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Carbon Dioxide Fixation by Microalgal Photosynthesis Using Actual Flue Gas from a Power Plant

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ABSTRACT

CO_2 fixation by microalgal cultures, a potential method for CO_2 emissions mitigation, was studied in small (approx 2 m^2) ponds using actual flue gas from power plant whose fuel is low sulfur heavy oil. Three algal stains were cultivated under semicontinuous dilution (30–50% dilution every 2–3 d) in seawater over a period of almost one year, in both a temperature controlled greenhouse and outdoors under ambient temperature conditions. Two algal strains (*Nannochloropsis salina* and *Phaeodactylum tricornutum*), obtained from a culture collection, required frequent (every 10–30 d in summer) cultures restart due to suddenly decrease of algal productivity. One strain (*Tetraselmis* sp.), isolated from local seawater, could be cultivated for over 150 d under fall and winter conditions. Laboratory experiments were carried out to measure algal productivity as a function of Standing biomass. The data was fitted to a derived equation that relates algal productivity to incident light intensity and Standing biomass. There was a reasonable correlation between the calculated and measured outdoor pond productivity.

Index Entries: CO_2 elimination; actual flue gas; field test; raceway cultivator; power station.

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INTRODUCTION

Increases in atmospheric CO_2 may result in future global warming. Technologies for mitigating CO_2 emissions fossil fuel-fired power plant stacks (flue gases) are being investigated, including physical chemical processes, such as wet or dry absorption and membrane separation techniques (*1*), and biological methods, in particular using microalgal photosynthesis (*2*). We have proposed and investigated (*3–5*) a conceptual system for utilizing CO_2 from power plant flue gases (Fig. 1). Algal biomass produced during this process is converted to fuel which is then utilized in the power plant. Previously we reported on laboratory experiments with marine microalgae cultivated at high CO_2 concentrations and on the effects of SOx, NOx, and particulate on such cultures (*3,4*). We also reported initial result of outdoor cultivation of algal cultures using actual flue gas from a power plant (*5*). Here we report on the effect of seasonal climatic changes on algal productivity and present equation that predicts algal productivities as a function of seasonal light intensity.

MATERIALS AND METHODS

Algal Strains

Nannochloropsis salina, strain NANNP-2, and *Phaeodactylum tricornutum*, strain PHAEO-2, were obtained from the National Renewable Energy Laboratory (Golden, CO) culture collection (*6*). These strains were selected on the basis of salinity tolerance, stable growth at high Co_2 level, and calorific value of the biomass (*3,4*). A novel strain, identified as *Tetraselmis* sp. named strain T-S3, was isolated from the local seawater.

Outdoor Test Facilities and Culture Conditions (Table 1)

The ponds used were of the raceway type, similar to those reported on previously (*5*), being 2 m long, 1 m wide, 0.3 m deep, with a single central baffle, rounded corners, and mixed with a paddle wheel. The inside surfaces of the ponds were 1.86 m^2. The ponds were operated at a culture depth of 20 cm at a mixing velocity of 15–20 cm/s. Two such ponds were installed outdoors and operated at ambient temperatures, and two ponds were installed in a greenhouse with temperature controlled in the 20–25°C range by indirect heat exchange with a chiller unit. Actual flue gases from power plant whose fuel is low sulfur heavy oil, containing 10–15% CO_2 and 70–150 ppm NOx and SOx each, was directly and continuously blown into the pond using dispersing nozzles between 0.5–2.0 L/min. Near-shore seawater filtered through a 10 μm filter and sterilized by chlorinating, $NaNO_3$ (300 mg/L), NaH_2PO_4 (20 mg/L), and Na_2SiO_3 (30 mg/L) added,

