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Cycling of Carbon in a Paddy Field

III. Organic matter production and solar energy utilization in a rice plant population*

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Rice plants are the main producer in paddy field ecosystems. Consequently, the plants are considered to play a great role in carbon cycling there. The objectives of this paper are to evaluate the role of rice plants with special reference to gross production, respiration loss, net production and solar energy utilization in organic matter production. In addition, carbon and calorie content of plant material were also examined.

Materials and Methods

1. *The research field and the manner of management*

Observations in this study were made simultaneously with those in Part I and II of this series, using the same paddy field. The conditions and manner for managing the field were described in the previous paper[18].

2. *Measurement of standing crop and LAI of a rice plant population*

The paddy field used for the observation was diveded into three subplots. In each subplot, the aboveground parts of five successive hills were sampled from a row. In other words, 15 hills were sampled in the whole paddy field. Out of them, 3 hills were used for estimating the ratios of leaf area, weight of leaf blades and weight of leaf sheath and stem to the top weight. After heading, panicles and the rest parts were weighed separately in all of the hills. In one subplot, the underground parts of the rice plants were sampled. At the sampling spot, soil was dug out to the depth of 20 cm. Roots were separated from the soil by flushing water and collected as thoroughly as possible. From the weight of the underground and aboveground part in this subplot, the top to root ratio was estimated.

LAI and biomass of whole plants and that of each plant part on land area basis were derived from the values obtained as above and planting density. Sampling was conducted from the beginning of growth to full maturation at about 10-day intervals, 13 times in total.

3. *Absorbance of photosynthetically active radiation (PAR) by the plant population*

Absorbance of PAR by the plant population was measured by using silicon photocells which were only sensitive to visible rays between 10 a.m. and 2 p.m. under clear sky conditions.

4. *Measurement of respiration rate*

The respiration rate of the aboveground part: Plant materials were taken from the field early in the morning. Respiration rate was measured by an air-flow chamber method under two levels of temperature, that is, about the maximum and minimum air temperature for the respective days. For each of the air temperature, 3 or 4 individuals of separate rice plants were used.

The respiration rate of roots: Materials were obtained in the same way as those for estimating root biomass. The roots of the plants were dipped into the tap water, pH value of which was lowered to 5 with dilute sulphuric acid, and air was bubbled into the water. This treatment was done

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twice. Then the same procedure was repeated a few times using distilled water until the pH value did not increase any more. This procedure was applied in order to remove bicarbonate adhering to the root surface.

The roots were fixed to a respiration chamber with the aboveground parts left outside. Air exchange between the atmosphere of roots and that of the aboveground parts was prevented by adhesive tape, allowing only O_2 diffusion through intercellular spaces of the plants.

Humidified N_2 gas was blown into the respiration chamber and the amount of CO_2 produced in the chamber was measured in the routine procedure. Thus, the root respiration was measured under the condition imitating that of anaerobic soil in which roots of the rice plants were growing.

5. *Determination of ash, carbon and calorie content of plant material*

Determination of ash, carbon and calorie content of plant material was conducted using plant samples collected at different 8 growth stages, the date of which are shown in Table 1. Content of crude ash was determined by ignition at 550°C. Carbon content was determined by a C-N Coder (MT550, Yanagimoto MFG Co. Ltd). Calorie content was determined by a calorimeter (New model Nenken-type adiabatic calorimeter, Yoshida Seisakusho Ltd) according to the routine procedure.

6. *Observation for environmental conditions*

Observation of environmental conditions was conducted as described in the previous paper[18].

Results and Discussion

1. *Content of ash, carbon and calorie of plant material*

The results obtained are presented in Table 1. Ash content of leaf blade increased gradually with growth. The content for leaf sheath and stem remained fairly constant throughout the season. "Ash" content of root was the highest of all the organs and increased with time. Most of the "ash" is considered to be ferric oxide judging by the color of the ash.

Table 1. Contents of ash, carbon (C) and calorie (Q) of the plant material on dry matter basis.

