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Seasonal Dynamics of the Seagrass *Zostera marina* on the South Coast of the Korean Peninsula

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Although seagrasses are relatively abundant, few studies have been conducted on seagrass physiology and ecology in Korea. *Zostera marina* is the most abundant seagrass species, widely distributed throughout all coastal areas of the Korean peninsula. To examine seasonal dynamics and spatial variations of eelgrass, *Zostera marina* distributed on the coast of Korea, morphological characteristics, biomass, tissue nutrient constituents, leaf productivity and environmental factors were monitored monthly from the eelgrass beds in Kabae Bay and Kosung Bay on the south coast of the Korean peninsula from June 2001 to June 2002. Eelgrass density, biomass, morphological characteristics, leaf productivities, and tissue nutrient constituents exhibited clear seasonal variations, and these seasonal trends reflected seasonal changes in water temperature. Eelgrass shoot density and biomass at Kabae Bay site showed more obvious seasonal trends than Kosung Bay. No strong seasonality in Kosung Bay site appeared to be caused by high water temperature (>30°C) during summer months at this site. Despite differences in nutrient availabilities between two study sites, eelgrass biomass and leaf productivities were not significantly different between study sites, and this lack of spatial variations implies that the ambient nutrient availabilities at the present study sites are in excess of seagrass nutrient demand. Eelgrass tissue N content and sediment pore water DIN concentrations exhibited reverse relationship at the present study. This reverse relationship suggests *in situ* nutrient concentrations are not good indicator of nutrient availabilities, and regeneration and turnover rates of sediment nutrients are also important factors to determine nutrient availabilities at the site.

Keywords: Seagrass, *Zostera marina*, Seasonal Variation, Biomass, Productivity, Tissue Nutrient Constituents

INTRODUCTION

Seagrasses are known to achieve high levels of production (McRoy and McMillan 1977; Zieman and Wetzel 1980; Lee and Dunton 1996), and are important primary producers in coastal and estuarine ecosystems. As primary producers, survival, distribution and production of seagrasses are influenced by underwater irradiance, water temperature, and inorganic nutrient availabilities. Insufficient underwater irradiance leads to rapid decreases in seagrass biomass, productivities, depletion of stored metabolic carbon in plant tissues, and consequently seagrass die-off (Dennison and Alberte 1982; Czerny and Dunton 1995; Lee and Dunton 1997). Therefore, underwater light condition is the most important factor for seagrass distribution and survival in a certain area.

Several seagrass physiological and morphological characteristics exhibit seasonal variations (Wetzel and Penhale 1983; Dunton 1994; Lee and Dunton 1996). Seagrass productivity, biomass, and plant size usually increase with increasing water temperature during spring and summer and decrease with falling temperature during fall and winter (Vermaat *et al.* 1987; Dunton 1994, Lee and Dunton 1996). In most cases, seasonal variation of seagrass characteristics seems to be controlled by water temperature. Since seagrasses have high productivities, they may need to assimilate large amounts of inorganic nutrients such as nitrogen and phosphorus. Thus, nutrient availability in the water column and sediment pore water plays an important role in controlling seagrass production. Spatial variations in seagrass productions are primarily regulated by *in situ* nutrient availabilities.

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Seagrasses have access to inorganic nutrient sources in both the sediment and the water column (Iizumi and Hattori 1982; Short and McRoy 1984; Stapel *et al.* 1996; Stapel and Hemminga 1997; Terrados and Williams 1997; Lee and Dunton 1999b). However, inorganic nutrient in the water column can lead to reduction of underwater irradiance as a result of epiphyte growth and phytoplankton blooms, and consequently seagrass decline (Orth and Moore 1983; Silberstein *et al.* 1986; Giesen *et al.* 1990; Tomasko and Lapointe 1991). Inorganic nutrients in the sediment pore water enhance seagrass growth and production, and have been reported to have no detrimental effects on seagrass growth (Agawin *et al.* 1996; Alcoverro *et al.* 1997; Udy and Dennison 1997). Therefore, seagrass responses to nutrient availability may vary depending on the nutrient sources. In the present study, we hypothesized that productivities of seagrass *Zostera marina* vary with sediment nutrient availabilities.

Eelgrass, *Zostera marina* is the most widely distributed of all seagrasses and dominates the north temperate oceans of the world (Short *et al.* 2001). *Z. marina* appears at the intertidal and subtidal zones, where the water depth is usually less than 5 m, and forms relatively large meadows. *Z. marina* can be observed in both muddy and sandy sediments. On the coasts of the Korean peninsula, most of the seagrass area is located on the south coast, and *Z. marina* is the most abundant seagrass species, widely distributed throughout all coastal areas (Lee and Lee 2003). Although abundant seagrass species are distributed on the coasts of the Korean peninsula, little study has been conducted on seagrass ecology and physiology. In this study, eelgrass productivities, tissue nutritional content, and morphological characteristics were examined at two different eelgrass beds in Kosung Bay and Kabae Bay. Since few ecological and physiological data exist concerning eelgrass distributed on the coasts of Korea, this study provides valuable data on the biology and ecology of eelgrass in Korea.

MATERIALS AND METHODS

Study sites

The study sites are located in Kosung Bay and Kabae Bay, Koje Island on the south coast of the Korean peninsula (Fig. 1). This study was conducted in monotypic meadows of *Zostera marina*. Eco-physiological characteristics of *Z. marina* and physical and chemical parameters of the study sites were measured every month from June 2001 to June 2002. The Kosung Bay site is characterized by low sand content in the sediment, but sediments at the Kabae Bay site have higher sand content.

