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Long-term changes in the *Zostera* bed area in the Seto Inland Sea (Japan), especially along the coast of the Okayama Prefecture

Zostera bed
Long-term change
Pollution
Reclamation
Transparency

Herbier de *Zostera*
Changement à long terme
Pollution
Gains de terrain sur la mer
Transparence

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ABSTRACT

The Seto Inland Sea is the largest enclosed sea in Japan (22,000 km^2 surface area), and is very shallow (average depth of 37 m). Large *Zostera marina* L. beds throughout the Sea play an important role in its ecosystems and environments. This study reviews the long-term changes in the area of the *Zostera* beds, as well as some direct and indirect environmental factors which influence their distribution. In 1924, the area of the beds was 4,137 ha in the waters of the Okayama Prefecture. By 1989, 87 % of these beds had been lost. Industrialization and urbanization around the coasts of the Seto Inland Sea began in the 1950s. In the 1960s, the area of the *Zostera* beds in this Sea amounted to 22,625 ha. Since 1977, 70 % of these beds has been lost. This decline is attributed to: a) reduced water transparency as a result of nutrient load increases and intensive drag-net operations (reversible effects: modification); and b) reclamation by coastal development and port construction activities (irreversible effects: destruction). It is estimated that the former was responsible for the loss of 44 % of the *Zostera* bed area, while the latter destroyed 40 % of the *Zostera* bed area in the Okayama Prefecture, between 1924 and 1977. Both types of destructive effects have been restricted since the enactment of a law on the environmental conservation of the Seto Inland Sea in 1973. However, most of the *Zostera* beds have not recovered. Only in Ajino Bay in the Okayama Prefecture has there been an extension – from 192 ha in 1977 to 710 ha in 1991. Limited reclamation activities, increased transparency, and the prevention of drag-net operations by the laying of artificial reefs have made regeneration possible.

RÉSUMÉ

Évolution à long terme de l'herbier de *Zostera* devant les côtes d'Okayama (mer intérieure de Seto, Japon).

La Mer intérieure de Seto est la plus grande mer fermée du Japon (22 000 km^2) mais elle est peu profonde (37 m en moyenne). De grands herbiers de *Zostera marina* L. jouent un rôle très important dans cet écosystème et dans son environnement. Le présent travail examine l'évolution à long terme des herbiers de *Zostera* et les facteurs directs et indirects qui déterminent leur répartition. En 1924, l'étendue de l'herbier était de 4 137 ha dans les eaux de la province d'Okayama. Une réduction de 87 % a été constatée vers 1989.

L'industrialisation et l'urbanisation des côtes de la mer intérieure ont commencé dans les années 1950. Une dizaine d'années plus tard, l'étendue de l'herbier de *Zostera* était de 22 625 ha. Depuis 1977, celle-ci a diminué de 70 %. Les causes de ce phénomène peuvent être classées en deux catégories : a) réduction de la transparence de l'eau due à une augmentation de la concentration en nutriments et à la pêche extensive par dragage (les altérations qui en résultent sont réversibles) ; b) conquête de terrains sur la mer en raison du développement côtier et des constructions portuaires (les destructions qui en résultent sont irréversibles). On attribue à la première cause la disparition de 44 % des herbiers de *Zostera* entre 1924 et 1977, et à la seconde la destruction de 40 % de l'herbier dans les eaux de la province d'Okayama.

Les dommages sont en diminution depuis 1973 grâce à une loi sur la protection de l'environnement dans la mer intérieure de Seto. Pourtant la plupart des herbiers de *Zostera* ne sont pas encore régénérés. Une reprise n'a été constatée que dans la Baie de Ajino (province d'Okayama) où l'herbier passe de 192 ha en 1977 à 710 ha en 1991. Les surfaces plus faibles gagnées sur la mer, la réduction de la turbidité de l'eau et la limitation des dragages par des récifs artificiels favorisent la régénération des herbiers de *Zostera*.

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INTRODUCTION

The Seto Inland Sea is the largest enclosed sea in Japan (22,000 km^2 surface area; 6,600 km total coastline; 800×10^9 m^3 volume), and is very shallow, with an average depth of only 37 m (Fig. 1). In this Sea there are two species of *Zostera*, *i.e.* *Z. japonica* Miki and *Z. marina* L. The former grows only in the intertidal zone, while the latter grows in the subtidal zone. *Z. marina* has had much greater distribution area than *Z. japonica*. Before the 1950s, extensive *Z. marina* beds existed in the Seto Inland Sea (except in Kii Channel, Bungo Channel, and Osaka Bay). Their total area is greater than that of other seagrass and seaweed populations in the area. Hereafter, the term "*Zostera* beds" will be used for the sake of simplicity, instead of "*Z. marina* beds".

