

Green tide formed by free-floating *Ulva* spp. at Yatsu tidal flat, Japan

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Abstract Green tides at Yatsu tidal flat, Tokyo Bay, Japan, were first reported in 1995 and formed by a bloom only of free-floating *Ulva* species. On the tidal flat, the bloom area in well-developed periods increased after 1995 and covered 27.1 ha in May 2002. Based on vertical aerial photographs, green tide remaining in winter during 1996–2007 covered 4.7 ha when first observed in 1999 and increased to 17.5 ha in January 2002 thereafter. We found that the expansion of green tide was related to such factors

as an increase in Kira's Warmth Index, a decrease in annual cumulative hourly air temperatures below 7°C in December, an increase in salinity, and unintentional introduction of *Ulva ohnoi*. We also found that green tide at Yatsu tidal flat occurred in the course of the improvement of water quality.

Keywords Lagoon · Green tide · Aerial photograph · Alien species · Warmth Index

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Introduction

Blooms of *Ulva* species in Japan have been reported in inner bays (Arasaki 1984), and more recently adjacent to megapolises, such as Tokyo, Yokohama, Osaka, Hiroshima, and Hakata (e.g., Notoya 1999; Kudo et al. 2003; Yamochi et al. 2003; Uchimura et al. 2004; Hiraoka et al. 2004).

The blooms and accumulations of ulvoid algae (Ulvo-phyceae), including *Ulva*, *Enteromorpha*, *Chaetomorpha*, *Cladophora* (Fletcher 1996), *Rhizoclonium*, *Percursaria* (Taylor et al. 2001), and *Ulvaria* (Nelson et al. 2003), were commonly called “green tides.” Ohno (1999) proposed that green tide should be used in a more limited sense to describe the bloom and accumulation only of *Ulva* species. The blooms of attached ulvoids have been found in intertidal (Uchimura et al. 2004) and eulittoral (Kim et al. 2004) rocky substrata, whereas the blooms of free-floating ulvoids have been mostly reported in intertidal muddy and sandy flats. The blooms of ulvoids reduce the yields of useful marine products (Hernández et al. 1997) and affect seagrass beds mainly through shading (Den Hartog 1994; Short et al. 1995; Sugimoto et al. 2007). Ulvoids that are washed up and deposited on shores decompose and produce noxious odors, and not only result in a decrease in

infaunal species (Franz and Friedman 2002), but also prevent people from utilizing the waterfront areas (Frankenstein 2000).

Yatsu tidal flat was designated as a registered wetland in 1993 under the fifth “Convention on Wetlands of International Importance especially as a Waterfowl Habitat” in Kushiro, Japan, known as “The Ramsar Convention.” In particular, many migratory birds, especially snipe and plover, come to Yatsu tidal flat, so the tidal flat was registered as part of “The East Asian-Australasian Shorebird Site Network.”

At Yatsu tidal flat, located in inner Tokyo Bay, green tides composed of *U. pertusa* (Ishii et al. 2001b) and *U. ohnoi* (Yauchi et al. 2006) have been observed in recent years. Thus, the first aim of this study is to show the yearly trends in the well-developed green tide area since 1995 at Yatsu tidal flat using a vertical aerial photograph with our field survey in 2002 and some information from published literature. The second aim is to show the yearly trends in the extent of the winter remnants of the green tide for 12 years since 1996 using vertical aerial photographs. Finally, we discuss the role of some environmental factors at Yatsu tidal flat, such as water quality and temperature, on the formation of the green tide.