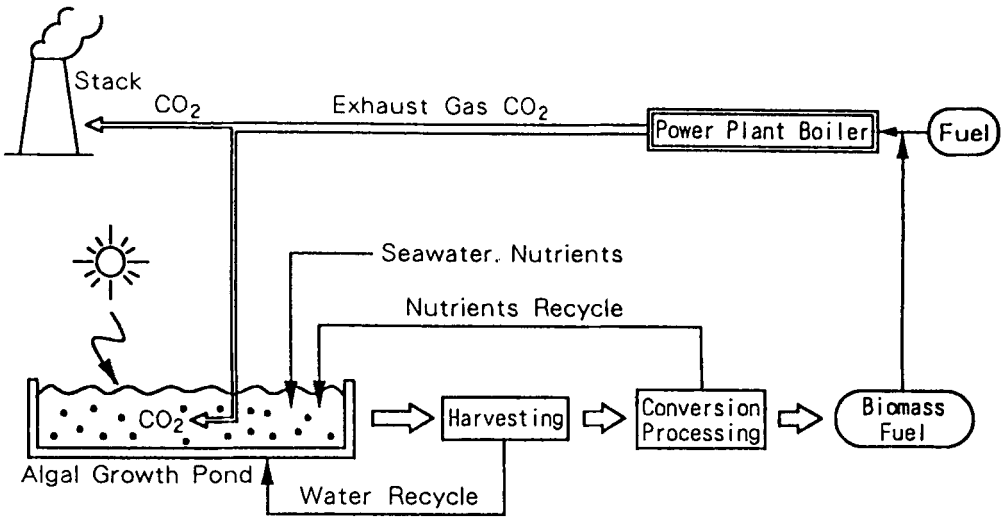

Fig. 1. Conceptual system of CO_2 fixation by microalgal photosynthesis.

Table 1
Testing Apparatus

Cultivator pond	Type: Raceway with 2 ways Size: 1 m × 2 m × 0.3 m (Width) (Length) (Height) Mixing: Paddle stirrer (1 set/pond)		
CO_2 supply	Direct supply of actual flue gas		
Seawater supply	Near shore sea water (filtration by 10 μm filter and sterilization by chloride)		
Other conditions	2 sets	Temperature controlled (20 ~ 25°C)	Place Greenhouse
	2 sets	Noncontrol	Outdoor

and used for dilution of the pond cultures. The pond cultures were diluted 30–50% every 2–3 d, depending on conditions. Algal productivity was measured by determining dry weight on a daily basis from pond grab samples. Dry weight is determined by measuring 50 or 100 mL samples filtered with a 0.3 μm filter after 4 h drying in a dryer in which temperature is kept 105°C. Incident light was measured with a silicon photocell. Temperature was measured by thermocouple. The ponds were inoculated with 10 L of algal culture grown in grass cylindrical vessels illuminated with fluorescent lamps.

Table 2
Composition of Modified f/2 Seawater Medium

1	N, P	$NaNO_3$	300 mg (as N = 50 mg)
		$NaH_2PO_4 \cdot H_2O$	20 mg (as P = 4.6 mg)
2	Si	$NaSiO_3 \cdot 9H_2O$ (only for PHAEO-2)	30 mg (as Si = 6 mg)
3	Vitamins	Thiamine-HCl	0.1 mg
		Biotin	0.5 μg
		B_{12}	0.5 μg
4	Trace elements stock solution[a]		1 mL
	Seawater		1000 mL

[a]Trace elements stock solution:

NaEDTA	4.36 mg
$FeCl_2 \cdot 6H_2O$	3.15 mg (as Fe = 0.66 mg)
$MnCl_2 \cdot 4H_2O$	180 μg
$CuSO_4 \cdot 5H_2O$	10 μg
$ZnSO_4 \cdot 7H_2O$	22 μg
$CoCl_2 \cdot 6H_2O$	10 μg
$Na_2MoO_4 \cdot 2H_2O$	6 μg
Pure water	1000 mL

Laboratory Tests

Algal cultures (strain NANNP-2) were carried out in rectangular flasks with optical depths of 5, 10, and 24 cm illuminated with xenon lamps at a light intensity of 10, 20, or 50 klx. The medium was a modified f/2 seawater medium shown in Table 2 with fourfold higher nitrogen and phosphorous levels prepared using Instant Ocean (Aquarium Systems, Inc.). The water temperature was controlled at 25°C. The CO_2 source was a 10% bomb balanced with N_2 gas, the pH was not controlled. The tests were carried out for 1 wk and the cultures were not diluted within the test periods. The culture density reached 400–2000 mg/L from 100 mg/L. Productivity was measured by determining dry weight.