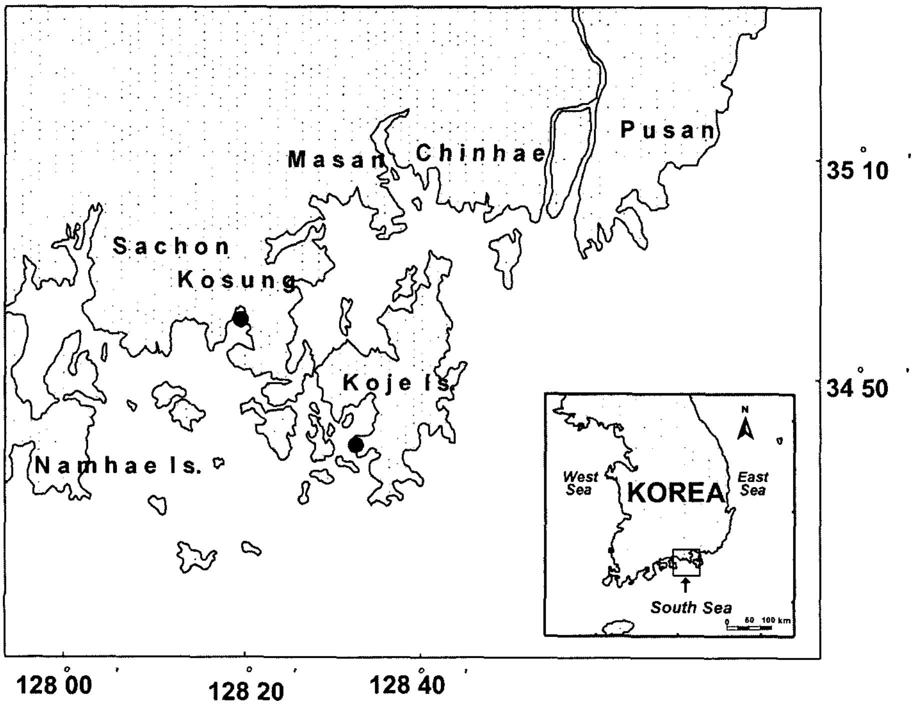

Fig. 1. Study sites in Kabae Bay, Koje Island and Kosung Bay on the south coast of the Korean peninsula.

Physical and chemical parameter measurements

Water temperature and salinity were measured every month during the experimental periods. Four replicate surface water samples for determination of water column nutrients were collected every month. Dissolved inorganic nitrogen (DIN, NH_4^+, $NO_3^- + NO_2^-$), and PO_4^{3-} concentrations were determined colorimetrically according to Parsons *et al.* (1984). Concentrations of $NO_3^- + NO_2^-$ were determined after running through a column containing copper coated cadmium, which reduces NO_3^- to NO_2^-. To measure sediment pore water nutrient concentrations, 6–10 replicate sediment samples were collected randomly from each site to a sediment depth of about 13 cm with a syringe corer. Samples were placed on ice and frozen pending lab analyses. Sediment pore water was obtained by centrifugation (5000×g for 15 min) and used for determination of pore water DIN and PO_4^{3-} concentrations. Concentrations of pore water DIN and PO_4^{3-} were determined after dilution (1:5; v/v) with low nutrient seawater. To determine sediment organic content, oven-dried sediments were burned at 550°C for 2h, and sediment organic content was calculated from the loss of sediment weight. Shells were removed from the sediments before combustion.

Biological measurements

Plant morphology, shoot density, biomass, and leaf production were measured every month. Ten to fifteen mature terminal eelgrass shoots were collected individually at the sampling sites to measure shoot morphology. Sheath length was measured from the meristem to the top of the sheath. Shoot height was measured from the meristem to the tip of the longest leaf, and the width of the longest leaf was measured. All shoots and below-ground tissues inside a randomly thrown quadrat (0.35×0.35 m; n=4) were collected for biomass and density measurements. Shoot density was estimated by counting the number of shoots in the quadrat. Collected samples were thoroughly cleaned of epiphytes and sediment, separated into above- (blade+sheath) and below-ground tissues (root+rhizome), and dried at 60°C to a constant weight.

Leaf production rates were measured using a modified blade marking technique (Zieman 1974; Kentula and McIntire 1986; Lee and Dunton 1996). Ten to fifteen randomly chosen shoots from each site were marked the bundle sheath with a hypodermic needle and then harvested after a period of 2 to 4 weeks. Leaf material was separated into leaf tissue produced before and after marking and dried at 60°C to a constant weight. The leaf production rate per shoot was determined by dividing the dry weight of new leaf tissue produced after marking by the number of days since marking.

Plant tissue constituent analyses

The second and third youngest leaves and rhizome and root tissues from the first to sixth youngest nodes were used to determine plant tissue carbon (C) and nitrogen (N) content. The dried tissues were ground using mortars and pestles. Approximately 2–3 mg of ground tissue was placed into a tin boat for determination of eelgrass tissue C and N content using a CHN elemental analyzer (Flash EA1112), and C:N molar ratios were calculated.

Statistics

All values are reported as means±1 SE. Statistical analyses were performed on a microcomputer using a general linear model procedure (SAS). Data were tested for normality and homogeneity of variance to meet the assumptions of parametric statistics. Differences in water column and pore water nutrient concentrations, plant morphological characteristics, shoot density, biomass, leaf productivities and tissue nutrient constituents among sampling time and between sampling sites were tested for significance using a 2-way ANOVA, with time as a block. When a significant difference among variables was observed, the means were analyzed by a Tukey multiple comparison test to determine where the significant differences occurred among variables.

