production schedule each year based on biological information such as the life cycle of *C. okamuranus* and *N. decipiens* (see [51,52]), as well as available environmental information such as the prediction of El Niño and La Niña occurrence, seawater temperature, and sea surface height anomalies. These have been repeatedly converged based on previous cultivation trials and the observations/experiences of producers. The cultivation procedures for the three types of Mozuku cultivated in Onna Village are as follows, and the basic processes (seed collection and preservation, mass cultivation of seeds, seeding nets, intermediate cultivation, main cultivation, and harvesting) are similar.

3.2.1. Seed (Spore) Collection, Preservation, and Mass Production

Spores are collected from each species' sporophytes (mother plants) before and during the harvest season. The washed mother plant is left standing in a closed water environment to isolate spores derived from plurilocular zoosporangium in *C. okamuranus*. In *N. decipiens*, spores and conchocelis derived from the assimilatory filaments and plurilocular zoosporangium are isolated under high salinity and high nutritional conditions (the late Yoshimi Higa, unpublished data). In repeated isolation, cleaned spores are stored in a liquid or agar medium until they are used for mass production. Large-scale cultivation is carried out in polycarbonate tanks after spore incubation under aeration with flasks from early summer in a culture room where room temperature can be controlled.

For *N. decipiens*, the OVFC has selectively bred mother plants that are tolerant to high temperatures. Currently, given recent climate changes, efforts are being made to obtain mother plants with a high and broad ability to adapt to environments (both high and low seawater temperatures).

3.2.2. Seeding Nets and Intermediate Nursery

Producers seed their nets each year according to a seeding schedule. The seeding of *N. decipiens* starts at approximately the end of October and *C. okamuranus* at the beginning of December. Onna-Mozuku starts in the intermediate period between both. Before seeding, producers layer five to six nets together. Seeds are seeded in an aquarium on land using seeds distributed by the OVFC. In either species, after seeding in a land tank for approximately seven to ten days, the seeded nets are transferred to seagrass beds at a depth of less than 1 m. They are cultivated until they are juvenile plants (approximately three to ten cm in height). At this time, the nets should be laid out loosely. During this period, the producers regularly conduct "weeding" of other unwanted seaweeds, excluding Mozuku from their nets. Although there are many unknowns about the relationship between seagrass beds and the sprouting of Mozuku, choosing an intermediate nursery is essential because its quality affects production, and it depends on the producer's experience and speculation.

3.2.3. Net Installation for Primary Cultivation

The stacked nets are moved to seagrass beds or coral gravel bottoms offshore from the intermediate nursery area. At this time, the fishermen take apart the stacked nets and tightly tie them one by one to metal stakes. This is called "Honbari" in Japanese. Producers continue to remove other algae from their nets regularly until harvest.

Especially for *N. decipiens*, there is a unique cultivation technique that takes advantage of the geographical and climate conditions of Onna Village and the ecological characteristics of the species. This method is called "Machiburasa" in the Okinawan dialect. For Onna Village, storms often occur in winter, causing the sporophytes of the species to break off and float in the sea. If some non-seeded nets are placed next to or on top of nets conducted in the main cultivation, the floating sporophytes become entangled in non-seeded nets and grow from there. The quality of the species deteriorates when the nets from which the sporophytes are tangled are forcibly removed from the main nets, so this is carried out based on the fishermen's experience, considering the current of the farm ground and the timing of the removal. For this reason, OVFC fishermen can produce high-quality *N. decipiens* with less gristly texture and less of a mixture of other seaweeds.

3.2.4. Harvesting

At the OVFC, harvesting is carried out while monitoring the growing period from intermediate cultivation to harvest, as well as the actual quality of the sporophyte. Harvesting is usually conducted in a team of two or three people. One or two people harvest the Mozuku underwater using suction pumps, while the remaining person on board sorts out foreign objects and fills the Mozuku into baskets. When Mozuku is unloaded at the fishing port, a quality inspection is conducted before proceeding to the initial treatment. A unique feature of the OVFC is that although it is a cooperative, each producer's Mozuku is sent to the processing company in a state in which individuals can be identified. The reason for this will be explained in Section 3.3. Each producer is paid a fee based on the quantity and quality of their landed products, providing an economic incentive to improve quality.