Zostera beds play an important role in shallow marine ecosystems and environments (*e.g.* Orth *et al.*, 1984; Kikuchi and Pérès, 1977; Burrell and Schubel, 1977). Because there is an abundance of fish production in such beds, they contribute to coastal fisheries in the Seto Inland Sea (Hoshino, 1972; Saitoh, 1979). The work performed for this paper examines long-term changes in the *Zostera* bed area in the Seto Inland Sea, with special reference to the waters of the Okayama Prefecture (Fig. 2). Some environmental factors influencing *Zostera* beds are discussed in relation to these long-term changes. Mechanisms involved in the decline and regeneration of *Zostera* beds are also discussed.

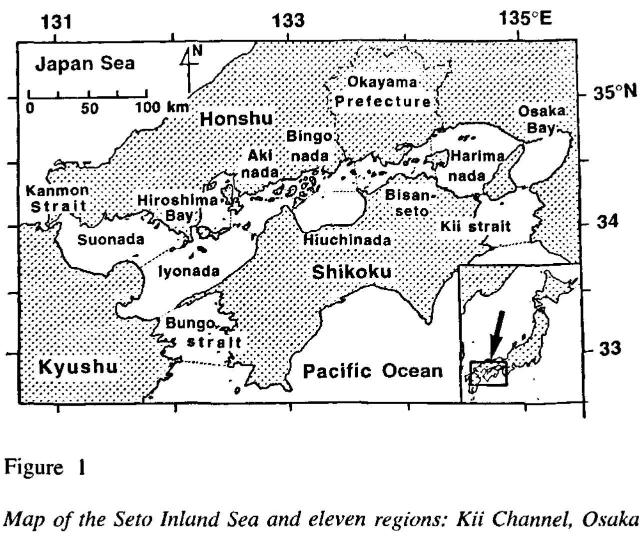

Figure 1

Map of the Seto Inland Sea and eleven regions: Kii Channel, Osaka Bay, Harimanada Sea, Bisanseto Sea, Bingonada Sea, Hiuchinada Sea, Akinada Sea, Hiroshima Bay, Hiuchinada Sea, Iyonada Sea, Suonada Sea, Bungo Channel.

METHODS

Data on long-term changes in *Zostera* beds

Historical data concerning *Zostera* beds in the Seto Inland Sea were obtained from previous research (Anon., 1967, 1974, 1996). Data on distribution were collected by two methods: a) questionnaires on the distribution of the beds addressed to fishermen and their cooperatives; and b) transect-line investigations by diving or observations from a boat involving experts from the prefectural fisheries

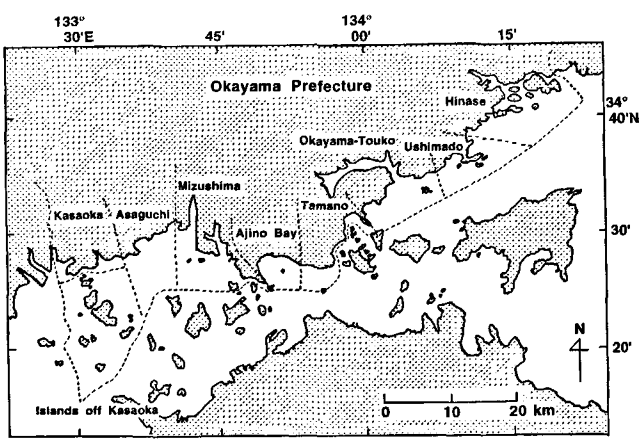

Figure 2

Map of nine districts in the waters of the Okayama Prefecture.

experimental stations on the coast of the Seto Inland Sea; c) aerial photography investigations (Saitoh, 1979). Data were compiled and classified according to the following six regions: Harimanada Sea; Bisanseto Sea; Bingo-Hiuchinada Sea; Akinada Sea including Hiroshima Bay; Suonada Sea; and Iyonada Sea (Fig. 1). The other regions (Osaka Bay, Kii Channel and Bungo Channel) were omitted due to the sparse distribution of *Zostera* beds. All these data were used to construct Figures 3 and 4.