Methods

Study area

Yatsu tidal flat, one of the innermost tidal flats of Tokyo Bay (Fig. 1), had been part of an extensive foreshore tidal flat along the coast before 1971. Since 1972, Yatsu tidal flat

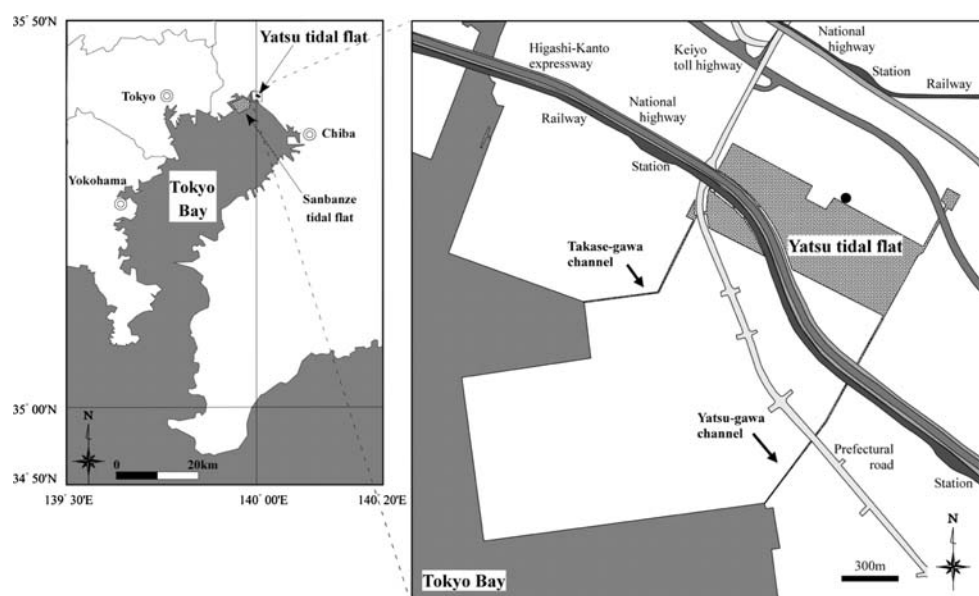
was isolated from Tokyo Bay by concrete walls because of the reclamation for industrial and residential uses in the surrounding area. At present, Yatsu tidal flat is a semi-closed area of about 40 ha that is classified as a lagoon-type tidal flat based on the hydrogeomorphic classification of tidal flats (Yabe et al. 2002). Yatsu tidal flat is connected with Sanbanze tidal flat in the inner Tokyo Bay by only two water channels, Yatsu-gawa and Takase-gawa channels, through which seawater is exchanged with each tidal cycle. The channels both have concrete walls and bottoms. Municipal sewerage systems were developed in the surrounding areas between 1990 and 1999, and the inflow of domestic wastewater, which is fresh water, to the tidal flat has gradually decreased.

Temporal variation of the green tide at Yatsu tidal flat

Data on the area of well-developed green tide were obtained from the following sources: 1984 and 1985, Center for Environmental Information Science (1984, 1986); 1991, A. Hasegawa, personal communication (2008); 1995, Ministry of the Environment Japan et al. (1996); 1999, 2000, Ishii et al. (2001a, b). These estimates of bloom area were based on only each field observation. In 2002, vertical aerial color photographs at a scale of about 1:4,500 were taken on 15 May, and the estimate was based on our field survey over the whole area with the photographs.

To assess the area of distribution of the remaining green tide in winter, including submerged portions, we classified and determined the area of the *Ulva* species in winter by using image analysis of vertical aerial color photographs at a scale of about 1:4,500 taken by Keiyo Sokuryo Co. Ltd.

Fig. 1 Location and map of Yatsu tidal flat. Filled circle, oblique photography point. The white areas adjacent to the Yatsu tidal flat indicate the reclaimed land



(Narashino, Japan) between January and March in each year from 1996 to 2007. Remote sensing data analysis software (PG-STEAMER; Pixoneer Geomatics Inc., Taejon) was used for this analysis. Pre-processing included digital scanning of the color photographs, applying a geometric correction, and extracting the tidal flat were operated for 12 photographs. Then, we implemented a supervised classification using a maximum likelihood classifier for each digitized aerial photograph based on information acquired from four spatially homogeneous areas of the tidal flat: a remaining green tide, an un-vegetated sandy or muddy bottom, a yellow wetland dominated by dead *Phragmites*, and a black shaded site by concrete walls, bridges, and roads. This classification was based on the below-mentioned oblique photographs taken from 1996 to 2001 and our field observations since 1999 for ground-truth. The oblique photographs of the tidal flat were taken from the top floor of a 14-story condominium located adjacent to the north shore of the tidal flat (Fig. 1) with a 35-mm compact camera (Fujinon compact; Fuji photo Films Co., Tokyo) using color film by a volunteer from whom cooperation was requested by the Environment Bureau in Narashino City Office.