3.2.5. Producer's Eyes

Mozuku producers belonging to the OVFC have a common understanding of the quality of good Mozuku through annual meetings hosted by the OVFC and Igeta Takeuchi Co., Ltd. at the end of production season, although production methods and techniques are left up to each individual as they are the sole proprietors. Mr. Kinjo, as a co-author of this paper and a Mozuku grower, shares the following tips and observations about Mozuku farming.

The length of the net is aligned with the direction of the tidal swell. This way, the net is less likely to be carried away by rough waves. High water temperatures are not good for the growth of Mozuku, but large fluctuations in water temperature also seem to be bad. This is because the Mozuku is constricted, making breaking from that part easier. Regarding *N. decipiens*, when the seawater temperature is high in March, it loses its sliminess, turning whitish and withering. Just like on farmland, algae other than Mozuku also grow on the nets, so manual weeding is required. It is also necessary to remove foreign substances from the harvest on the boat.

Regarding determining the harvest timing, if Mozuku is too young, it will easily dissolve when preserved with salt. Also, if it is too hard, the texture will not be good. When Mozuku releases its seeds at spring tide, they become slimy, so one should try to harvest them before spring tide.

By cultivating Mozuku with new characteristics on a trial basis, the OVFC has obtained Mozuku that is suitable for processing and adapted to the environment. Several producers have the eyes to find Mozuku with different characteristics. Mr. Kinjo is one such producer, and when he happens to find Mozuku with different characteristics, he brings it to the researchers at the OVFC and they check the difference in strains together. This kind of regular observation will lead to the continued production of Mozuku in the future, coping with climate change and market demand. In addition, the visits to the processing company that Mr. Kinjo started in 2009 when he was the Fisheries Cooperative youth group director continue to this day, with young producers visiting each year (Figure 4). One of the reasons producers visit processing plants on the mainland to check the quality of Mozuku is to confirm the traits that make it suitable for processing mutually between producers and the processing company. Another reason is that producers usually do not see the condition of salted and transported Mozuku and how it affects processing. Through such exchanges, processing companies understand which types of Mozuku are easy for producers to produce, and producers mutually understand the characteristics of Mozuku that are suitable for processing.

Figure 4. Young Mozuku producers belonging to OVFC and the quality managers of Igeta Takeuchi exchange opinions on the characteristics of Mozuku at Igeta Takeuchi's quality laboratory (incl. how it changes with salting) (copyright: Onna Village Fisheries Cooperative).

3.3. OVFC's Mozuku Production in Collaboration with the Processing Company

When salted Mozuku arrives from the OVFC, Igeta Takeuchi Co., Ltd. inspects every batch of Mozuku in the laboratory for sliminess and texture. The results are compared among three to four inspectors since the inspection of Mozuku partly depends on the experience of the quality control personnel. Figure 5 shows the records of inspections from January to March 2022, where sliminess and fiber (texture) were each evaluated on a five-point scale.

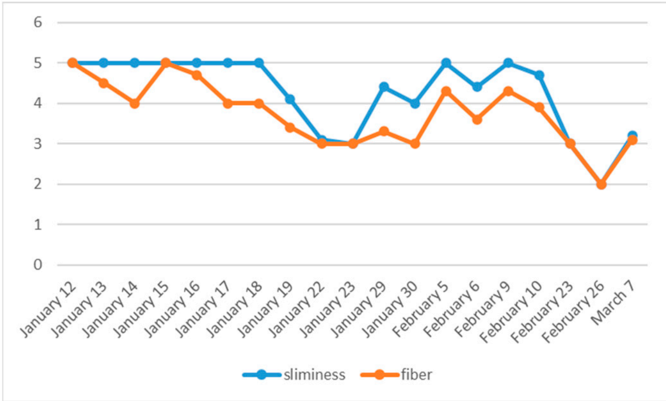

Figure 5. The result of sliminess and fiber of Mozuku (the higher the better).

Meanwhile, Mozuku processing at the plant begins with washing the Mozuku to remove salt and debris. Afterward, the seaweed is blanched to remove its unique odor and sterilized by heating. Therefore, the quality evaluation is also performed, assuming the state of Mozuku after this heat processing. The removal of foreign substances is conducted in a way that allows producers to be distinguished (traceable back to each producer) so the results can be shared with the producers themselves and can be used to improve quality the following year (Figure 6).