Data for *Zostera* beds in the waters of the Okayama Prefecture are based on the methods of a) and b) (Anon., 1924*a*, 1925, 1926*a*; Inoue, 1927), and the methods of a), b) and c) Katayama *et al.*, 1979 by the Okayama Prefectural Fisheries Experimental Station. Komatsu (1994) estimated the *Zostera* bed area from a boat equipped with a Geographic Positioning System (GPS) in Ajino Bay in 1991. Figure 7 was constructed from these data.

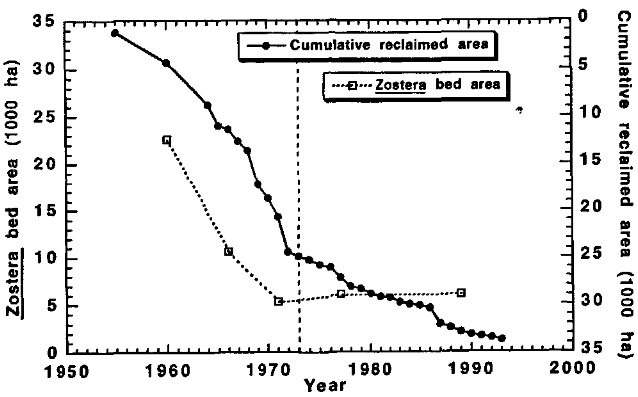

Figure 3

Chronological changes in Zostera bed area (open square) and cumulative reclaimed area (Closed circle) in the Seto Inland Sea between 1955 and 1992 (data source: see *text). The latter was plotted on the reverse vertical axis (right hand side axis). A vertical dashed line relates to the year when the law on the environmental conservation of the Seto Inland Sea was enacted.*

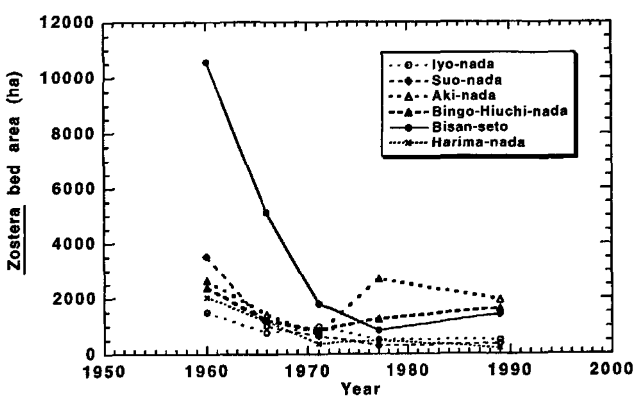

Figure 4

Chronological change in Zostera bed area by region in the Seto Inland Sea from 1960 to 1989 (data source: see *text).*

Data on long-term changes in environmental factors

Reclamation of the shallow subtidal zone in the Seto Inland Sea from 1965 to 1992 was investigated by the Environment Agency of Japan (Anon., 1994). Prior to this, Hoshino (1972) enumerated the total reclaimed area in 1955, 1960, 1965, and 1970. Data on cumulative reclamation from 1955 to 1992 (Fig. 3) were produced from these reports. The total reclaimed areas in the waters of the Okayama Prefecture up to 1977 are also shown in Table 1 (Katayama *et al.*, 1979).

Table 1

Zostera bed area between 1921 and 1925 and in 1977, and reclaimed Zostera bed area (data source: see *text). –: no data.*

District	*Zostera* bed area (ha) Situation in 1921-1925	Reclaimed *Zostera* bed from 1925 to 1977	Situation in 1977
Hinase-Bizen	(130)	0	210
Ushimado	954	477	74
Okayama-Touko	543	12	82
Tamano	–	20	131
Ajino Bay	827	7	161
Mizushima	812	690	0
Asaguchi	360	33	0
Kasaoka	511	466	3
Islands off Kasaoka	–	0	14

The Chemical Oxygen Demand (COD) load on the sea is an index representing a quantity of causal substances of eutrophication. The Environment Agency of Japan (Anon., 1975; 1994) calculated the COD load per day for the entire Seto Inland Sea, converting the total amount of organic substances estimated to enter the Sea from industrial and sewage discharge into a COD load. The data on COD load per day for the entire Seto Inland Sea from 1950 to 1989 were used to construct Figure 5.

Red tides occur when the sea is eutrophic. Thus, the total number of red tides is used here as an index of eutrophication. Each year, the Fisheries Agency of Japan has recorded the occurrence of red tides observed in the Seto Inland Sea. The Environment Agency of Japan also noted intermittent occurrences from 1950 to 1993 (Anon., 1975, 1994), as shown in Figure 5.