Temporal variation of environmental factors

There were no long-term and continuous water temperature data taken in Yatsu tidal flat, whereas hourly air temperature data have been collected at the meteorological observatory station since 1982 (Akitsu Observatory, Narashino City Office) adjacent to Yatsu tidal flat. We used water temperature data collected by the Environment Bureau in Narashino City Office at six points in the tidal flat every month from January 2000 to January 2002 for a comparison with the air temperature data.

We calculated the Warmth Index, WI (month-degrees), as proposed by Kira (1945, 1976), which is an annual index of cumulative monthly mean temperatures exceeding 5°C and is well-known as an index that is closely related to the distribution of vegetation. We also calculated the annual cumulative hourly temperatures (hour-degrees) below 7°C in December and above 25°C. Other species of *Ulva*, *U. lactuca* (Steffensen 1976), *U. scandinavica* (Malta et al. 1999), and *U. rigida* (De-Casabianca et al. 2002) have been observed to grow between about 7 and 25°C.

There were no continuous data collected in Yatsu tidal flat for concentrations of dissolved inorganic nitrogen (DIN) and phosphorus (DIP) in seawater. Instead we used the nutrient concentration data that were measured continuously from 1987 to 2003 in the inner Tokyo Bay adjacent to the estuary of the Takase-gawa channel, using JIS (Japanese Industrial Standards) K 0102. Ammonia nitrogen ($\text{NH}_4^+\text{-N}$) and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) were

measured by indophenol-blue absorptiometry, nitrite nitrogen ($\text{NO}_2^-\text{-N}$) by naphthyl-ethylenediamine absorptiometry, and orthophosphate ($\text{PO}_4^{3-}\text{-P}$) by molybdate-blue absorptiometry. The data included in water quality survey reports of public water from 1987 to 1997 (National Institute for Environmental Studies 2008) and from 1998 to 2003 (Chiba Prefectural Government Office 2008) were used to evaluate the temporal variations in these nutrient concentrations. We also used the electrical conductivity (EC) data measured at the innermost part of the tidal flat by the Environment Bureau in Narashino City Office from 1987 to 2003. In addition, we compared the daily variations of EC and salinity in January and August 1995 in the tidal flat (Ministry of the Environment Japan et al. 1996).

Results and discussion

Temporal variations of the green tide at Yatsu tidal flat

The yearly trends in the area of the well-developed green tide since 1984 are shown in Fig. 2. There were no ulvoids reported at the tidal flat in 1984 and 1985. Ulvoids were first observed in 1991 in the tidal flat. A well-developed green tide was first reported in August 1995, covering an area of 6.8 ha in the eastern part of the tidal flat. Thereafter, the area of the green tide gradually expanded westward. The area increased to 13 ha in August 1999 and 20 ha in August 2000. In May 2002, the area of the green tide reached 27 ha, which is about 63% of the total area of Yatsu tidal flat, despite being only the initial stage of the summer bloom.