Figure 6. "Sorting process foreign matter report" with foreign substances found during manual sorting, mostly a part of aquaculture nets. The hand writing in each column show the production site, batch number, amount and a factory tank number. Whose harvest it was discovered in and when it was discovered is recorded and returned to the producer (copyright: Igeta Takeuchi Co., Ltd.).

The most common way to enjoy Mozuku in Japan is a seasoned Mozuku called Ajitsuke-mozuku, which is sold in small packages at retail stores nationwide. Igeta Takeuchi Co., Ltd. was the first company in Japan to develop and sell packaged seasoned Mozuku in 1971. "Ajitsuke Mozuku" is seasoned with vinegar (Igeta Takeuchi Co., Ltd. uses rice vinegar or brown rice vinegar). Vinegar has the role of adding acidity and flavor and maintains quality through its antibacterial effect, mainly against E. coli. However, vinegar also has the property of softening brown algae (because alginic acid, which plays a role in holding algae, is eluted into the seasoning solution). Depending on the characteristics of the Mozuku species, Futo-mozuku (*C. okamuranus*) will melt and become pasty, while Ito-mozuku (*N. decipiens*) will have slimy components separated from the algae. Therefore, it is necessary to prepare a seasoning liquid that is optimal for taste, hygiene, and texture, and this varies depending on the type of Mozuku. The current product expiry date is set to 21 days. Processing must be performed to ensure texture and food safety during this period. The physical characteristics of the two types of Mozuku from the processing and processing techniques perspective are as follows.

Futo-mozuku (*C. okamuranus*) is valued for its ‘crunchiness’. The quality is also evaluated by considering the maturity level, shape, harvest status, and freshness of the Mozuku. In the case of Futo-mozuku, if it grows too much, the algae body will absorb water during processing and crumble, making it difficult to use in products. Additionally, if the freshness is low (due to poor cultivation conditions, poor preservation, or storage conditions such as salting), the algae may dissolve. Futo-mozuku products are designed to take advantage of their crunchy texture. Depending on the product, the amount of Mozuku (solid amount) per seasoning liquid is also large, so the texture of Mozuku is emphasized.

For Ito-mozuku (*N. decipiens*), the evaluation criteria are that it has a lot of ‘sliminess’, its ‘fibers’ are thin, and that there are no streaks in the algae (which is rarely seen these days because of improvements in seedlings and aquaculture techniques). In addition, the evaluation considers the algae’s maturity (immature ones are easily affected by vinegar), slime properties (wateriness other than the amount of sliminess), the shape of the algae, harvest status, freshness, etc. This is an empirical evaluation based on the Mozuku quality of the final product, which is also reflected in the rating. Igeta Takeuchi Co., Ltd. designs products to take advantage of Ito-mozuku’s ‘smooth texture’ and ‘soothing feeling going down the throat” due to the rich sliminess of Ito-mozuku, resulting in a product with a refreshing flavor and less sweetness. From the perspective of products manufactured using processing equipment, Ito-mozuku that is too slimy and Futo-mozuku that is too fresh and crunchy (such as the O strain), which are highly evaluated in terms of quality and texture, are hard to handle in the processing procedure.

In this way, the improvement in the quality of Mozuku products results from frequent communication and many years of co-creation between the producers, the fishery cooperatives, and the processing company.

4. Discussion

4.1. The Role of Mozuku Cultivation beyond the Food Supply: The Challenges and Countermeasures

Mozuku production in Okinawa, in general and specific to the OVFC, faces a series of challenges from terrestrial influences, coral reef degradation, and high water temperatures.

Onna Village receives a total of 2.94 million tourists who stay overnight each year. Many large resort hotels were built from the late 1970s to the 1980s. This period coincides with the time when the OVFC established the cultivation technology for Mozuku and began harvesting it.

In particular, the naturally distributing red soil run-off in the northern part of mainland Okinawa Island often flows directly into the ocean. That is because it is often affected by natural environmental factors such as heavy rain squalls, the steep slopes and short rivers typical of island regions, and human factors such as agricultural activities and development. The red soil run-off accumulates in lagoons with pool-like topography and has several negative effects, such as reducing photosynthesis of seaweeds and seagrasses due to turbidity and inhibiting zoospore/coral planula settlement [53,54].