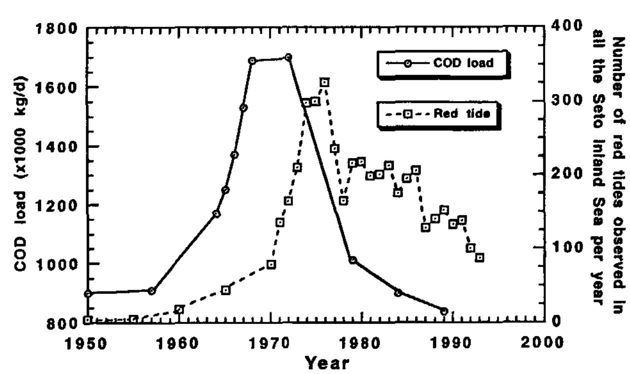

Figure 5

Estimated Chemical Oxygen Demand (COD) load per day and number of red tides due to phytoplankton bloom observed per year in the Seto Inland Sea from 1950 to 1992 (data source: see *text).*

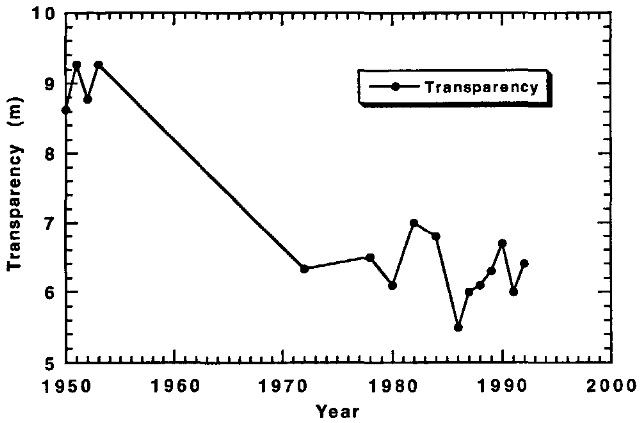

Figure 6

Chronological change in annual mean of transparency (Secchi depth) in the entire Seto Inland Sea from 1950 to 1990 (data source: see text).

Since the 1950s, transparencies have been measured at fixed stations with a Secchi disc by the fisheries experimental stations of Osaka, Hyogo, Okayama, Hiroshima, Yamaguchi, Fukuoka, Oita, Ehime, Kagawa, and Tokushima Prefectures. Since 1975, routine observations referred to as "Hydrographic Observations at Fixed Lines on Shallow Seas (*Senkai-teisen Kansoku*)" have been carried out. The Environment Agency of Japan (Anon., 1975, 1994) summarized the annual mean of Secchi disc depths in the entire Seto Inland Sea (Fig. 6).

The Okayama Prefectural Fisheries Experimental Station has measured nutrients at fixed stations in the salt waters of the Okayama Prefecture every month under the aforenamed programme since 1975. They provided time-series data of annual means of PO_4-P and Dissolved Inorganic Nitrogen (DIN) concentrations of sea water in the Harimanada and Bisanseto regions of the Okayama Prefecture between 1975 and 1992 (Fig. 8).

Since the 1920s, transparency has been measured in the waters of the Okayama Prefecture by the Okayama Prefectural Fisheries Experimental Station, which provided these data. Transparency of the sea water between February and April is a very important factor for the survival of seedlings of *Z. marina* and for increasing their distribution (Katayama *et al.*, 1979). A comparison of the horizontal distribution of transparency before (1922), during industrialization (1977) and at present (1992), was carried out in order to determine the mechanism responsible for the loss of *Zostera* beds in the waters of the Okayama Prefecture (Fig. 9). Fortunately, those in 1929 and 1977 were obtained from Katayama *et al.* (1979). The present horizontal distribution of transparency was derived from data on mean transparencies at the fixed points between February and April in 1992. Chronological data on mean transparency at the two fixed stations in the Bisanseto region (*cf.* Fig. 9) between February and April from the 1920s to 1977 (Fig. 10) were also reported by the Okayama Prefectural Fisheries Experimental Station (Anon., 1921, 1922, 1923, 1924*b*, 1926*b*, 1927, 1928; Katayama *et al.*, 1979). Figure 10 represents a collation of the above data as well as data collected between 1980 and 1992.