We determined the area of the green tide that remained in winter from 1996 to 2007 using vertical aerial color

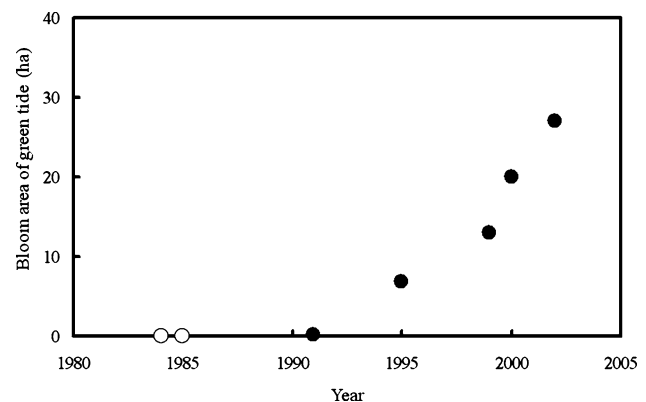


Fig. 2 Area of the well-developed summer green tide bloom on Yatsu tidal flat. No ulvoid algae or green tide was observed in 1984 or 1985 (open circles). Ulvoids were first reported in 1991, and the green tide (filled circles) was first reported in 1995

photographs (Fig. 3). The winter remnants of the green tide in these photographs were almost submerged and distinguished as more dark green than the green tide in summer. The winter remnants of the green tide were first observed in January 1999 in the eastern part of the tidal flat, covering about 4.7 ha. Thereafter, the area of green tide remaining in winter gradually expanded westward and covered over 15 ha in 2002 and the years following, but the area remained primarily in the eastern part of the tidal flat. The maximum area of the green tide remaining in winter was 21.7 ha in January 2004. *Phragmites*-dominated wetland and shaded areas were maintained virtually constant between 1996 and 2007. Un-vegetated sandy or muddy bottom decreased since 1999 and covered about 20 ha in 2002. It was shown that the un-vegetated sandy or muddy bottom had been covered gradually with the winter remnants of the green tide since 1999.

Temporal variation of environmental factors

There was a significant correlation between monthly mean water temperature as measured at six points on the tidal flat and monthly mean air temperature as collected hourly at Akitsu Observatory from January 2000 to January 2002 ($r^2 = 0.74$, $P < 0.01$), and then the air temperature was used in substitution for the water temperatures in the tidal flat.

The annual mean air temperature and WI for the 10 years after 1995 were significantly higher than for the 10 years before 1994 ($P < 0.01$, ANOVA) (Fig. 4a). The maximum WI was 133 month-degrees in 1999, and the average values for WI for the 10 years before 1994 and after 1995 were 116 ± 7 (SD) and 125 ± 5 (SD) month-degrees, respectively. WI values over 125 month-degrees

were observed five times during the period after 1995 (1997, 1998, 1999, 2000, and 2004), in contrast to only one time before 1994.

The cumulative hourly air temperatures in December below 7°C exceeded 900 h-degrees for all 10 years before 1994, but 4 years, 1995, 1999, 2000, and 2001, after 1995 (Fig. 4b). The summer cumulative air temperatures above 25°C exceeded 4,000 h-degrees in 1985, 1994, 1995, and 1999 over the 20 years studied (Fig. 4c).

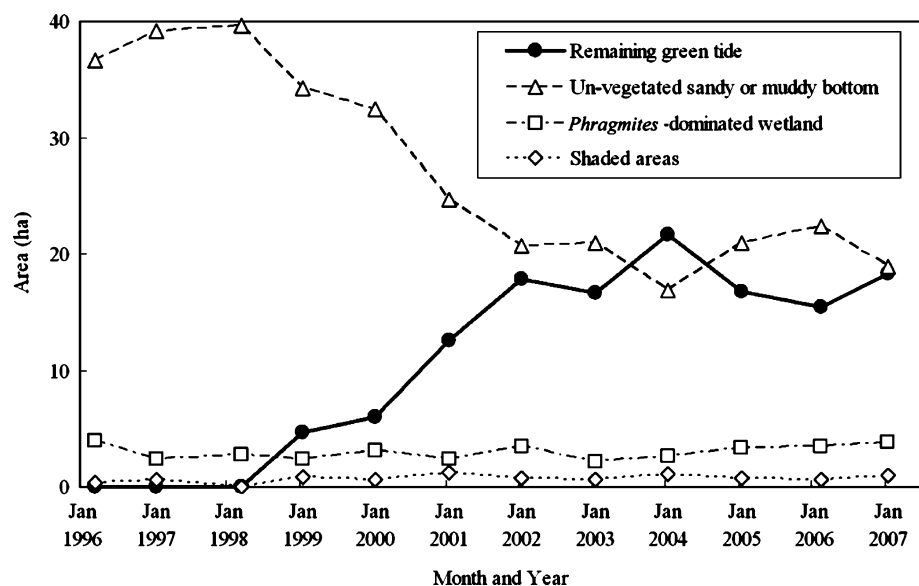
Temporal variations in nutrient concentrations are shown in Fig. 5. After the development of municipal sewerage systems in the surrounding area between 1990 and 1999, ammonia nitrogen ($\text{NH}_4\text{-N}$), nitrite plus nitrate nitrogen ($\text{NO}_2\text{-N} + \text{NO}_3\text{-N}$), and orthophosphate ($\text{PO}_4\text{-P}$) concentrations decreased significantly from year to year ($P < 0.01$ for $\text{NH}_4\text{-N}$ and $\text{PO}_4\text{-P}$; $P < 0.05$ for $\text{NO}_2\text{-N} + \text{NO}_3\text{-N}$).