Conflicts between developers and the OVFC led fishermen to protest marches by boats in 1986. As a result of many years of protests and consultations, the OVFC now plays a central role in managing sea surface use [55]. For example, rules have been established to prevent conflicts over the use of fishing grounds in Onna Village’s waters. It is required to consult the OVFC before starting out any marine leisure businesses in this area, and OVFC member vessels must be used for diving operations. Additionally, the Onna Village Environmental Conservation Ordinance stipulates that resort wastewater must undergo advanced treatment. In Onna village, when large-scale development is undertaken, countermeasures are required to be discussed at the Red Soil Runoff Prevention Council, which consists of the municipality, the ward, the OVFC, construction companies, and others.

Figure 7 shows the Suspended Particles in Sea Sediment (SPSS) values of 20 points in the estuary of Onna Village measured by the OVFC producers between 2010 and 2015. SPSS is a convenient measuring method of monitoring soil run-off and was developed in 1985 [56]. The sedimentation monitoring method is widely accepted in Okinawa due to its fast measuring times, mobile and simple operation, and lack of requirement for special equipment [57]. Boxes, central lines, interval lines above and below each box, and circles indicate 25th–75th quartiles, median, max, and min distribution values, and outlier values, respectively. The number below each point's initial letters indicates the pollution level, and a rank of six or higher (50 kg/m^3) is considered to be clearly contaminated by anthropogenic red soil or other run-off.

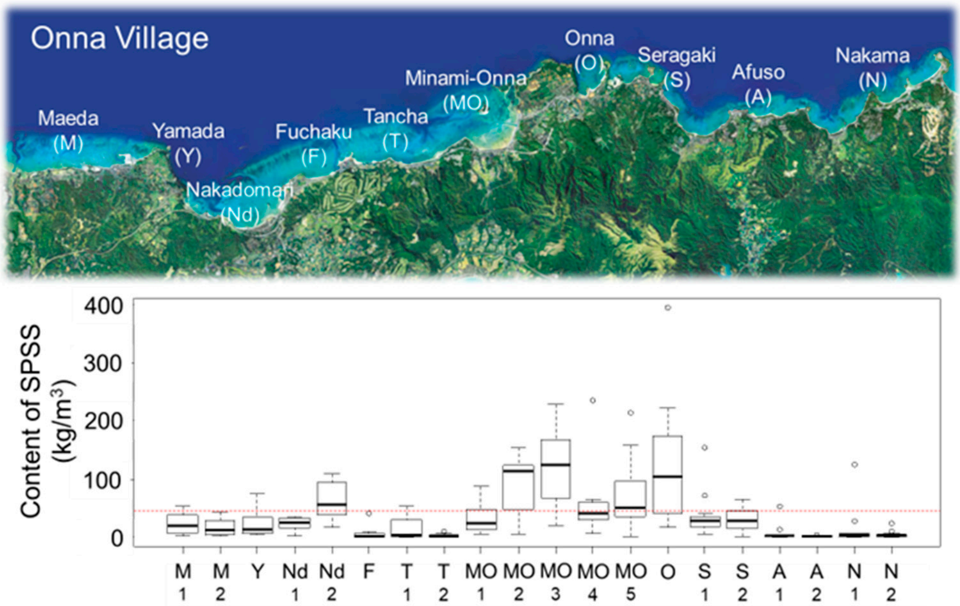

Figure 7. SPSS values of 20 points in the estuary of Onna Village measured by producers between 2010 and 2015. Values above the red dotted line indicate anthropogenic red soil run-off.

Measured red soil values in Onna Village are generally lower than in other areas in the northern region of Okinama main island because the entire region has taken preventive measures and established a system to monitor red soil run-off, and fishermen themselves have monitored and pointed out run-off conditions based on scientific evidence (Figure 7). However, further improvements are required because facilities to prevent red soil run-off are not functioning and run-off from agricultural lands, which are not covered by the monitoring system, is observed. Farmers in Onna Village are aging more rapidly than fishermen, and the labor and expense of implementing red soil run-off countermeasures pose a significant challenge. Currently, Onna Village Agro-Environment Coordinator Mr. Ryo Kirino is working tirelessly to establish sustainable measures, both in terms of finances and manpower. For example, the Honey & Coral Project transforms fallow land into flower gardens, generating both honey and revenue while reducing red soil run-off [58].