RESULTS

Water temperature and salinity

Water temperature at the study sites in Kabae Bay and Kosung Bay exhibited obvious seasonal variations (Fig. 2). Water temperature at Kabae Bay ranged from 9.6°C in February to 25.8°C in late August, while water temperature at Kosung Bay ranged from 6.0°C in February to 31.8°C in late July. Summer temperatures were higher at Kosung Bay site than Kabae Bay, while water temperatures during winter were lower at Kosung Bay. Salinity did not show clear seasonal trend at both study sites (Fig. 3). Salinity was slightly higher at Kabae Bay site than Kosung

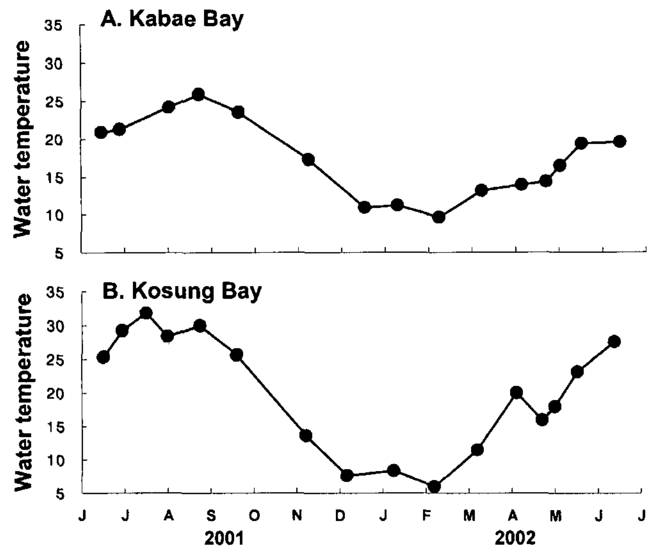

Fig. 2. Water temperature at eelgrass beds in Kabae Bay and Kosung Bay.

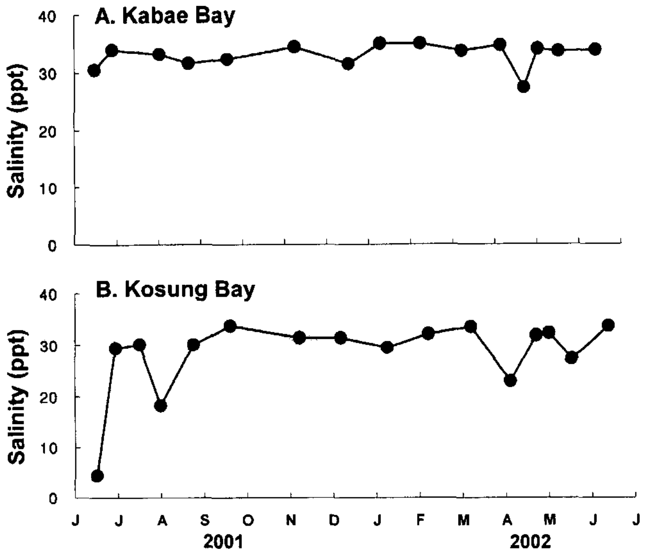

Fig. 3. Salinity at eelgrass beds in Kabae Bay and Kosung Bay.

Bay, and salinity of Kosung Bay was strongly affected by a rainfall.

Nutrient conditions in the water column and sediments

Water column NH_4^+ concentrations were significantly ($P<0.001$) higher at Kosung Bay site than Kabae Bay, and the NH_4^+ concentrations at Kabae Bay site were usually less than 3 μM during the experimental period (Fig. 4A, B). Water column NH_4^+ concentrations varied significantly ($P<0.001$) with sampling time at both study sites, but did not show any clear seasonal

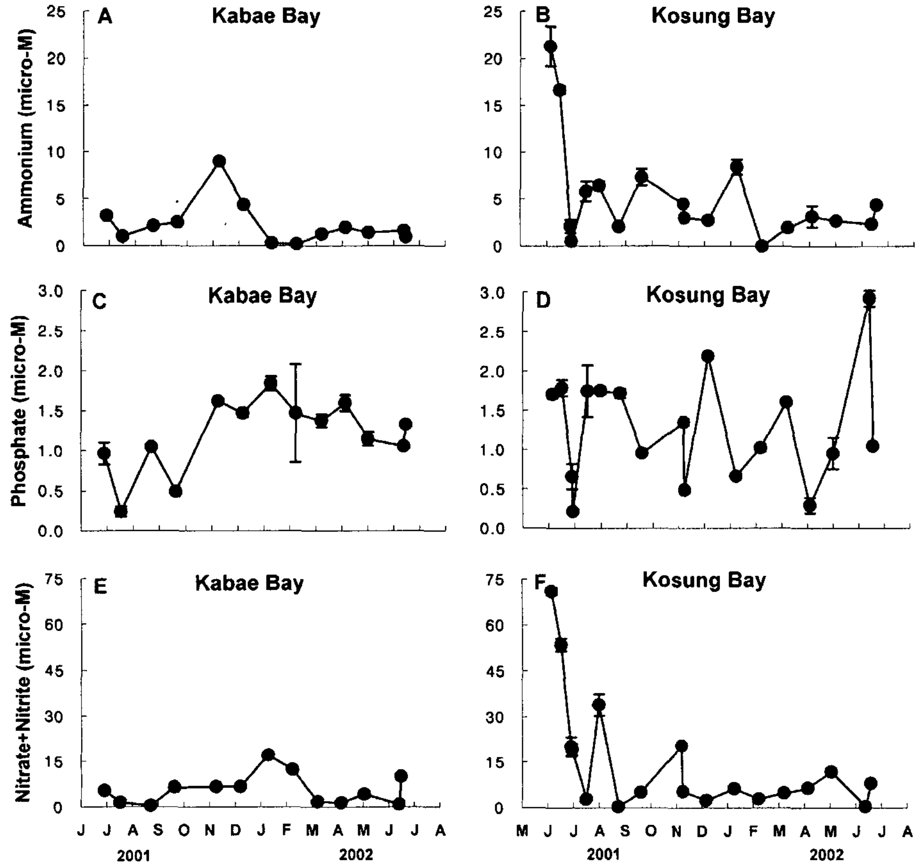

Fig. 4. Water column nutrient concentrations at Kabae Bay and Kosung Bay sites from June 2001 to June 2002. Values are mean±SE. Where no error bars appear, SE is less than the size of the symbol.