In contrast, EC increased over the same period, despite a decrease in nutrient concentrations (Fig. 5). EC is also affected to a large degree by the concentrations of Cl^- and Na^+ in the water on tidal flats in Japan (Yabe et al. 2002). Significant positive correlations were found between the hourly data for EC and salinity, as reported by the Ministry of the Environment Japan et al. (1996), in the tidal flat over the course of a day both in summer ($r^2 = 0.97$, $P < 0.01$) and winter ($r^2 = 0.98$, $P < 0.01$). Therefore, we suspect that the increase in EC resulted from increases in the concentrations of Cl^- and Na^+ over this period in Yatsu tidal flat.

Relationship between environmental factors and blooms of *Ulva* spp.

The increase in air temperatures at Yatsu tidal flat were presumed to have been caused by the heat island effect, in

Fig. 3 The area of green tide remaining in winter from 1996 to 2007, as determined from vertical aerial color photographs. Also included are the areas of un-vegetated sandy or muddy bottom, *phragmites*-dominated wetland, and shaded areas in the photographs



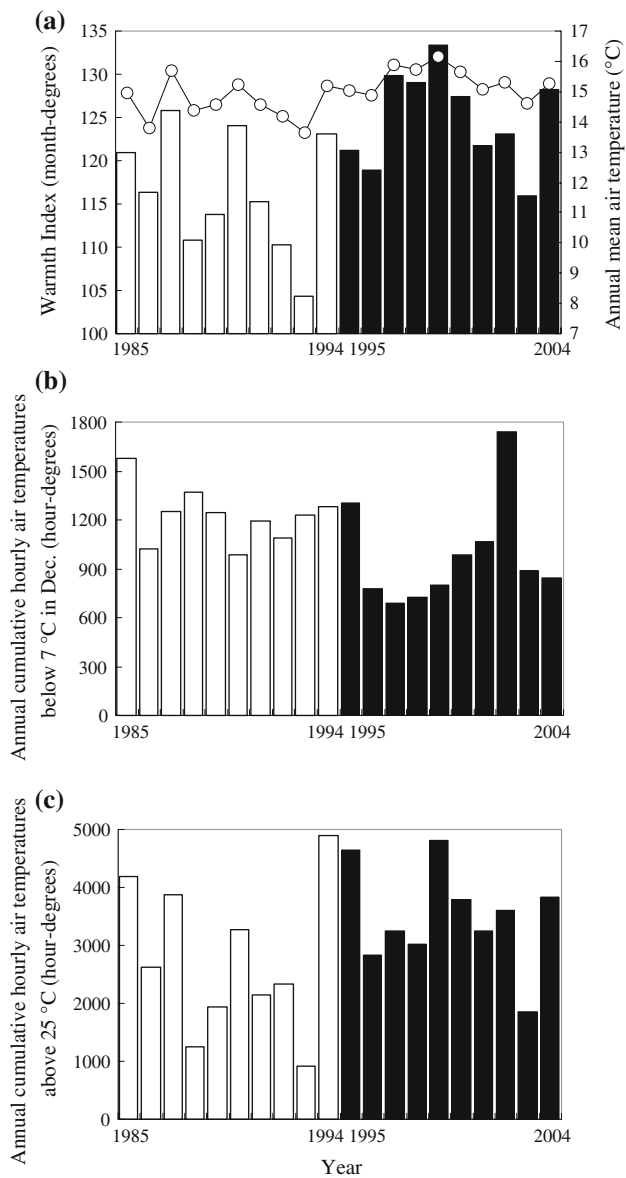


Fig. 4 Bar and line chart show the yearly change of the Warmth Index (month-degrees), referring to the left side and of annual mean air temperature (°C) and referring to the right side, respectively (a), change of annual cumulative hourly air temperatures below 7°C in December from 1985 to 2004 (b), and change of annual cumulative hourly air temperatures above 25°C from 1985 to 2004 (c). Open bars show during 1985–1994, and black bars show during 1995–2004