RESULTS

Long-term changes in *Zostera* beds in the Seto Inland Sea

The *Zostera* bed area in the Seto Inland Sea was estimated as comprising about 22,625 ha in 1960 and 11,163 ha in 1966 (Fig. 3). This area decreased to 5,000 ha by 1971 and has remained stable at 6,000 ha from 1977 to the present. It is estimated that an area of 25,000 ha was reclaimed in the Seto Inland Sea between 1955 and 1973 (Fig. 3). With the enactement in 1973 of a law restricting reclamation in order to ensure the environmental conservation of the Seto Inland Sea, the previously increasing activity of reclaiming coastal areas has been considerably reduced. However, by 1993, the total reclaimed area had reached 33,700 ha. The decrease in the *Zostera* bed area was proportional to the increase in the cumulative reclaimed area from the 1960s to the 1970s (Fig. 3).

The *Zostera* bed area in the Bisanseto region was the largest in 1960 (Fig. 4). From the 1960s to the 1970s, *Zostera* beds decreased in all regions. By 1977, the bed areas had levelled out in all regions except Bisanseto and Bingo-Hiuchi-nada, which showed an increasing trend.

During the reported period (Fig. 5) the COD load per day for the entire Seto Inland Sea was at its lowest in the 1950s. COD values increased considerably between 1968 and 1972, and then decreased gradually until 1989. The number of red tides observed annually had been very small before 1965 (Fig. 5); their frequency tides increased to a maximum between 1974 and 1976. Recently, there has been a gradual decline in frequency to one hundred. However, values are still greater than in the 1950s and 1960s. The maximum number of red tides lagged four years behind the maximum value of the COD load.

The annual mean transparency (Secchi depth) of the Seto Inland Sea in the 1950s was high at a depth of 9 m, and fluctuated around a depth of 6 m between 1970 and 1992 (Fig. 6).

Long-term changes in *Zostera* beds in the waters of the Okayama Prefecture

In 1924, the total area of *Zostera* beds in the waters of the Okayama Prefecture was 4,137 ha (Fig. 7). By 1966, this area had been halved. In 1971, the area of the beds in the Prefecture had declined to 16.7% of the 1924 level; by 1977 and 1989, it had decreased still further to 675 ha (15.6%) and 547 ha (12.7%), respectively. The area of the beds extinguished by reclamation amounted to 1,705 ha in 1977, *i.e.* 40% of the beds in 1924 (Table 1). In Ajino Bay, the total area reclaimed up to 1977 was only 7 ha.

Nutrients in the waters of the Okayama Prefecture decreased from 1976 to 1980. Recently, they have increased, but levels remain lower than in the 1970s (Fig. 8). In 1929, Secchi depths in most areas varied between 3 m and 6 m deep (Fig. 9). After declining to depths between 2 m and 4 m in 1977, they recovered to depths of 3 m to 6 m in 1992.

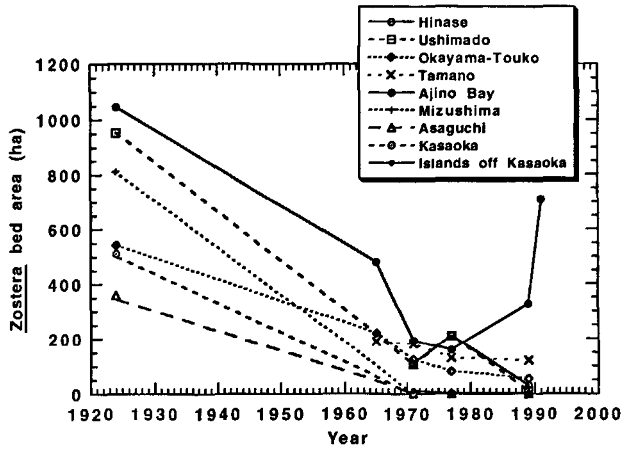

Figure 7

Chronological change in Zostera *bed area by district in the waters of the Okayama Prefecture from 1924 to 1991 (data source:* see *text).*

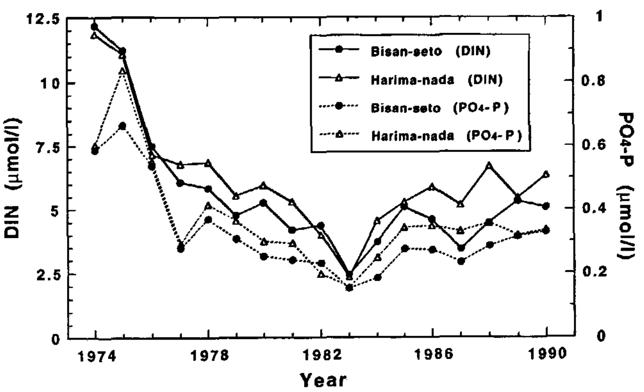

Figure 8

Chronological change in concentrations of DIN (Dissolved Inorganic Nitrogen) and PO_4-P in sea water in the Bisanseto and Harimanada in the Okayama Prefecture from 1975 to 1992.