Date		Leaf blade			Leaf sheath and stem			Panicle			Root			Whole plant	
		Ash (%)	C (%)	Q (kcal/g)	Ash (%)	C (%)	Q (kcal/g)	Ash (%)	C (%)	Q (kcal/g)	Ash (%)	C (%)	Q (kcal/g)	C (%)	Q (kcal/g)
May	27	13.4	36.3	4.37	15.5	39.0	3.94				23.7	32.5	3.52	36.3	3.97
Jun.	17	14.1	40.6	4.24	14.5	37.8	3.78				20.4	34.5	3.38	37.6	3.81
Jul.	7	14.6	40.6	4.24	15.7	34.6	3.68				19.8	33.8	3.44	35.7	3.80
Jul.	29	15.3	37.7	3.93	14.4	35.8	3.44				26.2	31.8	3.24	35.5	3.62
Aug.	18	17.1	34.6	3.92	12.8	35.4	3.80				30.6	28.0	3.04	34.3	3.73
Aug.	28							8.83	37.0	4.10					
Sept.	8	24.3	33.2	3.49	19.4	34.5	3.65	6.22	39.2	3.86	23.8	32.3	3.27	35.6	3.65
Sept.	18							5.51	38.9	4.09					
Oct.	1	21.4	34.6	3.66	15.3	33.9	3.47	9.07	38.9	3.83	26.5	32.7	3.29	35.3	3.60
Oct.	17	22.2	33.6	3.62	14.0	36.3	3.72	3.52	37.9	4.20	29.7	29.1	3.22	35.8	3.82
Mean		17.8	36.0	3.91	15.2	35.9	3.71	6.63	38.4	4.02	25.1	31.8	3.30	35.8	3.75
±SD		±4.2	±2.5	±0.31	±1.9	±1.7	±0.14	±2.33	±0.9	±0.16	±3.9	±2.2	±0.15	±0.9	±0.16

Table 2. Contents of carbon (C) and calorie (Q) on ash free dry matter basis and the ratio of calorie content to carbon content.

Date	Leaf blade			Leaf sheath and stem			Panicle			Root		
	C (%)	Q (kcal/g)	Q/C (kcal/gC)	C (%)	Q (kcal/g)	Q/C (kcal/gC)	C (%)	Q (kcal/g)	Q/C (kcal/gC)	C (%)	Q (kcal/g)	Q/C (kcal/gC)
May 27	41.9	5.05	12.0	46.2	4.66	10.1				42.6	4.61	10.8
Jun. 17	47.5	4.96	10.4	44.2	4.42	10.0				43.3	4.25	9.8
Jul. 7	44.1	4.78	10.8	41.0	4.37	10.6				42.1	4.29	10.2
Jul. 29	44.5	4.64	10.4	41.8	4.21	10.1				43.1	4.39	10.2
Aug. 28							40.6	4.50	11.1			
Sept. 8	43.9	4.61	10.5	42.8	4.53	10.6	41.8	4.12	9.8	42.4	4.29	10.1
Sept. 18							41.2	4.33	10.5			
Oct. 1	44.0	4.66	10.6	40.0	4.10	10.2	42.8	4.21	9.8	44.5	4.48	10.1
Oct. 17	43.2	4.65	10.8	42.2	4.33	10.3	39.3	4.35	11.1	41.2	4.58	11.1
Mean	43.9	4.76	10.9	42.4	4.38	10.3	41.1	4.30	10.5	42.5	4.41	10.4
±SD	±1.8	±0.16	±0.6	±2.0	±0.17	±0.3	±1.3	±0.14	±0.6	±1.3	±0.14	±0.4

Ash content of panicle was low and decreased with time.

There was large differences in carbon content among organs and materials sampled at different stages. For example, the content for leaf blade was consistently higher than that for root. In both of these organs, carbon content decreased with time. Just the same seasonal trend was observed in carlorie content. The levels of carbon content for each organ obtained in this study are lower than those by WATANABE[16]. The seasonal change in the carbon content of each organ is also different from his results. The reasons for these discrepancies are not clear. As for the calorie content of the whole plant, there was no marked developmental change as observed by MURATA et al.[11] and HIROTA et al.[3].

Carbon and calorie content on ash-free plant material basis are presented in Table 2. Both carbon and calorie content of leaf blade are a little higher than those for other organs. However, most of the differences among samples observed in Table 1 were not detected here. In most cases, carbon and calorie content on ash-free plant material basis were in the ranges of 41 to 44% and 4.3 to 4.5 kcal/g, respectively.