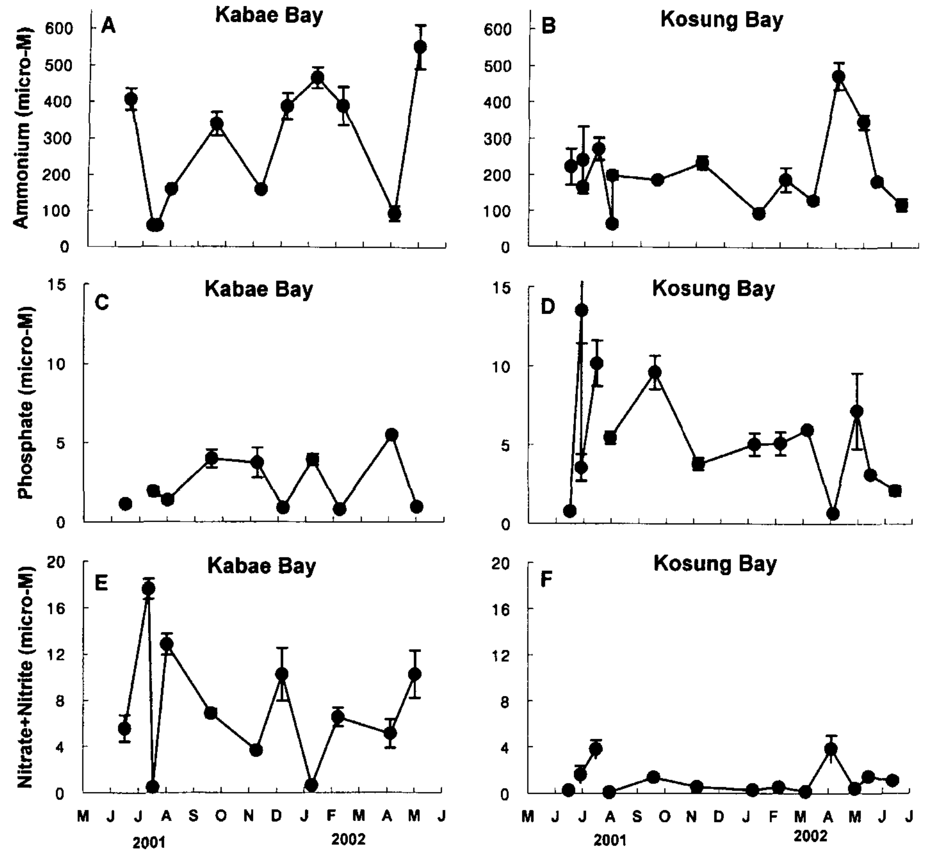

Fig. 5. Sediment pore water nutrient concentrations at Kabae Bay and Kosung Bay sites from June 2001 to June 2002.

trends. Water column PO_4^{3-} concentrations were not significantly (P=0.26) different between the study sites, and mean concentrations were about 1.5 mM at both sites (Fig. 4C, D). At Kabae Bay, water column PO_4^{3-} was higher during winter and lower during summer and fall, while the PO_4^{3-} concentrations at Kosung Bay were highly fluctuated, and showed no seasonal trends. Nitrate + nitrite concentrations in water column were significantly (P<0.001) higher at Kosung Bay site than Kabae Bay statistically (Fig. 4E, F). However, after raining seasons, the water column NO_3^- +NO_2^- concentrations were similar at two study sites.

Sediment pore water NH_4^+ concentrations were significantly (P<0.001) higher at Kabae Bay (344 μM) than Kosung Bay (211 μM; Fig. 5A, B). Sediment NH_4^+ concentrations significantly (P<0.001) changed with sampling time at both sites, but did not show clear seasonal trends. Sediment pore water PO_4^{3-} concentrations were not significantly different between sampling sites, and did not show seasonality at both sites (Fig. 5C, D). Sediment pore water NO_3^- +NO_2^- concentrations were significantly (P<0.001) higher at Kabae Bay than Kosung Bay (Fig. 5E, F). Mean NO_3^- +NO_2^- concentration was 6.7 μM at Kabae Bay site, and was 1.2 μM at Kosung Bay. Sediment pore water NO_3^-+NO_2^- concentrations did not show significant (P =0.06, and 0.24, respectively) temporal variations at Kabae Bay and Kosung Bay sites. Sediment organic content was significantly (P<0.001) higher at Kosung Bay site than Kabae Bay (Fig. 6). Sediment organic content showed significant (P<0.001) temporal variations, but no clear seasonality.

Shoot morphology

Shoot height was significantly (P<0.001) taller at Kabae Bay site (115.7 cm) than Kosung Bay (103.6 cm; Fig. 7A, B). Shoot height showed significant (P<0.001) seasonal variations at both study sites. Shoot height was least during winter, and greatest during summer. Sheath length was also significantly (P<0.001) longer at Kabae Bay site than Kosung Bay (Fig. 7C, D), and showed significant (P<0.001) seasonal variations. Blade width, however, was not significantly (P=0.058) different between two study sites (Fig. 7E, F). Blade width at both study sites showed significant (P<0.001) seasonal trends, decreasing during the fall and winter, and increasing during the spring and summer.

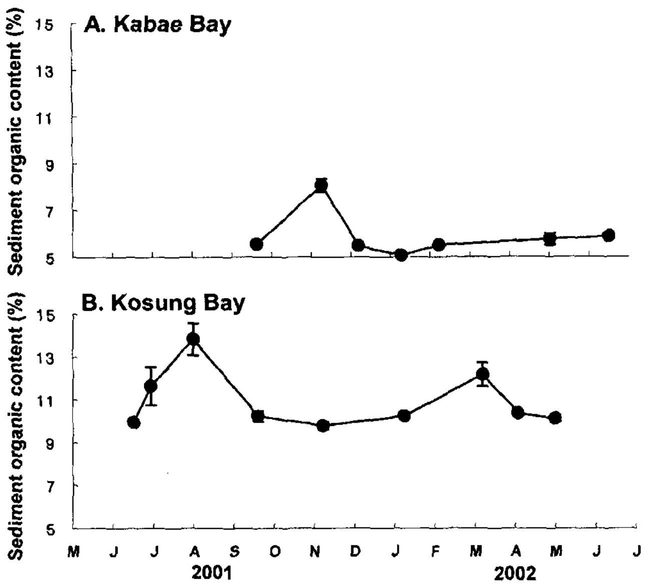

Fig. 6. Sediment organic content at Kabae Bay and Kosung Bay sites.