The fishermen have learned from experience that the production of Mozuku tends to be stable in the area where the corals are healthy, so they carry out activities to nurture the coral reef sea, such as cultivating parent corals and controlling the density of crown-of-thorns starfish (*Acanthaster planci*) as the predator of corals. In addition to tides, the flow of seawater on coral reefs is strongly influenced by topography and waves. During winter as well, sea surface temperatures in this environment remain higher compared to the rest of Japan; this temperature rarely drops below 15°(Celsius).

OVFC producers believe that a healthy coral reef ecosystem, including corals, seagrass beds, and sand and gravel bottoms, is essential for Mozuku production. Therefore, since the late 1990s, they have been dedicated to nurturing healthy and diverse coral reefs in Onna Village. They focus on caring for coral parents and promoting their spawning [59]. Sea surface temperatures in the seas around Japan have exhibited decadal-scale fluctuations, and the average rate of sea surface temperature increase is +1.24 °C per 100 years, which is higher than the global rate of sea surface temperature increase (+0.60 °C per 100 years) [57]. Recent climate change, represented by frequent El Niño and La Niña events, has significantly affected the stable production of seaweed aquaculture in the OVFC. Production of *N. decipiens*, which is at the southern limit of its natural distribution, is particularly susceptible to the effects of climate change. While the OVFC has been involved in selecting and breeding mother algae that are tolerant to high temperatures, given recent climate changes, there is a need to develop strong Mozuku varieties that can thrive within a wider range of suitable water temperatures. The OVFC continuously engages in selecting and breeding strains capable of withstanding environmental exposure each year to ensure stable production. In parallel with this effort, the OVFC was actively collaborating with Igeta Takeuchi Co., Ltd. to assess our products' quality.

As mentioned above, OVFC producers have worked to preserve and restore coral reefs to ensure the stable production of Mozuku. Measures taken to reduce red soil run-off not only prevent the reduction in Mozuku quality and quantity but also protect seagrass beds since Mozuku cultivators have continued to use seagrass beds as an important nursery. Seagrasses are known to be extremely important for maintaining ecosystems, but their area is decreasing dramatically around the world [60]. Seagrasses are disappearing at a rate of 110 km^2/year and nearly 30% of what we had in 1879 has disappeared [61]. Conservation monitoring is conducted around the world; however, it is often carried out at a scale that is too coarse or too infrequent to detect changes effectively [62]. This highlights the importance of conserving and monitoring the seagrass bed by the OVFC as their Mozuku nursery ground and accumulating data daily. Although it has been reported that the area of seagrass beds is decreasing due to the influx of red soil into the ocean in Okinawa [63], at least 189.94 ha of healthy eelgrass beds remain in Onna Village [64]. According to Onna Village, 11 species (three families) of seagrass inhabit the lagoon in Onna [65].

Mozuku cultivated by the OVFC is harvested, so the amount of blue carbon stored in the ocean is not large, but it is believed to exhibit a certain level of carbon sequestration during the cultivation period. In addition, since seagrass beds are used in Mozuku farms, healthy seagrass beds are essential and it will be possible to assess the blue carbon effect of seagrass beds to some extent. However, there are few studies on tropical and subtropical seagrasses, and the details are unknown. In recent years, a report on the carbon dioxide fixation ability of *C. okamuranus* was published [60] describing that it can fix 3.6 g C m^{-2} (0.034 g C m^{-2} d^{-1}). The whole picture of the blue carbon effect for *C. okamuranus* is still unknown, and future research including *N. decipiens* is expected.

In this sense, quantitative evaluation of environmental, economic, and social benefits through data accumulation, which is one of the principles of restorative aquaculture [24,28], is extremely important. Thus, the OVFC's efforts with related organizations to promote seaweed farming and coral reef nurturing activities in response to climate change can be considered pioneering, as producers are implementing climate change mitigation and adaptation measures while collecting data including water temperature, sea surface height anomalies, events related to El Niño and La Niña, water quality, and crown-of-thorns starfish population density.

