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Carbon Dioxide Fixation by Microalgae Photosynthesis Using Actual Flue Gas Discharged from a Boiler

HIROYO MATSUMOTO,*,[1] NORIO SHIOJI,[1]
AKIHIRO HAMASAKI,[1] YOSHIAKI IKUTA,[2]
YOSHINORI FUKUDA,[2] MINORU SATO,[3]
NORIYOSHI ENDO,[3] AND TOSHIAKI TSUKAMOTO[3]

[1] *Takasago Research and Development Center, Mitsubishi Heavy Industries, Ltd., 2-2-1 Shinhama, Arai-cho, Takasago, Hyogo 676 Japan;* [2] *Engineering and Construction Center, MHI Ltd., Japan; and* [3] *Thermal Department, Tohoku Electric Power Co., Inc., Miyagi, Japan*

ABSTRACT

To mitigate CO_2 discharged from thermal power plants, studies on CO_2 fixation by the photosynthesis of microalgae using actual exhaust gas have been carried out. The results are as follows.

1. A method is proposed for evaluating the maximum photosynthesis rate in the raceway cultivator using only the algal physical properties;
2. Outdoor cultivation tests taking actual flue gas were performed with no trouble or break throughout 1 yr using the strain collected in the test;
3. The produced microalgae is effective as solid fuel; and
4. The feasibility studies of this system were performed. The system required large land area, but the area is smaller than that required for other biomass systems, such as tree farms.

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

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*Author to whom all correspondence and reprint requests should be addressed.

INTRODUCTION

Ever since the Industrial Revolution, the CO_2 concentration in the atmosphere has been steadily increasing because of increasing consumption of fossil fuels accompanied by activities of human life. Associated with this, the issue of global warming is now causing great anxiety. Under such circumstances, researchers have so far tried a variety of approaches to the recovery and fixation of CO_2. We have been examining possible methods for effective use of CO_2 by fixing it using biological techniques. Special attention has been paid to microalgae, because they are fast in CO_2 fixation and can be industrially mass-cultured at high density. We have so far carried out confirmatory tests with respect to the effect of various exhaust gas components, such as CO_2, SOx, NOx, and heavy metal contained in dust, on the microalgae culture, and also the tests on culture conditions, including atmospheric temperature and solar radiation (*1–4*). This article reports the results we have obtained by subsequently performing the search for wild strains of microalgae, its evaluation method, outdoor year-round tests, fundamental tests for use of microalgae as fuel, and feasibility studies.

SCREENING OF WILD STRAIN AND ITS EVALUATION METHOD

Sampling sea water near the experimental place, we isolated the algal strains by survival screening method using the small outdoor pond (0.8 m width × 2.5 m length × 0.3 m depth). For the isolated strains, we measured the absorption coefficient ϵ of algal cell suspension and also measured the other algal properties by the oxygen-reaction monitor method (*5*). The productivity of these strains was evaluated by the method as follows. We considered the raceway-type cultivator model radiated from the upper part as shown in Fig. 1. We assumed that the light intensity in the algal suspension is expressed by the law of Lambert-Beer and also that the rate of photosynthetic reaction depends on the light intensity of the each point of the depth.

$$I = I_o \cdot \exp(-\epsilon \cdot C \cdot x) \tag{1}$$

Here, the O_2 production rate is used as the measure of the rate of photosynthetic reaction. The O_2 production rate of microalgae in raceway cultivator is expressed by (*5*):

$$q = K_p \cdot C \int_0^H [I / (I + \phi) - \rho / K_p] dx \tag{2}$$

where C = concentration of algal biomass (kg/m^3), I = light intensity (lux), K_p = productivity constant (mL/[kg ·h]), ϕ = light dependency constant (lux), ρ = respiratory rate (mL/[kg ·h]), x = optical pass length