Long-term changes in *Zostera* beds in Ajino Bay

In 1924 the area of *Zostera* beds in Ajino Bay amounted to 1,047 ha, *i.e.* about 41 % of the surface area of the bay (Fig. 7). This area decreased to 480 ha in 1966, to 192 ha in 1971, and to 161 ha (15 % of that in the 1920s) in 1977. During the 1980s, there was a slight recovery. Surveys in 1989 and 1991 indicated a cover of 327 ha (31 % of that in the 1920s) and 710 ha (68 % of that in the 1920s), respectively, reflecting considerable recolonization.

From 1921 to 1955, Secchi depths at Stations A and B (*cf.* Fig. 9) were greater than 6 m (Fig. 10). After 1956, they decreased to less than 5.5 m, the decrease persisting beyond the 1950s. In 1976, the transparency at Station B was at its lowest for the entire period between 1921 and 1991. Since 1981, Secchi depths at Stations A and B have increased to 6 m and 4.6 m, respectively.

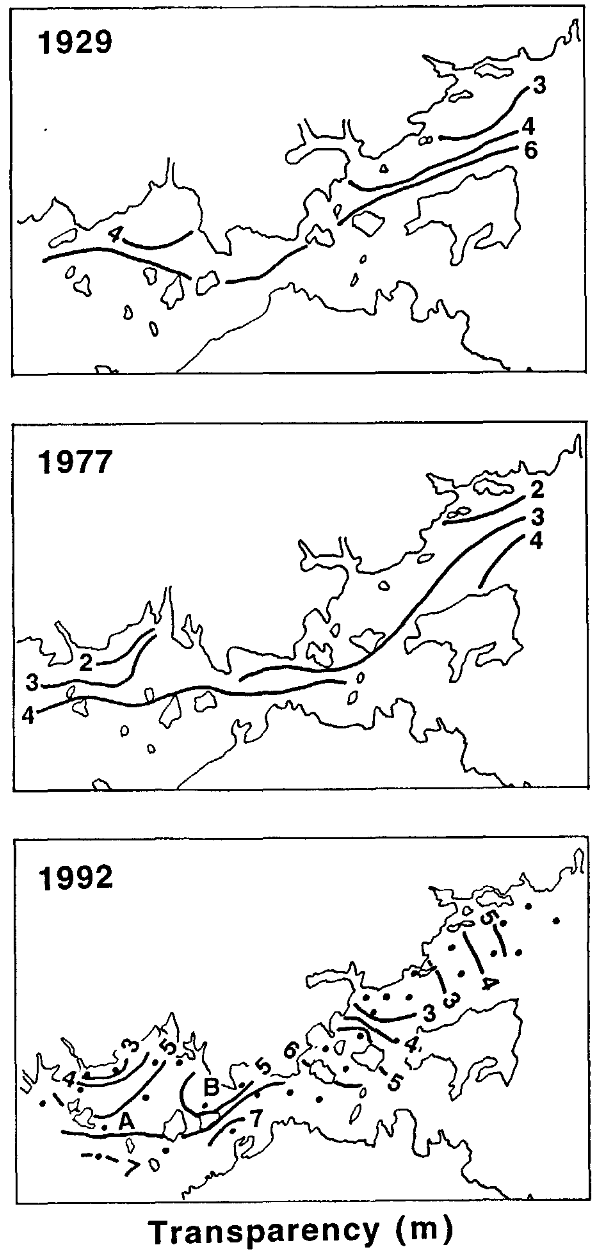

Figure 9

Horizontal distributions of transparency averaged in the months between February and April in a growing season of Zostera marina in the waters of the Okayama Prefecture in 1929, 1977 and 1992 (data source: see *text). Stations A and B are shown in the lowest panel.*

DISCUSSION

Since the 1950s, seagrass and seaweed beds have been damaged and have decreased as a consequence of coastal reclamation, pollution by industrial and urban wastes, and intensive trawling by fishermen in the Seto Inland Sea (Hoshino, 1972; Saitoh, 1979). There was a marked decline of *Zostera* beds between 1960 and 1971 (Fig. 3). The total area in shallow subtidal zones with depths less than 10 m (except the Kii Channel, the Bungo Channel, and Osaka Bay) amounted to 2,337 km^2 in 1960 (determined by the Resource Dept. of Naikai Fisheries Research Laboratory; Anon., 1967). *Zostera* beds are distributed on the sea bottom at depths less than 10 m. Thus, we can estimate the coverage rate of *Zostera* beds in the seas with bottoms at depths less than 10 m in the Seto Inland Sea. The coverage of *Zostera* based on available bottom of suitable depth was 9.6 %, 4.5 %, 2.3 %, 2.6 %, and 2.5 % in 1960, 1966, 1971,