Contents of carbon and calorie presented in Table 1 were fairly low compared with those in other species[6,10,14,15]. This may be universal and characteristic for paddy rice plants which usually contain a lot of SiO_2 and so of total ash[1]. The figures

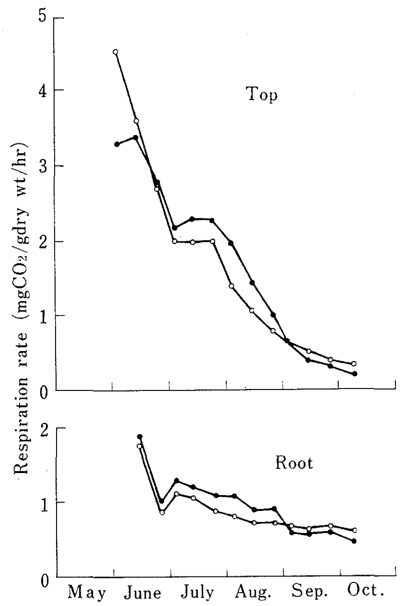

Fig. 1. Seasonal trends of top respiration rate and root respiration rate. Open circles indicate the respiration rate under the average temperature over the whole growth period (23.5°C for top and 21.9°C for root). Closed circles indicate the respiration rate under the average temperature of each growth period.

for carbon and calorie content on ash-free plant material basis are close to those of other species[8,10,14,15].

SiO_2 content of paddy rice plants may vary largely depend on environmental conditions. However, it may be feasible to estimate carbon and calorie content on the basis of ash-free plant material by applying the average contents, i.e. 43% for carbon and 4.5 kcal/g for calorie with little error.

The ratio of calorie content to carbon content, i.e. calorie per unit carbon is almost constant and the average value was 10.5 kcal/gC.

2. *Seasonal trends of respiration rate on dry weight basis*

The respiration rate was measured under two levels of temperature. From these data, the rate on dry weight basis under the average temperature of each growth period and that of the whole growth period (23.5°C for air temperature and 21.9°C for soil temperature) were derived. The results are presented in Fig. 1. The respiration rate of the aboveground part declined rapidly, whereas that of the underground part declined gently. The magnitude and time trend of the respiration rate are similar to those obtained by YAMADA et al.[17].

3. *Seasonal trends of standing crop and LAI*

Standing crop of rice plants and biomass of each part of plants, represented in terms of carbon, are shown in Fig. 2. These values were derived from plant biomass observed at 10-day intervals and carbon contents in Table 1. Carbon contents of samples which were not analyzed were estimated by interpolation.

Standing crop of the whole plant continued to increase throughout the growth season. After heading, the amount of panicle increased rapidly, while that of leaf sheath and stem decreased. The rapid increase in panicle ceased at the beginning of September. At that time, the amount of leaf sheath and stem turned to increase again. At the last stage of development, the increase in whole plant was based entirely on the increase in leaf sheath and stem.

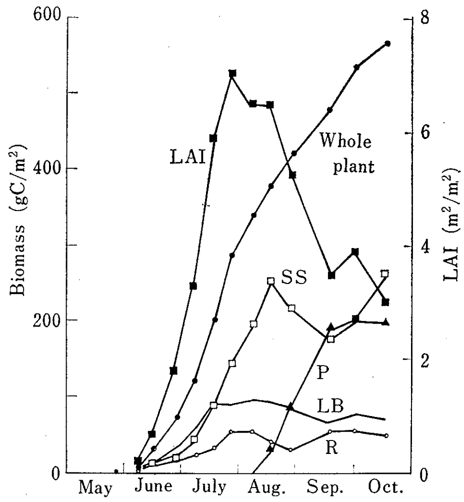

Fig. 2. Seasonal trends of standing crop and LAI.
LB: leaf blade SS: leaf sheath and stem
R: root P: panicle

The final amount in carbon of the whole plant was 567 gC/m^2 and that of panicle 198 gC/m^2. The values expressed in terms of dry matter are 1583 g/m^2 and 522 g/m^2, respectively.