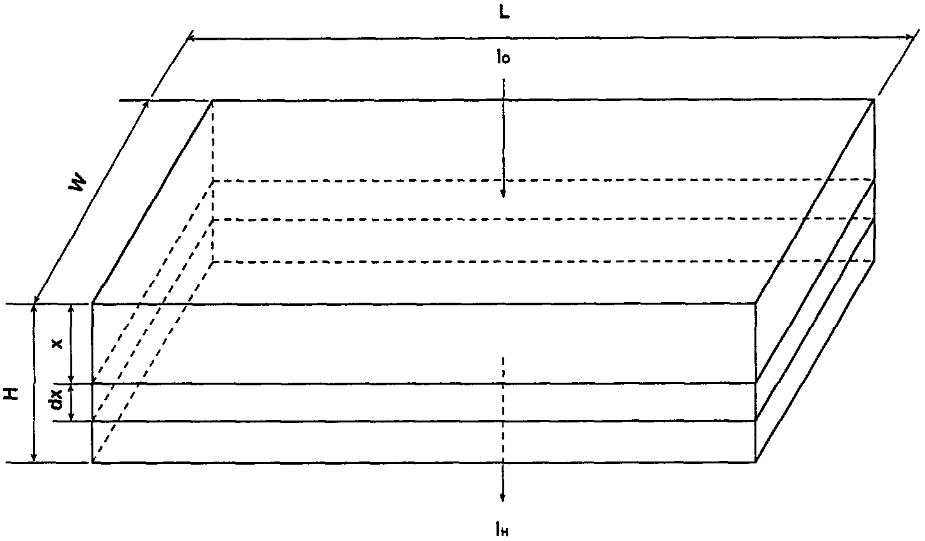

Fig. 1. Model of raceway-type cultivator.

(m), q = oxygen productivity (mL/[m^2 · h]), ϵ = absorption coefficient of algal cell suspended (m^{-1}[kg/m^3]$^{-1}$).

Integration of Eq. (2) gives:

$$q = (K_p / \epsilon) \{ [ln (I_o + \phi) / (I_H + \phi)] - (\rho / K_p) ln (I_o / I_H)\} \qquad (3)$$

where:

$$I_H = I_o \cdot \exp(-\epsilon \cdot C \cdot H) \qquad (4)$$

The condition under which Eq. (3) takes maximum value is as follows:

$$(\partial q / \partial C) = 0 \qquad (5)$$

Equation (3) is differentiated with respect to C to give:

$$(\partial q / \partial C) = K_p \cdot H [I_H / (I_H + \phi) - \rho / K_p] \qquad (6)$$

From Eqs. (5) and (6), the condition that makes q maximum is as follows:

$$C_M = 1 / (\epsilon \cdot H) ln [(I_o / \phi) (K_p / \rho - 1)] \qquad (7)$$

The equation for maximum I_H is obtained by substituting C_M for C in Eq. (4):

$$I_{HM} = \phi / (K_p / \rho - 1) \qquad (8)$$

Consequently, the maximum photosynthetic rate of raceway-type reactor is expressed by the following equation:

$$q_M = (K_p / \epsilon) ln [(I_o + \phi) / (I_{HM} + \phi)] - (\rho / K_p) ln (I_o / I_{HM}) \qquad (9)$$

Equation (9) indicates that the maximum photosynthetic rate of raceway-type reactor q_M is the function of the light intensity I_o and the algal properties K_p, ρ, ϕ, and ϵ only, and it does not depend on the concentration of algal biomass C and the depth of liquid H.. Therefore, we can evaluate the photosynthetic ability of collected microalgae in raceway cultivator by Eq. (9).

In Table 1, the algal properties of collected microalgae are shown. In this table, the physical properties of the general microalgae known as *Nannochloropsis salina* (NANNP-2) and *Phaeodactylum tricornutum* (PHAEO-2) are also shown for comparison. In Fig. 2, relationships between q_M and I_o calculated by Eq. (9) are shown. From this figure, we can see that higher photosynthetic rate strains than NANNP-2 and PHAEO-2 are obtained.

OUTDOOR CULTIVATION TESTS

Using the raceway-type cultivator, 17-mo long-term outdoor cultivation tests were carried out. Actual flue gas of thermal power plant and actual sea water were used in the test.

Test Conditions

The test conditions are shown as follows.