Shoot density, biomass and production

Eelgrass shoot density was significantly (P=0.019) higher at Kosung Bay site (98.1 shoots m^{-2}) than Kabae Bay (80.1 shoots m^{-2}; Fig. 8). Shoot density at Kabae

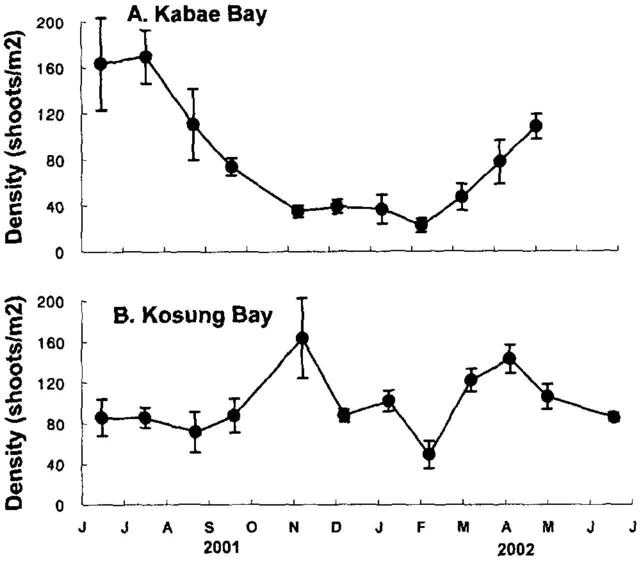

Fig. 8. Seasonal changes in eelgrass shoot density at Kabae Bay and Kosung Bay sites from June 2001 to June 2002.

Bay exhibited obvious seasonal variation, decreasing during fall and winter, and increasing during spring and summer (Fig. 8A). Shoot density at Kosung Bay site, however, showed bimodal peaks, peaks in late fall and late spring (Fig. 8B).

Above-ground, below-ground, and total biomass of

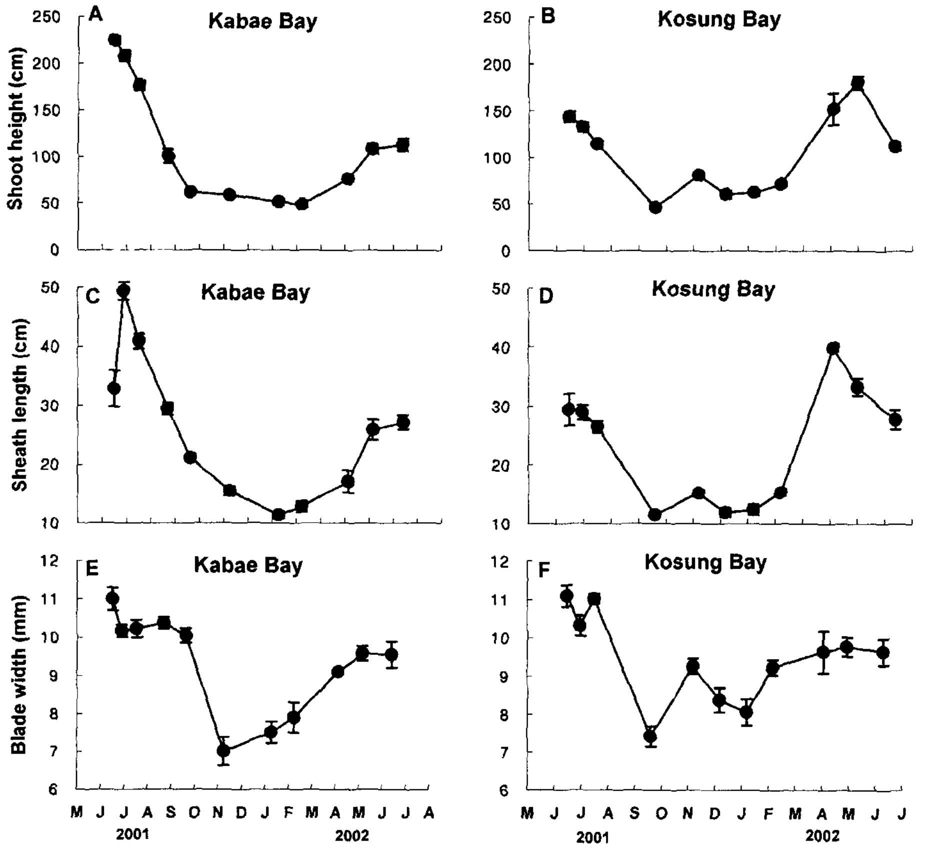

Fig. 7. Seasonal changes in eelgrass plant morphology: shoot height (A,B), sheath length (C, D), and blade width (E, F) at Kabae Bay and Kosung Bay sites from June 2001 to June 2002.