LAI increased with growth and attained its maximum at the end of July and turned to decrease. The magnitude was 7.0 at the maximum and 3.0 at the full maturation.

4. *Seasonal trends in the rates of net production, respiration loss and gross production on land area basis*

Estimation of net production

Net production in a period can be estimated as the sum of increment in standing crop (ΔW) and the litter fall (L) in the period. In this study, we estimated L as the sum of decrements in the amount of carbon in each part of the plant excepting leaf sheath and stem. The decrease in the amount of carbon in these parts at the early stages of ripening is considered to be caused by translocation of carbohydrates stored in these parts to panicles. Therefore, the decrease of carbon in them was not regarded as litter fall. The net production rate is defined as net production per day in this paper.

Estimation of respiration loss

Table 3. Carbon budget in the rice plant population

	Period	Δt days	$\overline{Ta}$ °C	ΔW	L	R $gC/m^2/day$	Pn	Pg	Pn/Pg (%)
I	May 28—Jun. 5	9	19.1	0.33		0.16	0.33	0.49	66.6
II	Jun. 6—Jun. 16	11	22.1	2.43		0.73	2.43	3.16	77.0
III	Jun. 17—Jun. 29	13	23.9	2.99		1.91	2.99	4.90	61.0
IV	Jun. 30—Jul. 6	7	25.5	7.03		3.23	7.03	10.26	68.5
V	Jul. 7—Jul. 16	10	26.8	8.07		5.86	8.07	13.93	57.9
VI	Jul. 17—Jul. 26	10	27.5	8.60		8.52	8.60	17.12	50.2
VII	Jul. 27—Aug. 7	12	28.1	4.56		10.07	4.56	14.63	31.2
VIII	Aug. 8—Aug. 17	10	27.9	3.97	1.43	8.85	5.40	14.25	37.9
IX	Aug. 18—Aug. 27	10	26.6	3.19	1.52	7.37	4.71	12.08	39.0
X	Aug. 28—Sept. 17	21	21.4	2.86	1.01	4.46	3.87	8.33	46.6
XI	Sept. 18—Sept. 30	13	20.5	4.08	0.17	3.27	4.25	7.52	56.5
XII	Oct. 1—Oct. 16	16	15.6	2.06	1.29	2.22	3.36	5.58	60.2
	Total	142		565	74	656 gC/m^2	639	1,295	49.3

The respiration loss in a growth period was estimated as the product of plant biomass and respiration rate on dry weight basis under the average temperature for the period (Fig. 1).

Estimation of gross production rate

The gross production rate (Pg) was estimated as the sum of the net production rate (Pn) and the respiration loss per day (R). Table 3 and Fig. 3-a show Pn, Pg and the Pn/Pg ratio for each growth period. After transplanting, Pn increased with time and attained a maximum at the end of July and then decreased. The time trend of Pg was similar to that of Pn but the depression in the latter half of the rice growing period was more rapid in Pg. The maximum rates of Pn and Pg were 8.60 and 17.1 $gC/m^2/day$, respectively.

At the early stages, the Pn/Pg ratio showed the value ranging 60–70%, as commonly observed for ordinary plants[5,6,9,13,19] in vegetative stages. However, after the beginning of July, it declined rapidly and fell to a value as low as 31% in the period VII. Afterwards, the ratio changed to increase and kept increasing during the latter half of growth, attaining 60% in the last period. Thus, the curve for seasonal changes in the Pn/Pg ratio takes the form of "V". According to the results reported on rice plant[13,19], maize[19], soybean[19] and rape seed plant[5], this ratio decreased slowly in the vegetative period and very rapidly in the ripening period in most cases. Therefore, the result obtained in this study is quite different from those in the previous studies. A possible reason for this discrepancy might be the effect of the seasonal change in temperature specific to this case. Thus, the carbon budget under a constant temperature (23.5°C, the average air temperature for the whole growth period and 21.9°C, the average soil temperature) was examined. Fig. 3-b shows the time trends of Pn, Pg and the Pn/Pg ratio obtained on the following assumptions, (1) gross production is not affected by temperature in the range of 23.5°C to the actural average temperature in each period, (2) the respiration rate in each period is equal to that presented by open circles in Fig. 1 and (3) there is no cumulative effect in plant biomass caused by the change of net production rate.