1. Algal Strains
   NANNP-2 (*Nannochloropsis salina*)
   PHAEO-2 (*Phaeodactylum tricornutum*)
   Tetra. sp. (*Tetraselmis sp.*, TM-S3)
2. Medium
   Standard medium of f/2 sea water based on SERI
3. Raceway-type cultivator
   Size = 0.8 m width × 2.5 m length × 0.25 m depth
   Liquid velocity = 0.1–0.2 m/s
4. Test place
   Shin-Sendai Thermal Power Station, Tohoku Electric Power Co. Inc. (Sendai City, Japan)
5. Fuel
   Heavy oil
6. Flue gas composition
   CO_2 = 14.1%; O_2 = 1.3%, SO_x = 185 ppm, NO_x = 125 ppm

Results

In Fig. 3, the data of duration period of algal cultivation are shown. In case of NANNP-2 and PHAEO-2, the duration period of algal cultivation is at most 2 mo, and the long and stable cultivation was difficult. On the other hand, *Tetra, sp.* (TM-S3) collected from the sea near the experimental place was cultivated through 1 yr stably without a break. The algal productivity of *Tetra sp.* is shown Fig. 4. The algal productivity is high in

Table 1
Physical Properties of Microalgae

Properties		Microalgae	NANNP-2	PHAEO-2	TM-S3	TM-T1	TM-S4	TM-S8	TM-S9
Productivity constant	K_p	mL/(kg·h)	2.10E + 05	1.14E + 05	3.29E + 05	1.96E + 05	2.72E + 05	3.07 + 05	3.85E + 05
Light dependency constant	ϕ	lx	6420	1560	9430	1990	3580	4830	6260
Respiratory rate	ρ	mL/(kg·h)	5710	8610	4310	5690	9480	5320	3860
Adsorption coefficient	ϵ	$m^{-1}\cdot(kg/m^3)^{-1}$	112	115	165	126	120	115	152

NANNP-2: *Nannochloropsis salina.*
PHAEO-2: *Phaeodactylum tricornutum.*
TM: *Tetraselmis sp.*

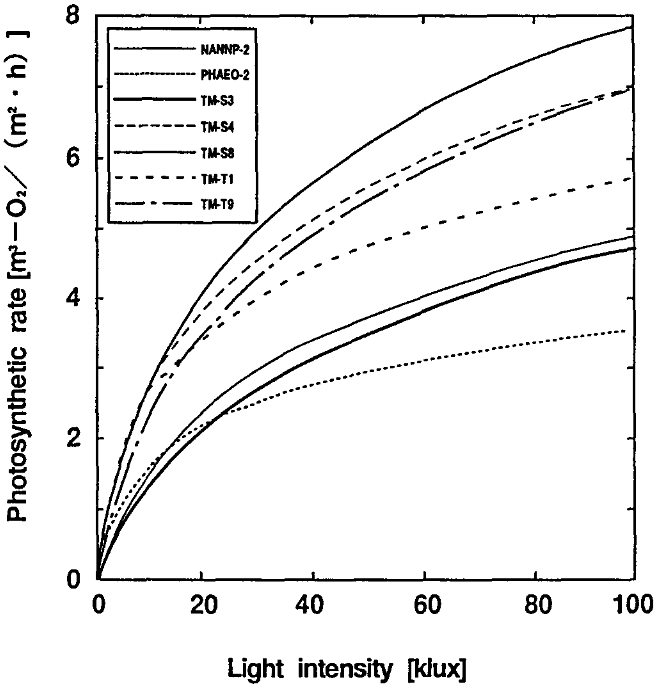

Fig. 2. Maximum photosynthetic rate of raceway-type reactor (calculated by Eq.[9]).

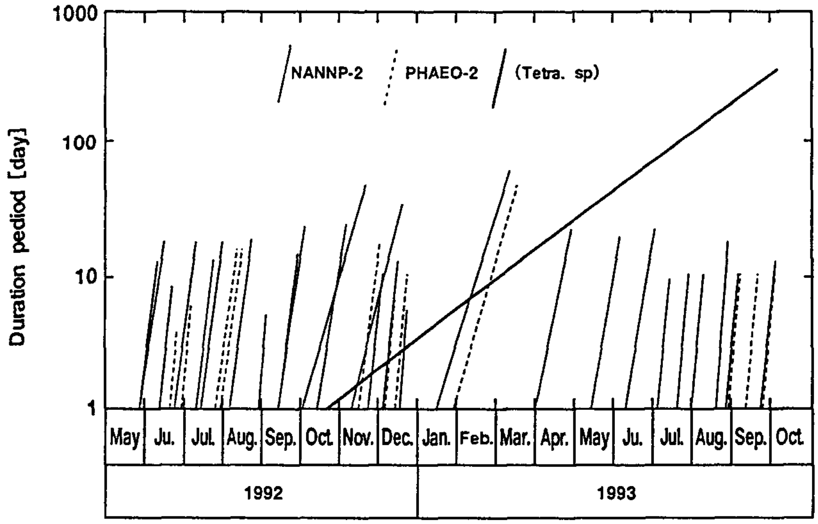

Fig. 3. Duration period of algal cultivation.