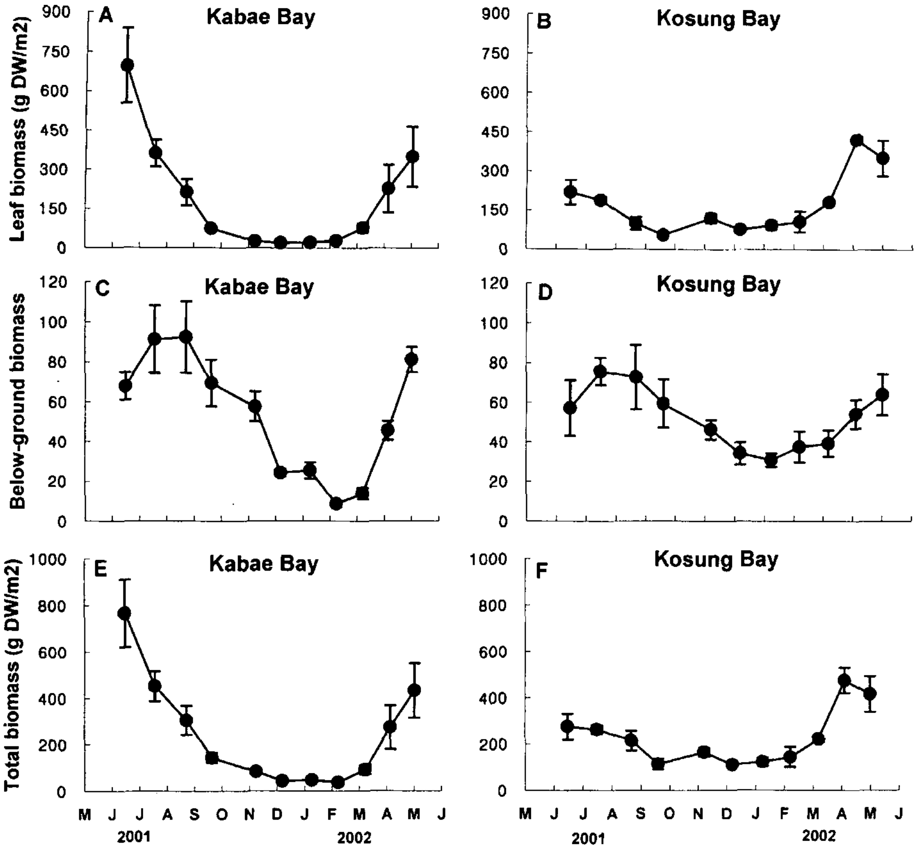

Fig. 9. Seasonal changes in total eelgrass biomass and biomass of different plant components at Kabae Bay and Kosung Bay sites from June 2001 to June 2002.

eelgrass were not significantly (P=0.77, 0.79, and 0.73, respectively) different between sampling sites (Fig. 9). Eelgrass biomass, however, varied significantly (P<0.01) with sampling time, highest in summer and lowest in winter at both study sites. Biomass at Kabae Bay site exhibited more obvious seasonality than that at Kosung Bay site. Leaf productivities significantly (P <0.001) varied with sampling stations (Fig. 10). Leaf productivities were significantly higher at Kabae Bay site than at Kosung Bay site. Leaf productivities also varied significantly (P<0.001) with sampling time, lowest during winter and highest during summer periods.

Plant tissue constituents

The C content of leaf tissues from Kabae Bay site (32.9%) was significantly (P<0.001) higher than that from Kosung Bay site (Fig. 11A, B). Leaf C content from Kabae Bay site was highest in late August (37.3%) and lowest in November (28.3%), while the C content from Kosung Bay site was highest in January (36.4%) and lowest in December (27.8%). Eelgrass leaf tissue C content did not show clear seasonal variations at both study sites. The N content of leaf tissue from Kabae Bay site (2.0%) was significantly (P<0.001) lower than that from Kosung Bay site (2.58%; Fig. 11C, D). Leaf tissue N content from Kabae Bay was lowest in July (1.48%) and highest in February (2.69%), while the N content from Kosung Bay was lowest in April (1.79%) and highest in Jan-

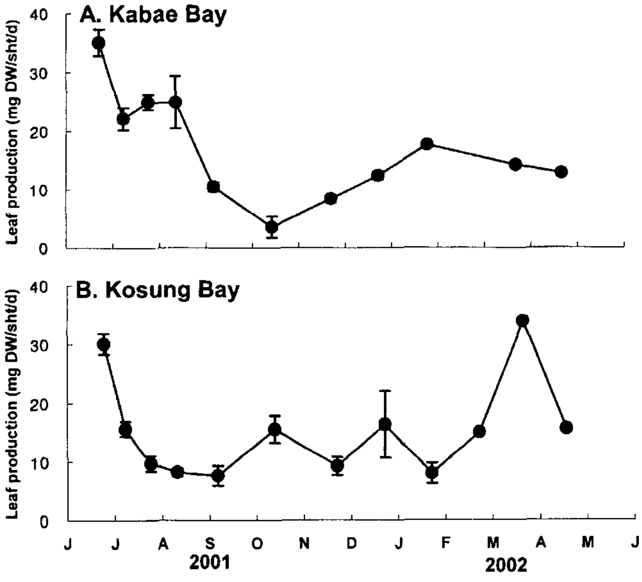

Fig. 10. Seasonal changes in eelgrass leaf productivities at Kabae Bay and Kosung Bay from June 2001 to April 2002