According to Fig. 3-b, the Pn/Pg ratio decreases simply with time without showing "V" form. Pn values at the middle stages are much higher than the actually observed values but those at the latter stages are lower than the actual values. These suggest that net dry matter production at midsummer has been heavily depressed by high temperatures in this season. While, net dry matter production in the ripening period was helped by low temperatures in fall. The constitutional tendency of rice

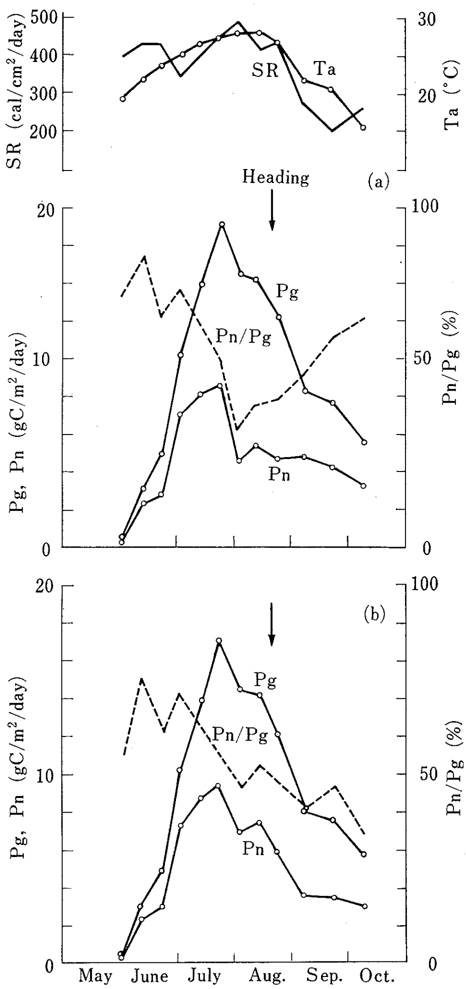

Fig. 3. Seasonal trends of gross production rate (Pg), net production rate (Pn) and the ratio of Pn to Pg (Pn/Pg) under the average temperature of each growth period (a) and under the average temperature over the whole growth period. See the text in detail.

plant in the Pn/Pg ratio may be to decrease with development.

In 1978, it was hotter than usual in summer. However, it does not seem to be exceptional. Therefore, the phenomenon observed in this study may hold true in the southern region of Kanto district, to some extent.

Gross production and net production for the whole growth period were 639 and 1,295 gC/m^2, respectively. The Pn/Pg ratio for the whole growth period was 49.3%. This ratio is less than those obtained by SUZUKI and MURATA[12] for rice plant in a southern region of Japan, i.e. 67%. The ratio is also lower than those obtained in rape seed plants (54%)[5] and barley plants (60%)[9]. However, the ratio obtained here is comparable to the value of 47.6% in rice plants derived from HIROTA and TAKEDA's Table 3[4].

Efficiency of solar energy utilization

Four kinds of efficiency for utilization of solar energy were examined. Definition and symbols are as follows:

$$(1)\quad En.t=\frac{Qn}{SR}\times 100(\%)$$

$$(2)\quad Eg.t=\frac{Qg}{SR}\times 100(\%)$$

$$(3)\quad En.eff=\frac{Qn}{PAR}\times 100(\%)$$

$$(4)\quad Eg.eff=\frac{Qg}{PAR}\times 100(\%)$$

where, En.t and Eg.t are efficiencies of total solar radiation incident on a field (SR) for net production and gross production, respectively. En.eff and Eg.eff are efficiencies of photosynthetically active radiation incident on a field (PAR) for net production and gross production, respectively. Qn and Qg are amount of energy fixed in net production and gross production, respectively.

In addition, two kinds of efficiencies for convertion of PAR absorbed by plant tissues (PARabs) were examined.

$$(5)\quad \Phi_{n.eff}=\frac{Qn}{PARabs}\times 100(\%)$$

$$(6)\quad \Phi_{g.eff}=\frac{Qg}{PARabs}\times 100(\%)$$

where, $\Phi_{n.eff}$ and $\Phi_{g.eff}$ are efficiency of PAR energy conversion for net production and gross production, respectively.