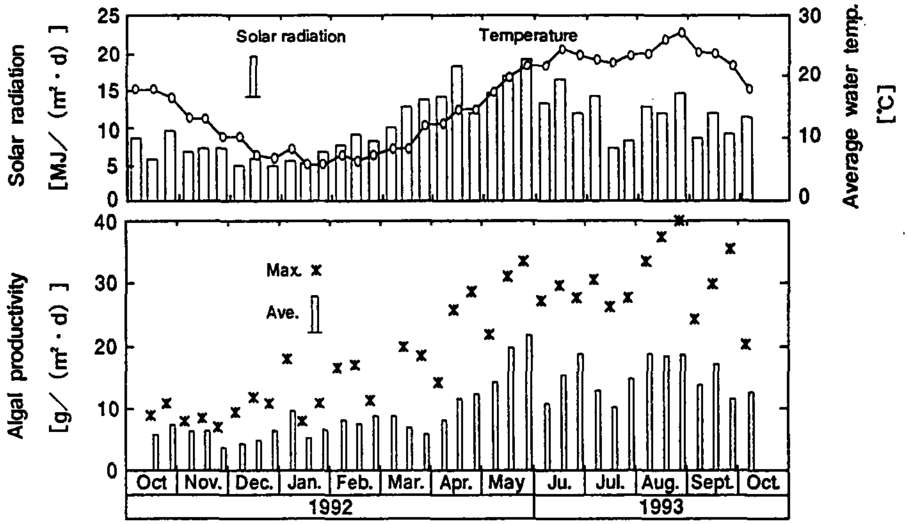

Fig. 4. Algal productivity of *Tetraselmis sp.*

the period from May to September owing to high solar radiation and average water temperature, and the maximum algal productivity in this period was 40 g/($m^2 \cdot d$). In the period from March to September when solar radiation is larger than 10 MJ/($m^2 \cdot d$), the maximum algal productivity showed the same tendency as the average water temperature, and it can be seen that the algal productivity is highly dependent on the average water temperature when solar radiation is higher than some critical value.

FUNDAMENTAL TEST FOR USE OF MICROALGAE AS FUEL

The fundamental tests for the combustion properties and dehydration of algal suspension were carried out with the object of using the product microalgae as solid fuel.

Combustion Properties of Microalgae

The comparison of combustion properties of algal strains and coal are shown in Table 2. The calorific value of microalgae is slightly smaller than coal, but the fuel ratio (fixed carbon/volatility) is lower than that of coal, indicating very good characteristics of both ignition and burn-out.

DEHYDRATION TEST OF ALGAL SUSPENSION

The dehydration test of the algal suspension was carried out using a belt-type continuous dehydrator as shown in Fig. 5. As shown in Table 3,

Table 2
Combustion Properties of Microalgae

Sample	Calorific value,[a] kcal/kg	Volatility, %	Fuel ratio, fixed carbon/volatility	C/H
NANNP-2	4050	64.4	0.15	6.5
PHAEO-2	4470	62.6	0.19	6.8
Tetra. sp.	4870	74.3	0.14	7.3
Coal	6700	27.2	2.06	17.7
Remarks	The higher the better	The higher the better	The lower the better	The lower the better

[a] Heat of combustion.