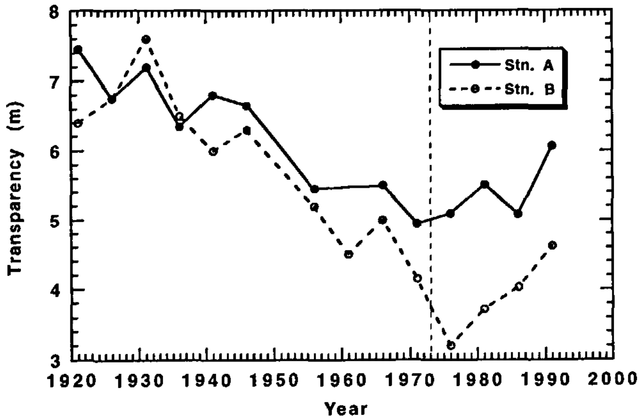

Figure 10

Chronological change in transparencies of five years average at Stations A. and B (see Figure 9) in the months between February and April from 1921 to 1991 (data source: see text*). The vertical dashed line signifies the year when the law on the environmental conservation of the Seto Inland Sea was enacted.*

1977, and 1989, respectively. *Zostera* beds covered large areas in 1960, but abruptly decreased between 1960 and 1971.

Most coastal reclamation is carried out in areas shallower than 10 m. We can calculate percentage reclamation in depths shallower than 10 m in the Seto Inland Sea, except the Kii Channel and the Bungo Channel where reclamation amounted to limited. This area amounted to 2,524 km^2 in 1960. The percentage reclamation was 5 %, 8.2 %, 10.8 %, and 13 % in 1966, 1971, 1977, and 1989, respectively. The reclaimed area also abruptly increased from 1960 to 1971. This increasing trend negatively correlates with the decline of *Zostera* bed cover in the Seto Inland Sea. Since 1973, when the law on the environmental conservation of the Seto Inland Sea was enacted, reclamation has been controlled by the national and prefectural governments (Fig. 3). Nevertheless, coastal reclamation continues to increase.

To maintain water quality, the discharge of pollutants into rivers and seas has also been restricted by the law on the environmental conservation of the Seto Inland Sea and the water pollution control law since the 1970s. Thus, pollutant loads, for example the COD load, have been reduced since the late 1970s (Fig. 4). Red tides frequently occurred between 1974 and 1976 because nutrient inflow provided good conditions for phytoplankton blooms (Fig. 4). The red tides or phytoplankton blooms caused poor transparency, leading to a shallower depth limit of the *Zostera* beds. In the 1950s, mean Secchi depths were between 8.5 m and 9.5 m; by the 1970s they had decreased to 6.5 m. The observed decrease in *Zostera* bed cover may be attributed to poor water transparency. Nutrients in the sea water during the 1980s decreased to lower levels than in the heavy pollution period in the 1970s (*e.g.* Fig. 9). Nevertheless, the *Zostera* beds have not recovered.

These discussions lead to the conclusion that the main cause of the decrease in *Zostera* beds in the Seto Inland Sea is the increased reclamation of the shallow sea areas, another cause lying in the fact that transparency has not recovered to the level of the 1950s (Fig. 5). We cannot estimate the influences of intensive drag-net operations in the *Zostera* beds because of the lack of data.

Meinesz *et al.* (1990) pointed out that reclamation and the construction of ports have an irreversible detrimental impact on the littoral flora and fauna in the region of Provence-Côte d'Azur (eastern French Mediterranean coast). The causes of the decrease in *Zostera* beds in the Seto Inland Sea can be placed in two categories: a) degradation of environments through increasing nutrient loads, transparency decreases, deterioration of water quality and intensive drag-net operations ("reversible modification of environments"); and b) destruction of environments through reclamation and construction of ports and piers ("irreversible destruction of environments"). This classification is useful for understanding the mechanisms responsible for the decline of *Zostera* beds.