which air temperatures in and around megalopolises are notably elevated compared to nearby areas. The Tokyo Bay area, including Narashino city, has been developed for industrial and residential use, and the population density of this region is also very high; Yatsu tidal flat in particular is surrounded by heavily trafficked roads and railways (see Fig. 1). We believe that thermal pollution from the many human activities (e.g., the exhaust from automobiles and discharges from air conditioning units), along with the increased heat radiation coming from the increased number

of concrete buildings and the decreased evaporation due to the lack of vegetation in the city, have brought about this higher temperature phenomenon (Inter-ministry Coordination Committee to Mitigate Urban Heat Island 2004).

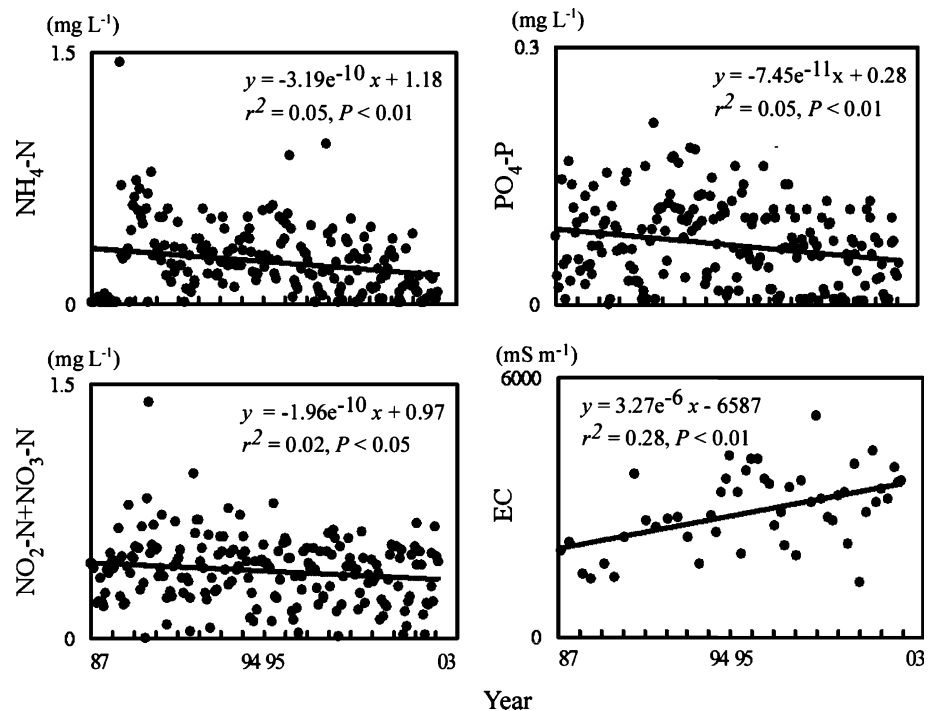
Green algae, including species of *Ulva*, are distributed throughout almost all of the relatively warm sea areas in Japan (Yoshizaki 1979). *U. pertusa* can maintain photosynthetic activity in winter water temperatures of about 5°C in Japan (Yokohama 1971), and the lowest temperature reported for growth of *U. rigida* is 7°C in France and Italy (De-Casabianca et al. 2002). The increase in Kira's Warmth Index and the decrease in the cumulative hourly air temperature below 7°C in December after 1995—in other words, the increase in warm winters (Fig. 4a, b)—seemed to cause the expansion in the duration and area of the green tide bloom on Yatsu tidal flat. A summer decline of *Ulva* bloom on Yatsu tidal flat was only observed in 1999 by the oblique photographs and our field survey during 1996–2002, probably because the cumulative air temperatures above 25°C exceeded 4,000 h-degrees in 1999 (Fig. 4c).