4.2. The Role of the Market

One of the research questions in this paper is, "What quality assurance technique is necessary to continue restorative aquaculture as a market-based solution over the long term?". As explained in Section 3.3, the basis of long-term relationships is a shared definition of quality between producers and processing companies, as well as a mutual understanding of the constraints imposed on each by the natural environment and food processing sites. From the perspective of producers' livelihoods, this close relationship in the supply chain is also reflected in the price of Mozuku. When the unit price of Mozuku was JPY 83 or 84 per kilogram around 2008 and 2009 (Table 2), the unit price at the OVFC was JPY 120. Figure 8 shows unit prices for Okinawa Prefecture as a whole and the OVFC before and after 2009. As mentioned above, although the OVFC produces more *N. decipiens* than other fishermen's cooperatives, this comparison focuses on *C. okamuranus*, because producing *C. okamuranus* is the mainstream in the prefecture and the actual price trend is also greatly influenced by *C. okamuranus*. It should be noted that the unit price for Okinawa as a whole includes *N. decipiens*, but judging from the total amount, the unit price trend is largely influenced by *C. okamuranus*. The unit price at the OVFC has almost always been higher than Okinawa's average and it never goes below JPY 120. Most of all, unlike other fishery cooperatives, the OVFC never has to adjust production or stop harvesting due to overstock or extreme price drops.

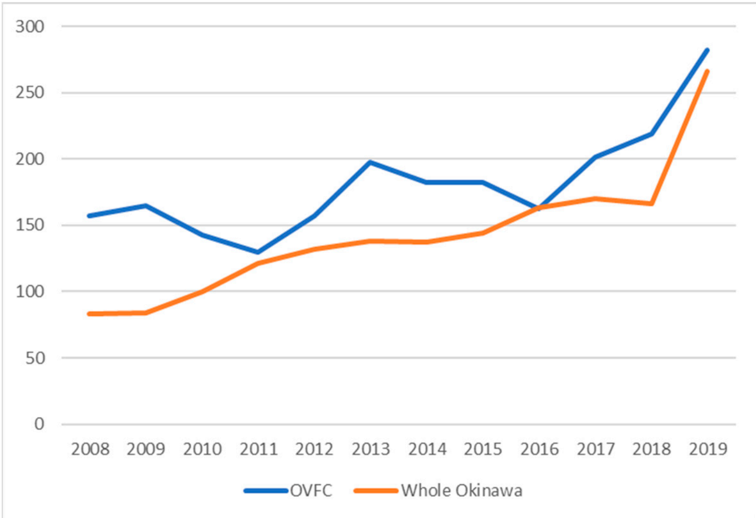

Figure 8. The Mozuku unit price (yen/kg) comparison between OVFC and the whole of Okinawa.

To address the second research question, "What social platforms and communication channels are available to stakeholders to sustain restorative aquaculture in the long term?", it can be stated that the OVFC mainly markets its Mozuku to consumer cooperatives throughout Japan. Co-ops in Japan have both stores and home delivery services, but in the case of home delivery, customers place orders by looking at a weekly order catalog. The amount of information in the catalog helps inform consumers about the activities behind the Mozuku produced by the OVFC, such as coral conservation and soil run-off prevention. The OVFC started planting multiplied corals in 1998, and a few consumer co-ops joined this activity in 2007. From then until the end of 2022, 43,646 corals were planted (Figure 9). The Mozuku Fund (Mozuku Kikin) scheme was established in 2009 to support this activity as a whole supply chain. One package of seasoned Mozuku is sold, and about one yen (almost equivalent to one cent) is returned to the OVFC. Since then, consumer co-ops from all over Japan have participated one after another. The number of consumer household members of these co-ops is about 6 million in total. There were 6.1 million packages of Mozuku products sold through this scheme in 2022, and 34,160 corals were planted through the support of consumer cooperatives over the years. Consumer cooperatives participating in this program also provide their members opportunities to visit production areas. Producers are also offered opportunities to ride together in delivery trucks (Figure 10), allowing consumers and producers to interact with each other on various occasions. This interactive distribution is also a feature of the consumer cooperatives participating in the Mozuku Fund. This project involves consumer participation across Japan, all contributing to the development of Onna Village's Satoumi [47]. As a result of these efforts, the coral cover in the coastal area of Onna Village has exceeded 50%, making it an exemplary model of Satoumi creation for coral reefs in the sub-tropical regions.