Amount of SR was estimated from the record of routine observation for environmental conditions[18]. The amount of PAR was estimated as SR×0.535. The factor 0.535 is the average proportion of PAR to SR reported by KISHIDA[7].

The amount of PARabs was estimated

Table 4. The efficiencies of solar energy utilization for net production (En.t) and for gross production (Eg.t).

Table		Δt days	SR (cal/cm²/day)	Qn	Qr (kcal/m²/day)	Qg	En. t (%)	Eg. t
I	May 28—Jun. 5	9	396	3.4	1.7	5.1	0.086	0.130
II	Jun. 6—Jun. 16	11	433	24.5	7.7	32.2	0.564	0.743
III	Jun. 17—Jun. 29	13	429	31.7	20.3	52.0	0.739	1.21
IV	Jun. 30—Jul. 6	7	332	77.4	34.3	111.7	2.331	3.36
V	Jul. 7—Jul. 16	10	403	81.7	62.2	143.9	2.029	3.57
VI	Jul. 17—Jul. 26	10	448	82.4	90.2	172.8	1.839	3.86
VII	Jul. 27—Aug. 7	12	485	56.7	106.8	163.5	1.169	3.37
VIII	Aug. 8—Aug. 17	10	413	55.0	93.9	148.9	1.332	3.61
IX	Aug. 18—Aug. 27	10	431	55.5	78.2	133.7	1.287	3.10
X	Aug. 28—Sept. 17	21	267	37.2	47.3	84.5	1.393	3.35
XI	Sept. 18—Sept. 30	13	192	51.4	34.7	86.1	2.682	4.48
XII	Oct. 1—Oct. 16	16	261	33.8	23.6	57.4	1.295	2.20
Whole period		142	51,262 cal/cm²	6,774	6,984 kcal/m²	13,734	1.325	2.68

according to KISHIDA's equation[7)],

$$\alpha_{eff}=1-r_{eff}-\tau_{eff}+r_{0.eff}\times\tau_{eff}$$

where α_{eff}, r_{eff} and τ_{eff} are absorbance, reflectance and transmittance of a plant population for PAR, respectively. $r_{0.eff}$ is reflectance of the water or soil surface for PAR.

In our calculation, values for τ_{eff} were actually measured as described in Materials and Methods 3. Values for r_{eff} and $r_{0.eff}$ were assumed to be both 0.08 considering the results obtained by KISHIDA[7)] and HIROTA et al.[3)].

Amount of energy fixed in net production was estimated from the amount of net production in each period and calorie content of unit biomass (Table 1). The amount of energy consumed through respiration was estimated from the respiration loss of carbon (Table 3) on the assumption that 1 g of respired carbon is equivalent to 10.5 kcal. The amount of energy fixed in gross production was estimated as the sum of the amount of energy fixed in net production and that consumed through respiration.

The results are shown in Table 4 and Fig. 4. The maximum values for En.t, Eg.t, En.eff and Eg.eff were obtained in the period XI. However, light intensity in this period was exceptionally low. If we neglect the values in this period, the time trend of these efficiencies can be characterized as follows:

En.t and En.eff increased with time after transplanting and attained maxima (2.33% and 4.36%) at the middle of July and then decreased. However, after the end of July, they persisted at a constant level. i.e. ca. 1.3% for En.t and 2.4% for En.eff. Much information has been accumulated about developmental changes in En.t of rice plant[2,3)]. According to it, in most cases, En.t increases with time in the early season and attains a maximum at the middle stage and then decreases. The time trend of En.t in the latter half of the growing season in this study is somewhat different from that of other's. The reason for this discrepancy is not clear, but it may be caused by the low Pn/Pg ratio in August. En.t and En.eff for the whole growth period were 1.3% and 2.5%, respectively. These values are comparable to those reported by HIROTA et al.[3)] (1.34% and 2.42%) and to the value of En.t derived from SUZUKI and MURATA[12)] (1.48% in the early planting culture and 1.47% in the normal).

Eg.t and Eg.eff both increased with time in the early season and attained maxima at the middle of July and then gradually decreased. The maximum values were 3.86% and 7.21%, respectively, neglecting the values obtained in the latter half of

Table 5. The efficiencies for conversion of photosynthetically active radiation for net production ($\Phi_{n.eff}$) and for gross production ($\Phi_{g.eff}$).