RESULTS

Outdoor Cultivation

Incident light intensities, precipitation and temperatures are shown in Fig. 2A–D. Figure 3A–B shows daily productivities and the actual operations for the two greenhouse ponds, whereas Fig. 3C–D shows for the out-

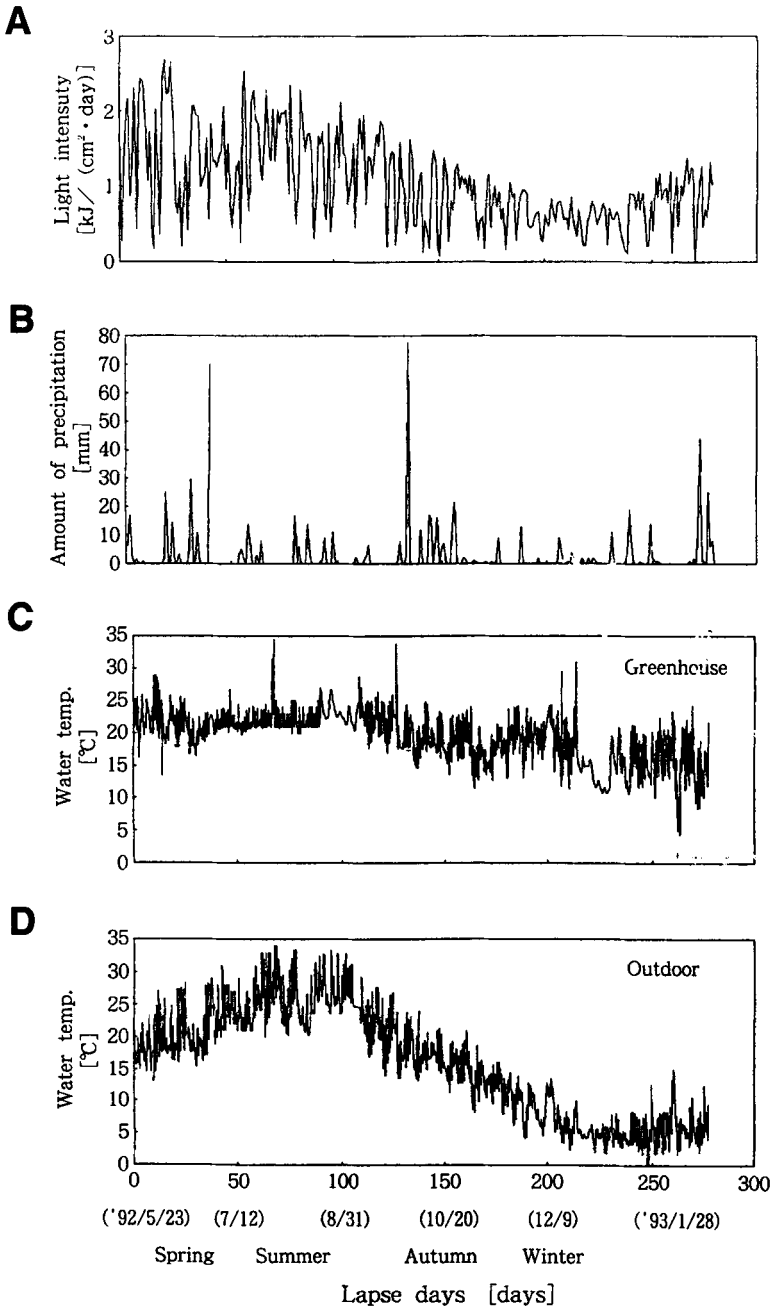

Fig. 2. The conditions of algal cultivation.

door ones. As can be seen from Fig. 3, the cultivation of NANNP-2 and PHAEO-2, especially PHAEO-2, was not stable in the spring and summer, with cultures lasting typically only 10–30 d before they had to be restarted. Cultures were lost owing to suddenly decrease of algal productivity by biological contamination, algae coagulation, and/or algal color changes.