Reversible modification of environments can be improved when appropriate treatments are applied to them, for example, the upgrading of sewage treatment plants and reduction of the discharge of pollutants. These factors may reduce the frequency of phytoplankton blooms, thereby increasing transparency. Increased transparency enlarges the potential area of *Zostera* colonization by increasing the lower depth limit of *Zostera* beds. In addition, recolonization of *Zostera* beds can be promoted by transplanting and seeding. Several prefectural fisheries experimental stations along the Seto Inland Sea in fact developed seeding and transplanting techniques after the reduction of heavy pollution since the 1970s (Hade *et al.*, 1976; Fukuda *et al.*, 1984; Shimokawa, 1992). A fishermen's cooperative has also attempted to seed the territory in their fisheries ground where *Zostera* beds previously existed (Fukuda and Sato, 1987).

Irreversible destruction of environments cannot be remedied, because it is practically impossible to repopulate the reclaimed coastal area with the original shallow benthic communities. In the waters of the Okayama Prefecture, intact *Zostera* beds were estimated to cover an area of 4,000 ha in the 1920s. By 1977, about 40 % of the 4,000 ha present in 1924 had been lost by irreversible destruction of the environments, *i.e.* reclamation from 1925 to 1977 (Tab. 1). Another 44 % of the 4,000 ha present in 1924 was extinguished by the reversible destruction of environments as a consequence of pollution, decreased transparency due to eutrophication, and the intensive operation of drag-nets and trawls (Katayama *et al.*, 1979). In the 1920s, transparencies (Secchi depths) in *Zostera* beds were between 2.7 m and 4.2 m; by 1977 they had decreased to 1.5 m to 2.0 m (Katayama *et al.*, 1979). Thus, a decrease in transparency was responsible for the reversible decrease in *Zostera* beds in the 1970s. Since the enactment of the law on the environmental conservation of the Seto Inland Sea in 1973, nutrients have been reduced, and transparency has become greater in the waters of the Okayama Prefecture (Figs. 8-10), whose quality since the 1980s has become much better than during the most polluted period in the early 1970s. There was, however, no increase in the cover of *Zostera* beds area, except in Ajino Bay from 1979 to 1989.

In Ajino Bay, the area of *Zostera* beds subjected to irreversible destruction due to coastal reclamation amounted to only 7 ha in 1977 (Katayama *et al.*, 1979). The area of the beds increased to 327 ha in 1989 (Anon., 1996) and to 710 ha in 1991 (Komatsu, 1994). In Ajino Bay, 288 plastic cubes of 15 m^3 (4,320 m^3), 3,900 concrete blocks of 3.375 m^3 (13,162.5 m^3) and 20,000 m^3 of rocks were placed on 77.6 ha of the bottom as artificial reefs for nursery of fish larvae and young fish from 1980 to 1982 by the Okayama Prefecture (Anon., 1987). These reefs have prevented fishermen from operating drag-nets and trawls. After they were set in place, diving observations as well as questionnaires to fishermen on the states of the *Zostera* beds revealed that their area had increased (Anon., 1987). This period of increase in the *Zostera* bed area in Ajino Bay corresponds to a recovery of transparency at Station B near Ajino Bay (Fig. 10). Thus, it seems natural for the amelioration of reversible modifications of environments to promote the increase of the *Zostera* beds in the areas concerned, unless there has been irreversible destruction by reclamation. By 1991, *Zostera* beds had recovered from a loss of 85 % of their area in 1924, and about 68 % of the eelgrass present in 1924 had regrown.

CONCLUSION

In the Seto Inland Sea, the decline of *Zostera* beds became serious from the 1950s onwards. This decline persisted until the 1990s. The long-term data set on the evolution of the seagrass beds and the environmental conditions indicates that the foremost cause of the decrease in *Zostera* beds has been coastal reclamation in the shallow subtidal zone since the 1950s. In the waters of the Okayama Prefecture, the area of *Zostera* beds decreased from 4,300 ha in 1924 to 720 ha in 1977; 1,705 ha (40 % of the 1924 level) were irreversibly extinguished by reclamation; 1,875 ha (44 % of the 1924 level) had been reversibly extinguished by the decrease in water transparency due to eutrophication and intensive operations of drag-nets and trawls. In 1973, the law on the environmental conservation of the Seto Inland Sea was enacted. Since then, the nutrient load entering the Sea has been restricted. As a consequence, transparency and other environmental factors have been recovering, with a delay of some years in the waters of the Okayama Prefecture, but not throughout the Seto Inland Sea. In Ajino Bay of the Okayama Prefecture, *Zostera* beds had recovered naturally by 1991. It is very important for the conservation of seagrass beds to restrict the irreversible destruction of the environment through coastal reclamation and the construction of ports and piers.

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