	Period	Δt days	α_{eff}	PARabs (cal/cm²/day)	$\Phi_{n.eff}$ (%)	$\Phi_{g.eff}$ (%)
I	May 28—Jun. 5	9)				
II	Jun. 6—Jun. 16	11	0.150	34.75	7.05	9.26
III	Jun. 17—Jun. 29	13	0.296	67.94	4.67	7.65
IV	Jun. 30—Jul. 6	7	0.473	108.6	7.13	10.29
V	Jul. 7—Jul. 16	10	0.584	125.9	6.49	11.43
VI	Jul. 17—Jul. 26	10	0.638	152.9	5.34	11.30
VII	Jul. 27—Aug. 7	12	0.705	182.9	3.10	8.94
VIII	Aug. 8—Aug. 17	10	0.765	169.5	3.25	8.79
IX	Aug. 18—Aug. 27	10	0.814	187.7	2.96	7.12
X	Aug. 28—Sept. 17	21	0.844	100.8	3.69	8.38
XI	Sept. 18—Sept. 30	13	0.860	88.3	5.82	9.75
XII	Oct. 1—Oct. 16	16	0.860	120.1	2.81	4.78
	Whole period	133		15,980 cal/cm²	4.24	8.59

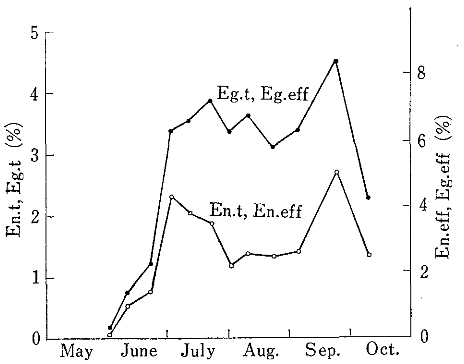

Fig. 4. Seasonal trends of efficiency for utilization of solar energy in rice plants. En.t and Eg.t are the efficiencies of total solar radiation incident on the field for net production and gross production, respectively. En. eff and Eg. eff are the efficiencies of photosynthetically active radiation incident on the field for net production and gross production, respectively.

September. The values for the whole growth season were 2.68% and 5.01% respectively.

The efficiencies for solar energy conversion are presented in Table 5 and Fig. 5. The maximum value for $\Phi_{g.eff}$ appeared at the middle of July. At that time, LAI was at the maximum and so it may be that the heavy mutual shading has resulted in low light saturation loss. Most of leaf blades of the canopy looked dark green and physiologically active. Further, the plant did not have much amount of non-photosynthetic organs at this stage. Thus inactive absorption of light by these organs was considered to be small. These may be the basis for the highest $\Phi_{g.eff}$ value at that time.

The maximum value of $\Phi_{g.eff}$ amounted to 11.4%. The efficiency for the whole season was 8.6%. SUZUKI and MURATA[12] obtained $\Phi_{g.eff}$, 4.6% to 7.7%, for rice plants. Our values are fairly higher than these values. On the other hand, HIROTA and TAKEDA[4] reported $\Phi_{g.eff}$ ranging 5.36 to 12.74% for rice plants. The efficiency for the whole growing season derived from their data amounted to 8.14%. This is very close to our corresponding figure.

Summary

Organic matter production, carbon budget and efficiencies for solar energy utilization in organic matter production were examined in a paddy field. In connection with this, carbon and calorie content of plant biomass were also investigated. The main results obtained are as follows:

1. Carbon and calorie content of plant biomass varied largely with growth stage and from organ to organ. The average values for the whole plant and the whole

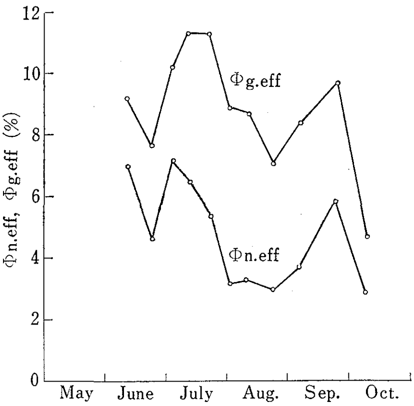

Fig. 5. Seasonal trends of efficiencies of photosynthetically active radiation absorbed by rice plants for net production ($\Phi_{n,eff}$) and for gross production ($\Phi_{n.eff}$).

growth season were 35.8% and 3.75 kcal/g, respectively. These values are low compared with those for other species, probably due to higher SiO_2 content in biomass of rice plant.