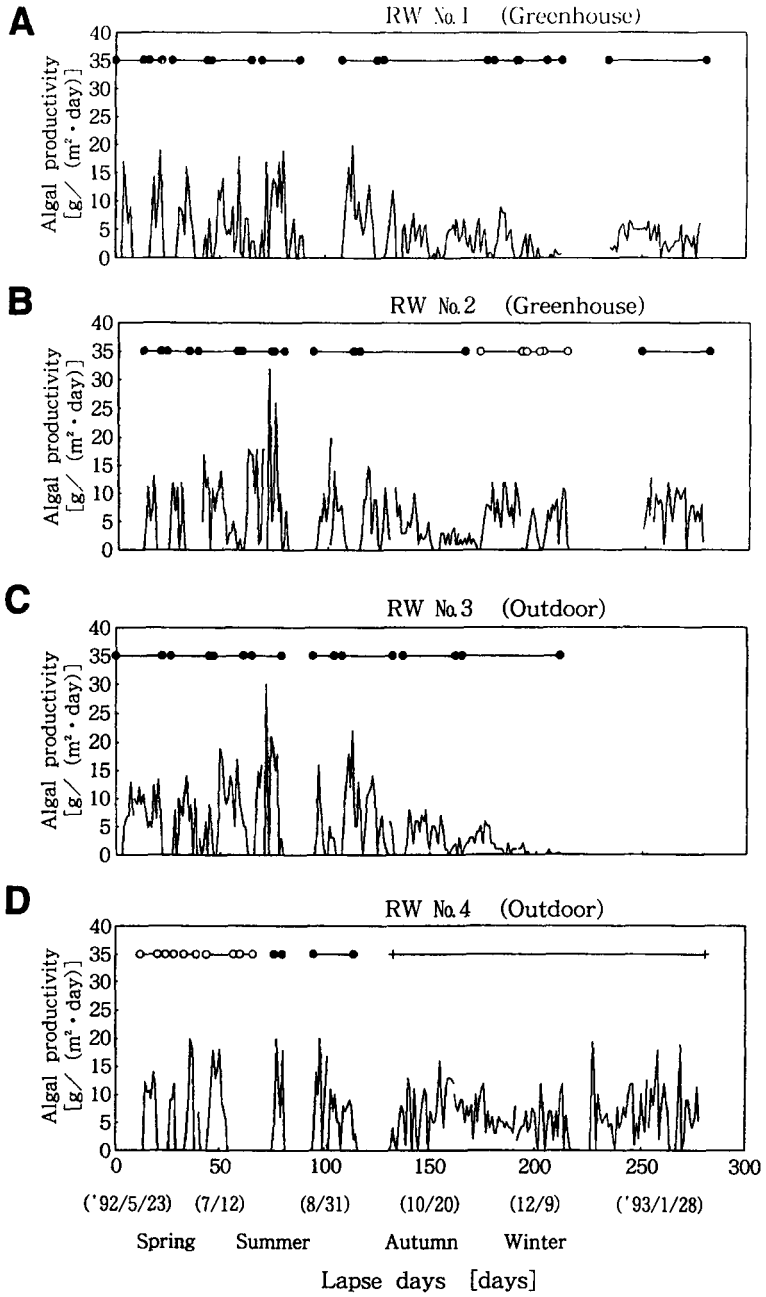

Fig. 3. The results of algal cultivation.

In autumn and winter somewhat longer cultivation periods (over 40 d) were possible with these algae, but that may have been also owing to the lower temperatures delaying culture loss. By contrast, strain T-S3, which was cultivated only starting in the fall, could be cultivated continuously for over 150 d, throughout the fall and winter, without need for replacing the culture. Also, during these seasons the productivities of