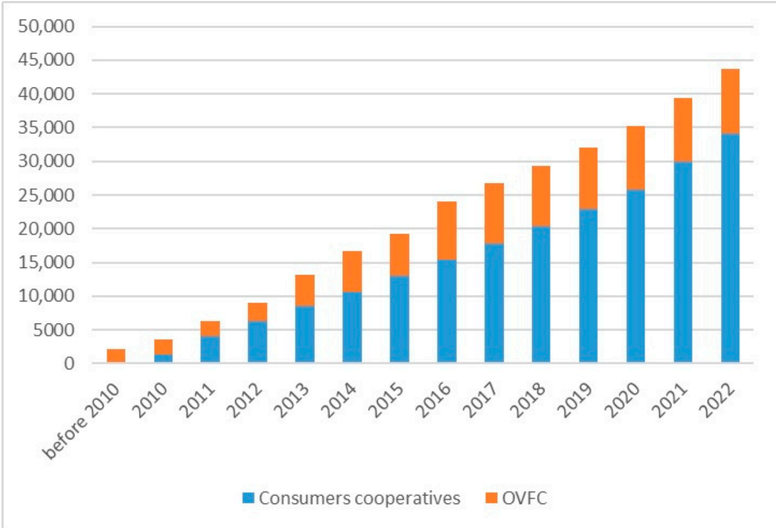

Figure 9. The number of corals planted by OVFC and consumer cooperative all over Japan.

Figure 10. A young Mozuku producer on the delivery truck of Palsystem Consumers' Co-operative, one of the consumer cooperatives that operates around Tokyo (copyright: Onna Village Fisheries Cooperative).

Market-based solutions [24] mean that commercial restorative aquaculture can offer environmental solutions for ocean health. Reflecting on the OVFC case, we have concluded that the entire supply chain needs to be involved in solving both the environmental and socio-economic issues of the producers and production area. This can be achieved by developing and selling products that highlight the locality. As for aquaculture techniques that improve the quality, especially for *C. okamuranus*, other production areas will eventually catch up, so it will be difficult for OVFC's producers alone to carry out Mozuku aquaculture as a form of restorative aquaculture while reaping economic benefits. In the case of the Onna Village Fisheries Cooperative, one way to solve this problem is to carry out Satoumi conservation, which involves working with each distribution stakeholder for many years.

Japanese consumer cooperatives have become the world's largest organizations in terms of membership and turnover, and they are characterized by strong member participation [66]. They established a distinct business model centered around a weekly catalog and order system, focusing on home delivery and strongly emphasizing social and environmental activism. The difference between large-scale retail stores and consumer co-ops is that because consumer co-ops are membership-based, the characteristics of products are communicated to a specific number of people rather than to an unspecified number of people. Through the Mozuku Fund system, each distribution stage is seamless, sharing issues concerning the ocean in Onna Village and supporting the conservation of coral in Onna Village's ocean. A two-way exchange has been established in which the entire distribution chain, including consumers, resolves environmental issues in production areas. In 2017, the government of Onna Village joined this initiative as a partner, which means that the private sector's coral conservation centered on algae farming has been incorporated into official government policy.

The OVFC's Mozuku case discussed in this paper falls into type 3 of the supply chain approach [45], which seeks to be spatially extended, meaning that the value and meaningful information about the place of production and the people involved in producing the food are transmitted to consumers who are not located in the region where the food is produced. As Marsden et al. [45] adds, "Notable here are the additional identifiers which link price with quality criteria and the construction of quality. A common characteristic, however, is the emphasis on the type of relationship between the producer and the consumer in these supply chains and the role of this relationship in constructing value and meaning rather than solely the type of product itself" (p. 425). The relationship between producers and consumers characterizes Japan's consumer co-op system, and consumers are not only interested in simply consuming Mozuku but also have a good understanding of its environmental significance and climate challenges.