2. Carbon and calorie content on ash-free plant material basis were fairly constant irrespective of kind of organ and growth stage. The averages were 42.6% and 4.48 kcal/g, respectively.

3. The calorie/carbon ratio was highly constant irrespective of organ and growth stage. The average was 10.51 kcal/gC.

4. The standing crop of rice plant expressed as the amount of carbon increased with time and attained 567 gC/m^2 at the time of full maturation. The amount of carbon contained in panicles was 198 g/m^2 at the full maturation stage.

5. The gross production rate (Pg) increased with time and attained a maximum (17.1 gC/m^2/day) at the end of July and then decreased. The net production rate (Pn) also attained a maximum at the end of July and then decreased. However, the latter held an almost constant level from the beginning of August to the full maturation.

6. The Pn/Pg ratio fluctuated in the range of 60 to 77% in the first one and a half month and then decreased rapidly, being as low as 31% at the beginning of August. After then, however, it began to increase again and attained 60% at the last stage of development. The extremely low Pn/Pg ratio at midsummer was brought about by increase in respiration loss due to high temperatures. The increase in the Pn/Pg ratio in the latter half of growth season was caused by decrease in respiration loss due to lowering temperature. The Pn/Pg ratio for the whole growth period was 49%.

7. The efficiency of solar energy utilization for net production (En.t: amount of energy fixed in net production/amount of total solar radiation incident on a field) increased with rice growing, attaining a maximum (2.33%) at the beginning of July and then decreased for a while. However, after the beginning of August, it held an almost constant level until full maturation. The efficiency for the whole growth period was 1.33%.

8. Efficiency of conversion of PAR energy absorbed by plant for gross production ($\Phi_{g.eff}$) attained a maximum (11.4%) at the middle of July and then declined. The average value for the whole growth period was 8.59%.

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〔和 文 摘 要〕

水田における炭素循環に関する研究

第3報 水稲の物質生産と太陽エネルギーの利用

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水稲の物質生産，炭素収支，日射エネルギー利用効率，乾物の炭素，熱含量について調べ次の結果をえた.

1. 乾物の炭素，カロリー含量は器官，生育時期により大幅に変動した. 個体全体，全生育時期の平均値は 35.2%，3.69 Kcal/g であった.

2. 乾物から粗灰分を差引いたものをベースとしたこれらの含量はかなり一定で平均値はそれぞれ 42.6 % および 4.48 Kcal/g であった.

3. 炭素 1g 当たりのカロリーはほとんど一定で，平均 10.5 Kcal/gC であった.

4. 炭素であらわした水稲の現存量は生育に伴い増加し，最終的には 576 gC/m^2 となった. 穂に含まれる炭素の量は成熟期において 198 gC/m^2 であった.

5. 総生産速度 (Pg) は7月下旬に最大値 17.1 gC/m^2/日 に達し，以後下降した. 純生産速度 (Pn) は同じ時期に最大値 8.6 gC/m^2/日 に達した後，下降したが，8月上旬から成熟期までの下降はごくゆるやかで，ほとんど一定の値を保った.

6. Pn/Pg 比は生育初期の約1.5か月は 60〜77% であったが，後急減し，8月上旬には31% まで下落した. しかしその後上昇に転じ成熟期には約 60% に達した. 生育中期における Pn/Pg 比の低さはこの時期の高温に，後期におけるこの比の増大は温度の下降にもとづくことが示唆された. 全生育期間の Pn/Pg 比は 49%であった.

7. 投下された全日射エネルギーをベースとした純生産へのエネルギー利用効率は最大 2.33%，全生育期間の平均は 1.33% であった.

8. 植物に吸収された光合成有効放射のエネルギー変換効率（総生産への）は最大 11.4%，全生育期間の平均 8.59% であった.

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