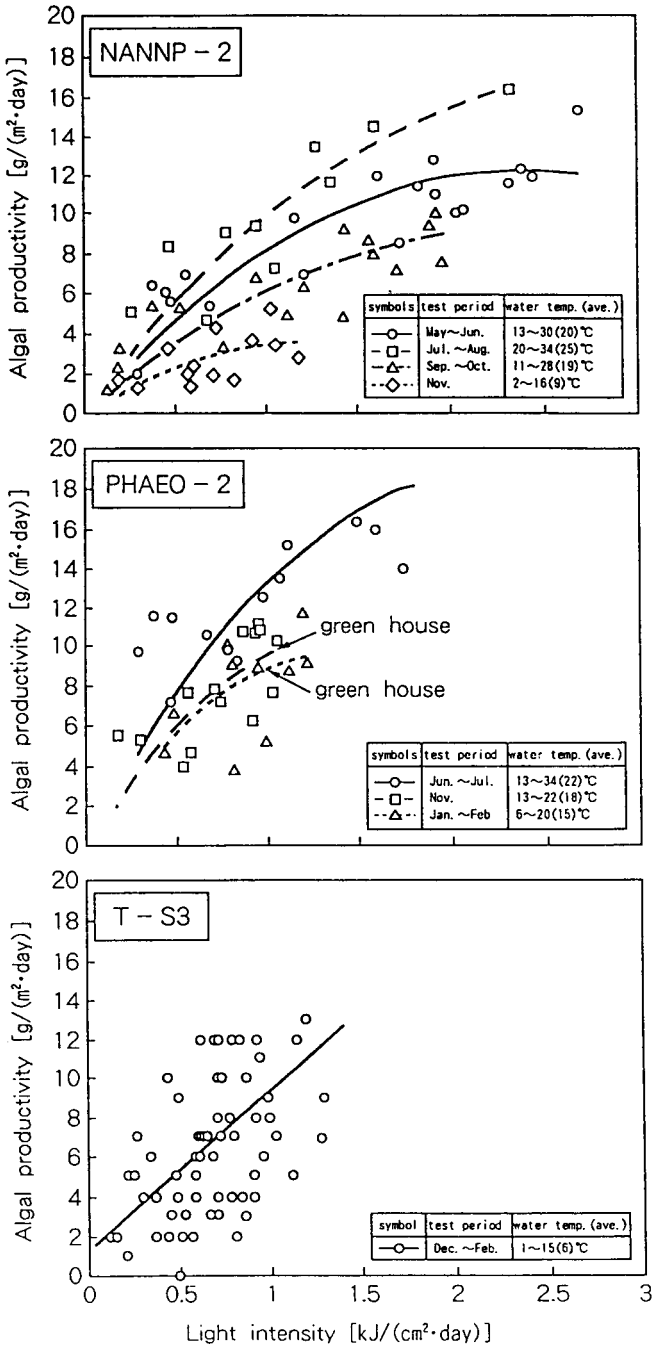

Fig. 4. Comparison of the algal productivity each algal strains.

NANNP-2 and PHAEO-2 decreased dramatically, but T-S3 productivity remained relatively high. This suggests that T-S3 is better adapted to cultivation under low temperatures and low light intensities than the other strains. Figure 4 shows daily productivity data as a function of light intensity. Although there is considerable scatter in the data, as would be expected

with such outdoor systems, there is a clear tendency toward higher productivities for NANNP-2 and PHAEO-2 with increasing temperatures and light intensities.

Algal Productivity and Light Intensity

We had derived an equation relating algal productivity, light intensity, algal biomass and water depth by combining the equation of photosynthesis by algal cells as a function of light intensity with the light absorption by the algal cultures (5). We modified the equation relating algal productivity, light intensity and Standing biomass.

$$P = Kp / \epsilon \{\ln (1 + I0 / \Phi) - \epsilon X / \alpha - \ln (1 + IL / \Phi)\} \quad (1)$$

where;	P:	algal productivity	[g/(m²h)]
	K_p:	productivity constant	[h⁻¹]
	I_0:	light intensity at the surface	[kW/m²]
	X:	Standing biomass	[g/m²]
	$X =$	$C \cdot L0$	
	C:	algal density	[kg/m³]
	L_0:	water depth of the culture pond	[m]
	I_L:	light intensity at the bottom	[kW/m²]
	$IL =$	$I0 \cdot \exp(-\epsilon \cdot C \cdot L0)$	
	ϵ:	absorption coefficient	[m²/kg]
	α:	respiration constant	[−]
	Φ:	light dependency constant	[kW/m²]

An important characteristic of this equation is that the algal productivity is a function of the Standing biomass (X = algal biomass concentration × water depth of the culture). Laboratory experiments were carried out with strain NANNP-2 to obtain the constants for Eq. 1. The results of the laboratory cultures are shown in Fig. 5.