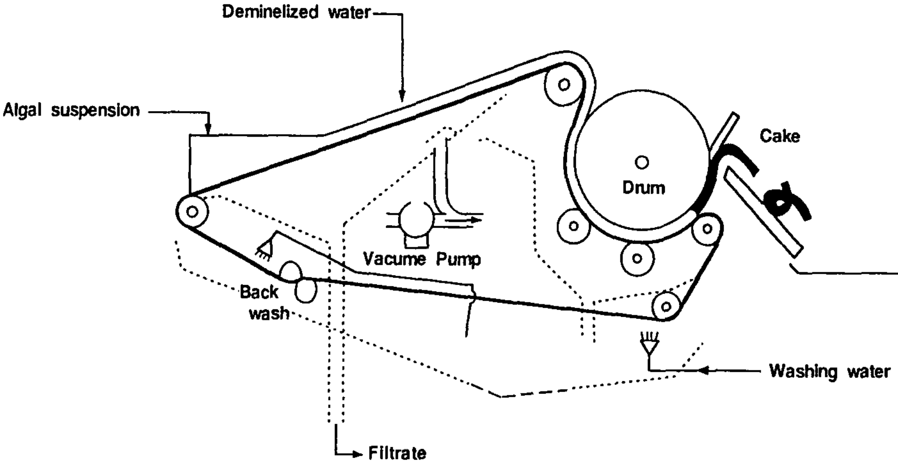

Fig. 5. Belt-type continuous dehydrator.

the difference in the dehydration performance between algal strains is small. For instance, in the case of *Tetra sp.* the filtration rate is 1.3 $m^3/(m^2 \cdot h)$, the percentage of water content is 74 wt%, and recovery of cake is 83.5 wt%, suggesting that much higher recovery of cake is necessary.

FEASIBILITY STUDIES

The feasibility studies on the CO_2 fixation using microalgae and use of it as fuel were carried out based on the fundamental data that had obtained and the results of the previous works (*6–8*).

Conditions

1. Plant size: Flue gas produced by the 500 MW power plant
2. Gas condition: 30.85 kg C/S (CO_2 conc. in dry flue gas: 14.2% vol)

Table 3
Dehydration Test Result

Item	Microalgae	NANNP-2	PHAEO-2	*Tetra. sp.*
Filtration rate	($m^3/m^2{\cdot}h$)	0.9	1.3	1.3
Water content of cake	(%)	75.2	75.2	74.0
Recovery of cake	(%)	81.0	82.2	83.5
Conc. of coagulating agent	(ppm)	90	90	90

3. Biofixation conditions
   - 100% of the CO_2 produced by power plant is fed to biological system and 90% of the CO_2 fed to the system is utilized during daylight summertime hours
   - Direct biofixation of CO_2 is applied where CO_2 in flue gas produced by power plant is directly fed to algal ponds for photosynthesis
   - Both 10% (case 1) and 20% (case 2) of photosynthetic efficiency based on visible are studied
   - Location: Sendai Japan
4. Operation of the plant: Power plant is operated at 70% operation factor. That is to say, the plant is operated at 100% of rated capacity for 16.8 h (70% of 24 h) during daytime and is shut down for 7.2 h (30% of 24 h) during nighttime.
5. CO_2 production rate
   - Hourly CO_2 production: 407 t CO_2/h
   - Annual CO_2 production: 2,495,724 t CO_2/yr
6. Monthly solar radiation in Hiroshima Japan (Table 4).
7. Algal strain: NANNP-2
8. Conceptual system: Fig. 6

Results

Table 5 presents preliminary cost estimates for a large-scale microalgal system for biomass fuel production. The cost estimates in Table 5, which were adopted from previous studies (*6–8*), reflect numerous favorable assumptions about both the engineering and biological aspects of such a system. For example, the growth ponds, a standard of raceway agitated by paddle wheels, would be 10 ha in size, over ten times larger than any operated previously. For economy, the ponds would be of earthwork construction without plastic liners and only with a clay sealer. Only limited experience exists with the operation of such large unlined ponds.

In Table 5, two different productivities, 42 and 84 g/square meter/d were assumed. These correspond to about 10 and 20% solar conversion efficiencies, respectively. The lower productivity reflects what could be expected based on the present experience. The higher productivity is the theoretical limit.