Public sewerage improvements around Yatsu tidal flat have reduced the direct inflow of non-saline domestic wastewater, which was also probably responsible for the decrease in nutrient concentrations (Fig. 5). Despite the decrease in concentrations of nutrient salts, the EC in the tidal flat increased, presumably as a result of an increased proportion of seawater in the tidal flat; in other words, the water in the tidal flat became more similar in composition to seawater in Tokyo Bay. Many other *Ulva* species—*U. expensa*, *U. curvata*, *U. lactuca*, *U. scandinavica*, *U. fenestrata*, and *U. rigida* (Fong et al. 1996; Malta et al. 1999; Nelson et al. 2003)—show the highest growth rates at oceanic salinities of between 24 and 35 psu. The increase in salinity in Yatsu tidal flat is regarded as another favorable condition for the green tide bloom.

The characteristics of the green tide at Yatsu tidal flat

The green tide at Yatsu tidal flat included at least two *Ulva* species. We identified *U. pertusa* in May, and *U. ohnoi* had been identified in September and December (Yauchi et al. 2006). Green tides with *U. pertusa* in spring and summer and *U. ohnoi* in the summer and autumn were observed at Sanbanze tidal flat (Sanbanze Fisheries Restoration Planning Committee 2006), which is connected with Yatsu tidal flat through two channels (see Fig. 1), and it seems reasonable that the two species show similar seasonal bloom patterns on Yatsu tidal flat. *Ulva ohnoi*, which may have been introduced to Japan from tropical and subtropical waters (Hiraoka et al. 2003), could have already been unintentionally introduced to the Yatsu tidal flat between

Fig. 5 Changes in nutrient concentrations and electrical conductivity (EC) from 1987 to 2003. The equations describe the linear regression lines



1991 and 1995 at least through the two connecting channels from Tokyo inner Bay including Sanbanze tidal flat.

The green tide at Yatsu tidal flat has two interesting features. First, we detected a summer decline of the green tide in 1999. A summer decline of *Ulva* biomass has often been reported around the world (Sfriso et al. 1987; Sfriso and Marcomini 1996; Hernández et al. 1997; De-Casabianca et al. 2002; Kim et al. 2004; Uchimura et al. 2004), and the most common reason for the decline is temperatures too high for growth. The same probably applies to that in 1999. The second feature of the green tide at Yatsu tidal flat is that it was not induced by eutrophication of the seawater, as has been reported for green tides worldwide (Fletcher 1996; Anderson et al. 1996; Hernández et al. 1997; Notoya 1999; Taylor et al. 2001; Nelson et al. 2003; Kim et al. 2004; Nelson et al. 2008). The nutrient concentrations in Yatsu tidal flat have still remained at levels sufficient for the bloom of the green tide (Steffensen 1976; Maegawa 1999; Ishii et al. 2001a, b) after the development of public sewerage systems. Thus, the green tides at Yatsu tidal flat have occurred, not during the process of eutrophication, but during and following the remediation of water quality.

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