Absorption coefficient was obtained as 130 [m²/kg] by measuring the ratio of back to front light intensity of each rectangular flask with algal density between 100–200 mg/L. From this value and Fig. 5 the following constants can be calculated:

$\epsilon = 130$	[m²/kg]	$Kp = 0.07$ [h⁻¹]
$\Phi = 0.027$	[kW/m²]	$\alpha = 14$

The productivity was calculated, based on Standing biomass and incident actual light intensities every hour, from Eq. 1 and the above laboratory derived constants and summed up to daily productivity. The productivity actually measured with strain NANNP-2 in the ponds for two different periods of cultivation (5/25 to 6/11 and 9/9 to 9/23). They are compared in Fig. 6a–b. Overall there was a rather good agreement between the measured and calculated productivities, with an average ratio calculated productivity to measured one of 0.9.

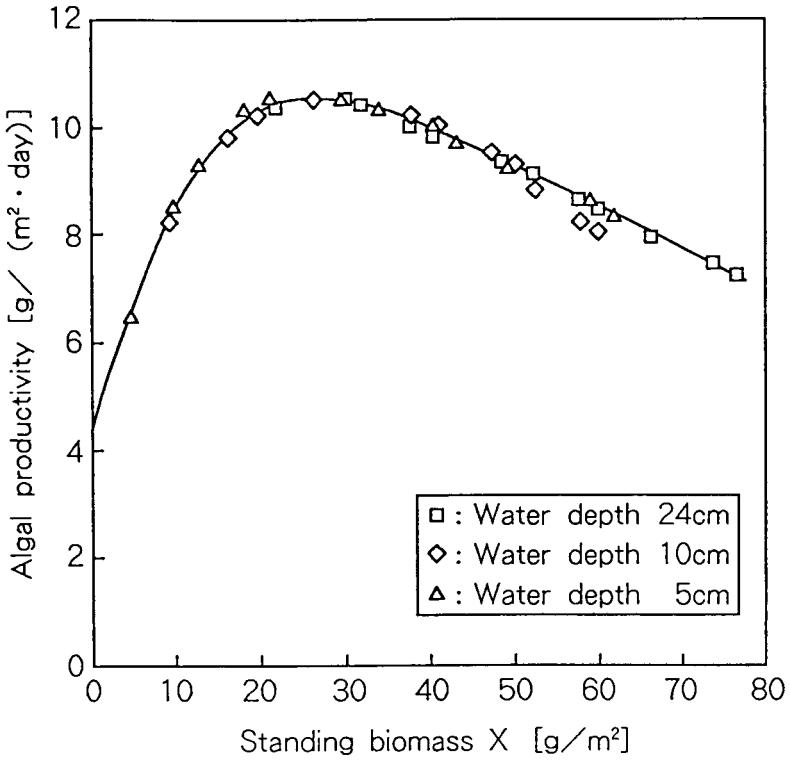

Fig. 5. Correlation between standing biomass and algal productivity (Laboratory test conducted at room temperature.)

DISCUSSION

The outdoor production of microalgae clearly requires strains well adapted to the particular environmental conditions in the ponds. This was most clearly demonstrated by the long-term stability and relatively high productivity, of a local isolate, T-S3, compared to the two culture collection strains, NANNP-2 and PHAEO-2. However, T-S3 has not yet been cultivated during the spring and summer periods, thus the adaptation of this strain to higher temperatures and light intensities must still be determined.

The factors resulting in loss of cultures during the summer have not yet been fully clarified. High light intensities, temperatures, and dissolved oxygen tensions could all be contributing factors. These will need to be studied in the future.