4.3. Conclusions

In recent years, the further use of blue foods has been advocated [4]. Seaweed is currently underused, has the potential for increased production, and is gaining attention due to its low environmental impact. Restorative aquaculture occurs when aquaculture provides direct ecological benefits, potentially generating net-positive environmental outcomes [24]. This is very similar to the Satoumi concept [47,48], which claims that ocean biodiversity increases with appropriate human intervention. In this paper, we first explored what quality assurance technique is necessary to continue restorative aquaculture as a market-based solution over the long term. The OVFC has been working on coral conservation from an early stage based on this Satoumi concept, focusing on the interactions between Mozuku growth and coral health. In addition, they are devoted to pursuing the quality of Mozuku as food, and at the same time, they continue to select strains that can cope with climate changes, such as high water temperatures. It is not easy to find suitable strains for processing that have good taste and texture and are adaptable to climate change. In addition to climate change, the OVFC has also responded to environmental changes and impacts from the land area, such as soil run-off caused by heavy rainfalls and agricultural activities, as the impact of severe weather on algae aquaculture will increase [18].

"Alternative Food Networks" (AFNs) are a practice and an academic body of literature concerning the emergence of alternative food practices as a reaction against industrial, standardized, globalized, and unethical food systems [67,68]. Represented by practices such as community-supported agriculture, fair trade, and farmers' markets, AFNs explore a new form of food provisioning connecting rural producers (production area) and urban consumers [69]. The term localization is often associated with AFNs and is discussed in two senses; one focuses on the close geographical proximity to where food is produced, represented by direct "face-to-face relations". In the broader sense, food localization is defined as attempts of practices to enhance transparency in production and distribution channels and to connect the identities of the production area and producers to products while communicating the unique values of the area to the wider world [70]. It does not make sense to define an AFN over distance in this context [69]. This type of AFN has also been discussed and centered on social "embeddedness" linking food to place. However, this analysis mainly focused on consumer–producer relationships, and little attention was paid to the mechanism within AFNs to redistribute and capture value [68,71].

This leads to our second research question: "What social platforms and communication channels are available to stakeholders to maintain restorative aquaculture in the long run (and over the distance)?". Laginová et al. [69] points out that AFN models are often built upon organizational innovations, which are often associated with introducing information and communication mechanisms.

Consumer cooperatives involved in the supply chain of the OVFC's Mozuku are membership-based and offer home delivery, and themselves have been a form of AFN with a strong focus on social and environmental activism. In this regard, the consumer cooperatives in this case study are the type of AFN associated with the broader sense of localization and function as a social platform enabling stakeholders to maintain environmentally/economically sustainable Mozuku production. More specifically, to redistribute and capture value in the Mozuku distribution, the Mozuku Fund works as a communication channel in this case. The Mozuku Fund labels (showing an illustration of coral and fish) on each package of Mozuku products capture values other than economic value and visually articulate the redistribution of economic gain to restorative aquaculture practices. Notably, consumer cooperatives can have a large number of members and generate social impact. In this type of AFN, irrespective of geographical distance, trust born through proximity, such as face-to-face relations, is supplemented and substituted by the scheme proving "authentication", such as certifications and labels [72].

A study of the carbon dioxide fixation ability of *C. okamuranus* has been published [58]; however, the whole picture of the blue carbon effect for *C. okamuranus* is still unknown, and future research including *N. decipiens* is expected. Such research could expand the possibilities of the role of locally appropriate commercial algae farming as a climate change mitigation measure and the importance of market-based solutions worldwide.

Author Contributions: Conceptualization, R.O. and M.U.; resources, M.U., D.S. and M.K.; data curation, M.U. and R.O.; writing—original draft preparation, R.O. and M.U.; writing—review and editing, R.O.; funding acquisition, R.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by JSPS KAKENHI grant numbers JP19K13443, JP19H00555.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Publicly available datasets were analyzed in this study and data can be found where indicated in the reference list.

Conflicts of Interest: Author Masato Uehara was employed by the organization Onna Village Fisheries Cooperative. Author Daigo Seki was employed by the company Igeta Takeuchi Co., Ltd. Author Masaru Kinjo was an Onna Village Fisheries Cooperative member with a cooperative investment. The remaining author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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