Table 4
Capital and Operating Cost

Items	Case 1	Case 2
Solar conversion efficiency (%)	10	20
Productivity of microalgae (g/m^2/d)	42	84
CO_2 fixation (tC/ha/yr)	48.4	96.8
Average annual utilization of CO_2 (%)	54	54
Land area required (ha)	8900	4500
Capital cost ($/ha)		
Ponds, harvesting and processing	76,400	116,500
Engineering, contingency, fees	16,700	25,700
Land-related	3800	5800
Total capital cost	96,900	148,000
Operation cost ($/ha/yr)		
Power, nutrient, maintenance, labor	15,400	27,000
Annualized capital cost (10% DCF)	10,048	15,346
Credit for business fuel (82.4 $/t)	−8400	−16,793
Net operating cost	17,048	25,553
CO_2 mitigation cost ($/tC)	352	264

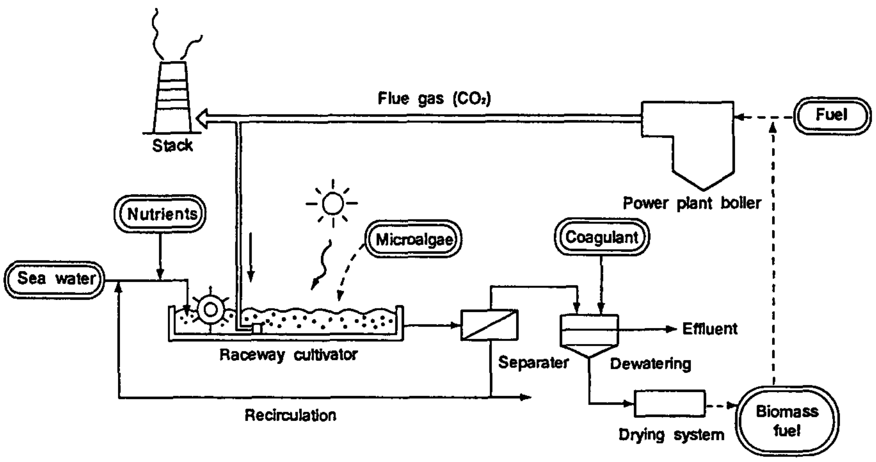

Fig. 6. Conceptual system of CO_2 fixation by microalgae.

Average annual utilization of CO_2 in these systems is 54% for both cases, even though the system is sized to utilize most of the CO_2, produced during peak summer daytime releasing night and much of the winter CO_2 outputs. In Japan, the load of the power plant is high during daytime and low in nighttime. In this process, produced biomass is used as solid fuel for the boiler. Many aspects of this process require R&D. Harvesting assumes flocculation, in which the algae is settled in settling ponds. Dry-

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Operation cost ($/ha/yr)		
Power, nutrient, maintenance, labor	15,400	27,000
Annualized capital cost (10% DCF)	10,000	15,300
Credit for business fuel (82.4 $/t)	−8400	−16,800
Net operating cost	17,000	25,600
CO_2 mitigation cost ($/tC)	352	264

[a] The rate of CO_2 sparging during daytime is determined based on 90% of CO_2 absorbed in cultivation pond.

ing assumes drying in the sun, which is to be the only method for this kind of system once the form of biomass is solid fuel. Burning of algae, which may include salts, also must be carefully investigated. A major constraint on this system is the availability of sufficient land near the power plant. A 500-MW power plant requires 8900 or 4500 ha, depending on the productivity assumption (Table 5). However, land required for algae system is smaller than that required for other biomass systems, such as tree farms.

CO_2 mitigation cost deeply depends on productivity of algae and solar radiation as shown in Table 5. Although much R&D is still needed, no insurmountable problems are apparent, and no breakthroughs are required. If such R&D is successful and the economic projections in Table 5 are verified, microalgae systems could be one of the technologies in future.

CONCLUSIONS

A method is proposed for evaluating the maximum photosynthesis rate in the raceway cultivator using only the algal physical properties. Based on this method, the evaluation of productivity of the wild microalgae collected in this test was performed, and the several algal strains that have larger photosynthesis rate than other microalgae tested were found. Using one of these strains, outdoor cultivation tests taking actual flue gas were performed with no trouble and break throughout 1 yr. As for use of microalgae as fuel, the calorific value of microalgae is slightly smaller than coal, but the fuel ratio is lower than that of coal indicating potential as an effective solid fuel. The preliminary feasibility studies were performed in case of applying this system to a 500-MW thermal power plant. The system required about 9000 ha land area, but this is smaller than of that required for other biomass systems, such as tree farms.

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