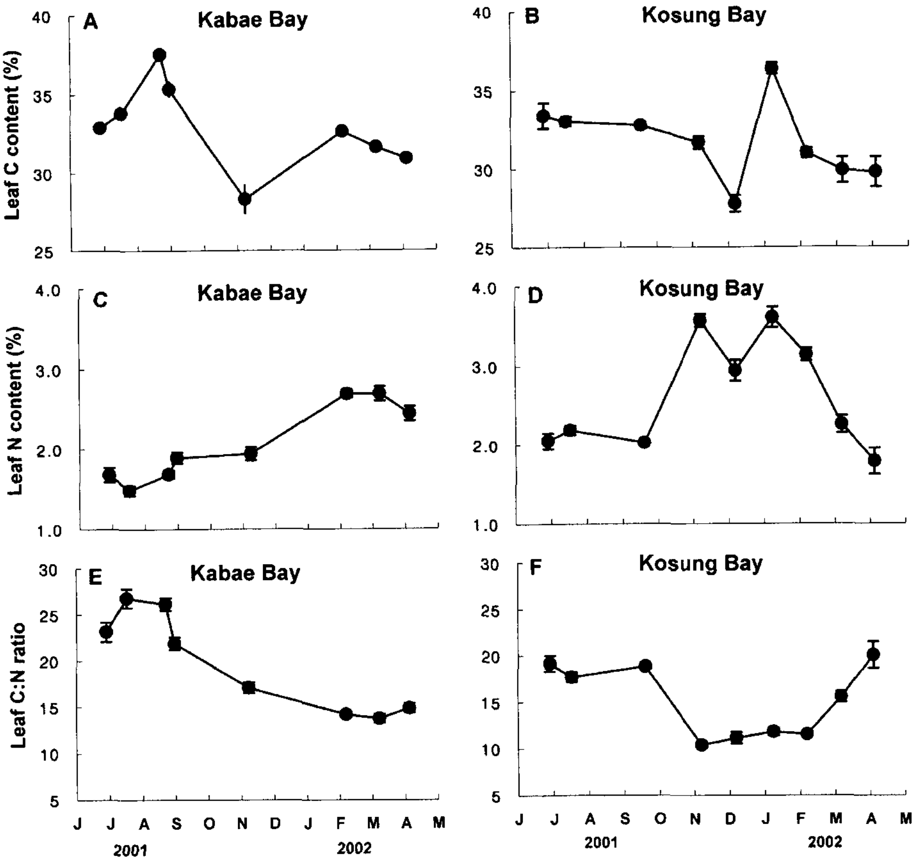

Fig. 11. Carbon and nitrogen and C:N molar ratios of eelgrass leaf tissues at Kabae Bay and Kosung Bay sites from July 2001 to April 2002.

uary (3.61%). Leaf N content was lowest during high growing season and highest during low growing season. The C:N ratios of eelgrass leaf tissues were significantly ($P<0.001$) higher at Kabae Bay site (20.3) than Kosung Bay (15.4; Fig. 11E, F). The C:N ratios of leaf tissues from both study sites exhibited clear seasonal variations, highest during summer and lowest during winter.

The C content of rhizome tissues was also significantly ($P<0.001$) higher in Kabae Bay site (32.6%) than Kosung Bay (31.1%; Fig. 12A, B). Rhizome tissue C content showed more clear seasonal variations than the content of leaf tissues. The C content of rhizome tissues was highest in August at Kabae Bay site (36.4%), and in July at Kosung Bay (35.3%) and lowest in February at both Kabae Bay and Kosung Bay (27.2%, and 25.4%, respectively). The N content of eelgrass rhizome tissues from Kosung Bay site (1.52%) was significantly ($P<0.001$) higher the content from Kabae Bay (1.10%; Fig. 12C, D). Rhizome tissue N content also showed more obvious seasonal variations than leaf tissues at both study sites, highest in November (1.74%, and 2.78% at Kabae Bay and Kosung Bay, respectively) and lowest in April (0.52%, and 0.66%). The C:N ratios of eelgrass rhizome tissues were significantly ($P<0.001$) higher at Kabae Bay site (39.1) than Kosung Bay (28.8; Fig. 12E, F). The C:N ratios of rhizome tissues also showed more obvious seasonality than leaf tissues. The ratios were highest during the high growing seasons and lowest during low growing seasons.

DISCUSSION

Temporal variations

Eelgrass *Zostera marina* at the present study sites exhibited seasonal trends in plant morphology, biomass, productivities, and tissue nutrient constituents. Seasonal variations in seagrass characteristics have been reported by several authors (Orth and Moore 1986; Macauley *et al.* 1988; Dunton 1990; Thom 1990; Lee and Dunton 1996; Vermaat and Verhagen 1996), and were attributed to changes in underwater irradiance and temperature. Water temperature has been considered as a major factor regulating seagrass growth and production (Phillips *et al.* 1983; Lee and Dunton 1996). In the present study, water temper-

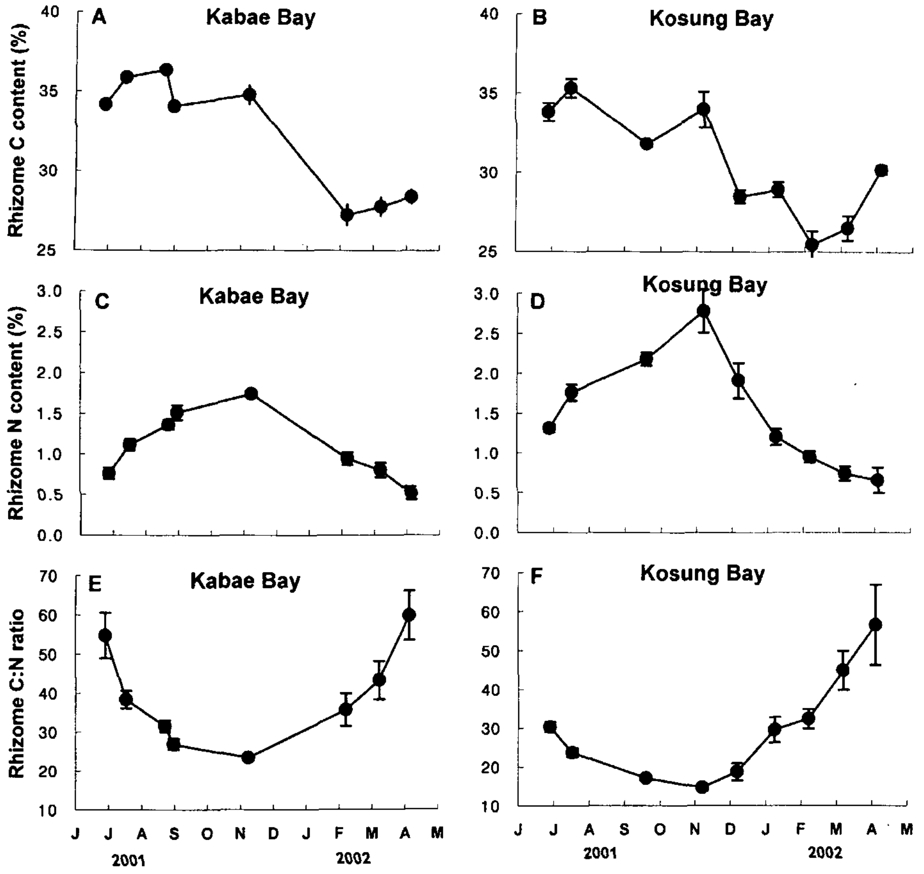

Fig. 12. Carbon and nitrogen and C:N molar ratios of eelgrass rhizome tissues at Kabae Bay and Kosung Bay sites from July 2001 to April 2002.

ature showed obvious seasonal trends at both study sites, but the strength of seasonality was different between two study sites. Water temperature during summer was higher at Kosung Bay site than Kabae Bay, but temperature during winter was higher at Kabae Bay site. This pattern of water temperature implies that Kabae Bay site are affected by ocean more than Kosung Bay site, which showed stronger seasonality of water temperature.