The equation developed herein that relates algal productivity to light intensity and Standing biomass allows a relatively good prediction of algal production from these parameters. It thus can be used to optimize productivity by adjusting Standing biomass through culture dilution. In the

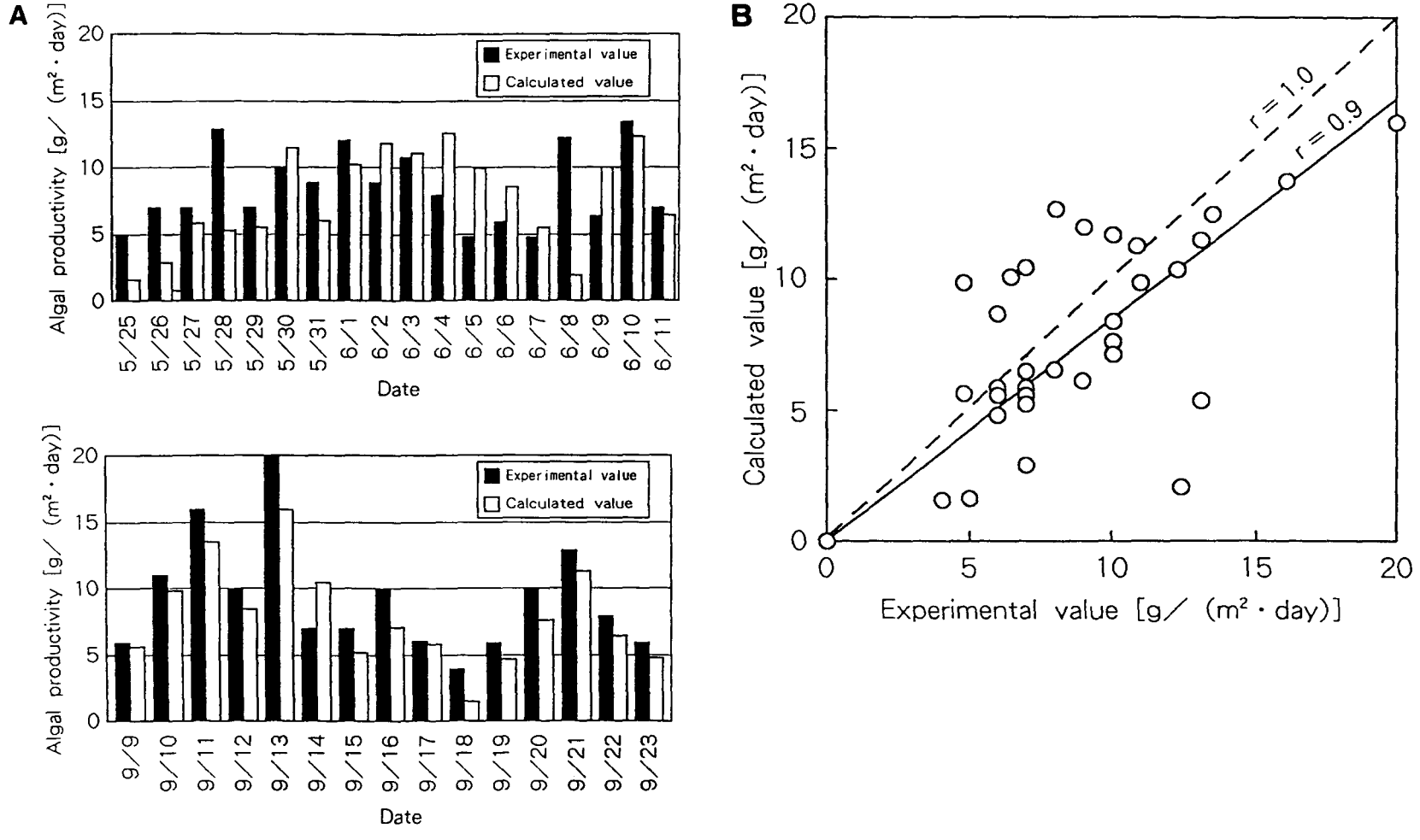

Fig. 6. **A**. The day by day experimental values and calculated values. **B**. Comparison between experimental values and calculated values. (The same data in Fig. 5 are plotted.)

future, improvements in this equation will be made by incorporating a term for temperature, which clearly influences productivity by, among others, affecting the respiration of the cultures.

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