It appears that the patterns of water temperature were reflected in seasonal changes in eelgrass density, biomass and productivities at study sites. Shoot density in Kosung Bay site showed bimodal peaks, and the density decreased during summer period when water temperature exceeded 30°C. An extensive eelgrass leaf loss has been reported in July and August when water temperature approached 30°C (Orth and Moore 1986). Additionally, rapid increases in eelgrass leaf respiration also have been reported at high water temperature of over 30°C (Biebl and McRoy 1971; Drew 1979; Bulthuis 1983; Marsh *et al.* 1986). Marsh *et al.* (1986) have been demonstrated that even short-term leaf exposure to high temperature of >30°C reduces net photosynthesis, increases respiration, and leads to a reduction in P:R ratios in the temperate seagrass, *Zostera marina*. Therefore, production and biomass of *Z. marina* can be limited by seasonal high water temperature and could be significantly limited by even short term or episodic water temperature elevation (Wetzel and Penhale 1983; Evans *et al.* 1986; Marsh *et al.* 1986). Decrease in shoot density at Kosung Bay site during summer period is probably due to high water temperature (> 30°C) during this season.

Biomass at Kabae Bay site exhibited more obvious seasonal trend than Kosung Bay in the present study. At Kabae Bay site, biomass during summer month was significantly higher than spring or fall, but biomass during summer month did not increase at Kosung Bay site. Therefore, biomass was similar during spring, summer, and fall at Kosung Bay site, and this temporal similarity probably results in no strong seasonality in biomass at this site. This seasonal biomass pattern also seems to reflect seasonal trends of water temperature. As a result of high water temperature during summer months at Kosung Bay site, leaf productivities decreased during these months, and leaf productivities were highest during spring at this site.

Spatial variations

Study site in Kabae Bay has higher sand content and lower organic matter in sediments than Kosung Bay site. However, sediment pore water DIN concentrations were significantly higher at Kabae Bay site than Kosung Bay, which has muddy sediments and higher sediment organic content. Nutrient availability in muddy substratum is usually higher than that in sandy sediments (Short 1983, 1987). In the present study, however, Kabae Bay site, which has sandy sediment, had higher pore water DIN concentrations. Higher pore water NH_4^+ conditions in low sediment organic site are unusual, but higher nitrate concentrations in Kabae Bay than Kosung Bay site can be explained by higher ammonium and oxygen concentrations in Kabae Bay site. Sandy sediments are more easily oxidized than muddy sediments. Nitrification is the oxidation of ammonium to nitrate, and it occurs only under aerobic conditions. Therefore, *in situ* nitrification rates depend on ammonium and oxygen concentrations. Since Kabae Bay site has sandy sediments and high ammonium concentrations, nitrification rates probably were high, and consequently high nitrate concentrations in this site. Water column nutrient concentrations were usually higher at Kosung Bay site than Kabae Bay. High peaks of water column nutrient concentrations at Kosung Bay appeared occasionally, and coincided with rainfalls. Rain-water inflow into Kosung Bay probably caused peaks of water column nutrient concentrations in this study site.

Seagrass growth, biomass, morphology, and tissue nutrient constituents are strongly linked to available nutrient resources (Burkholder *et al.* 1992, 1994; Short *et al.* 1995; Udy and Dennison 1997; Udy *et al.* 1999). Strong correlation between sediment N availability and leaf morphology of eelgrass *Zostera marina* has been reported (Short 1983). Eelgrass shoots characterized by short and narrow leaves grew in low N conditions, while shoots exhibiting long and wide leaves were found in high N areas. Tissue nutrient constituents and plant morphological parameters reflect the nutrient regime experienced by the seagrass (Lee and Dunton 1999a, 2000). Shoot height and sheath length were significantly longer at Kabae Bay site than Kosung Bay, but blade width was not significantly different between two study sites. Differences in shoot height and sheath length between two study sites probably were not caused by differences in nutrient availabilities between sites. The differences appeared to be due to differences in other physical parameters such as water depths or strength of currents between the study sites.

Despite differences in nutrient concentrations between study sites, eelgrass biomass and leaf productivities were not significantly different between two study sites. A similar lack of changes in seagrass biomass, density, and production in response to changes in nutrient availabilities has been reported from several seagrass beds (Bulthuis and Woelkerling 1981; Dennison *et al.* 1987; Lee and Dunton 2000). They demonstrated that the ambient nutrient level in the study areas provided an adequate reserve of nutrients for seagrass growth. No significant difference in eelgrass biomass and productivities between two sites of the present study implies that the ambient nutrient availabilities at the study sites are in excess of seagrass nutrient demand.

Eelgrass tissue N content and sediment pore water DIN concentrations exhibited reverse relationship at the present study sites. Sediment DIN concentrations were significantly higher at Kabae Bay site than Kosung Bay, but eelgrass leaf and rhizome tissue N content was significantly higher at Kosung Bay site. This reverse relationship between *in situ* DIN concentrations and eelgrass tissue N content suggests that *in situ* nutrient concentrations do not well represent nutrient availabilities at the area. Sediment nutrient concentrations can be indicative of nutrient availabilities for seagrass growth in some areas, but regeneration of sediment nutrient and turnover rates of sediment nutrient pool are also important factors that determine nutrient availabilities at the site (Jørgensen 1982). In the present study, sediment organic matter was significantly higher at Kosung Bay site than Kabae Bay. Therefore, nutrient regeneration rates were probably higher at Kosung Bay site than Kabae Bay, and higher tissue N content at Kosung Bay site reflected the higher nutrient regeneration at this site.

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