Rice Production in Unfertilized Paddy Field
—Mechanism of grain production as estimated from nitrogen economy—

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Abstract: Rice grain production in a long-term unfertilized paddy field was compared with that in an adjacent paddy field which had been supplied with the standard level of fertilizers in 1980-1998 to elucidate the mechanism of maintained grain production in the unfertilized field. Average grain yield (brown rice) in the unfertilized paddy field was 382.7 g m⁻² while that in the fertilized field in the adjacent field was 480.0 g m⁻², indicating that 80% of grain production was constantly maintained without supplying any nitrogen fertilizer. The amount of nitrogen absorbed by rice plants for producing 1 g grain was estimated to be 14.1 mg, 55% higher than that in the fertilized field in terms of grain production efficiency. The amount of nitrogen absorbed by rice plants per year in the unfertilized field was calculated to be 5.4 g m⁻². This amount of nitrogen should have been supplied annually to maintain the stable grain production for the period of 18 years. Quantitative analysis of nitrogen in the unfertilized field demonstrated that 1.4 g m⁻² of nitrogen was supplied from irrigation water containing suspended solids, 0.68 g m⁻² from biological fixation, and 9.0 g m⁻² from soil, respectively, to maintain the stable grain production. Total nitrogen of soil in the unfertilized paddy field had been maintained at a constant level during these 18 years, suggesting that grain production of around 380 g m⁻² (brown rice) could be supported without fertilization for an extended period of time.

Key words: Grain production, Nitrogen economy, Production mechanisms, Rice plants, Unfertilized paddy field.

Nitrogen is one of the most important nutrients for the regulated growth and grain production of rice plants in paddy fields, as has been reported in the literature dealing with the kinds of fertilizer (Nakanishi et al., 1990; Wada et al., 1991), the amount and time of application (Wada et al., 1971; Yamamoto et al., 1992), and the location of application of fertilizers (Okumura et al., 1982; Hirano et al., 1998). For the practical rice production, high-yield cultivation systems based on application of a large quantity of inorganic nitrogen fertilizers have been established along with the development of synthetic pesticides and fungicides.

In contrast to these highly fertilized cultivation, there are some small paddy fields where rice plants had been cultivated without application of any fertilizers and pesticides. The grain production level in these unfertilized fields is lower than in those fields supplied with inorganic or organic fertilizers and sprayed with pesticides. Thus the unfertilized cultivation system has not been widely practiced among rice growers and little is known about the mechanism of rice grain production in unfertilized fields.

We found several paddy fields that had not been supplied with any fertilizer or pesticide, but that had maintained rather high yields of grains for a long period of years (Hasegawa et al., 1977). This fact indicated that mechanism of grain production could not solely be explained by the amount of nitrogen fertilizer applied to the paddy fields.

This study aims at analyzing the structure of grain production system in the unfertilized paddy field and applying the derived information to the improvement of the current high yield cultivation systems. As the first step, grain production and nitrogen economy in a long-term unfertilized field was compared with those in the adjacent fertilized fields to understand the mechanisms of maintained productivity in unfertilized fields.

Materials and Methods

Paddy fields and cultivation
A long-term unfertilized paddy field (this field will be referred to as U-field in the following), 9 a in acreage, located in Ritto-cho, Shiga prefecture, Japan, was selected as a test field. No fertilizer (neither chemical nor organic) and no pesticide had been applied in this field since 1951. Tsuge and Matsumoto (1979) demonstrated that the soil in this field was a fine clay containing 0.16%, 0.45% and 0.81% of P₂O₅, K₂O and total carbon respectively. Water management in this field was continuous irrigation during the period from the beginning of planting until 20 days before the harvest. That total amount of water was around 4 t m⁻² irrigated from Yasu river (Okumura et al., 1981). The fifth leaf stage seedlings of the late maturing cultivar,Beniasahi, with long culm and heavy panicle, had been planted in early May, at a density of 19.2 plants m⁻² every year. Rice was harvested by hand cutting and rack drying. All rice straw was taken away from this field after threshing. A fertilized paddy field (referred to as F-field in the following), adjacent to the U-field, 20 a in acreage, was...
selected for comparison. The soil in this field was a fine clay containing 0.57%, 1.31% and 1.75% of P\textsubscript{2}O\textsubscript{5}, K\textsubscript{2}O and total carbon, respectively (Tsuche and Matsumoto, 1979). The fifth leaf stage seedlings of the medium maturing cultivar, Nipponbare, with medium culm and panicle number type had been planted in early May at a density of 19.6 plants m\textsuperscript{-2} every year. The total amount of fertilizer applied to this field was 14.6 g N, 13.6 g P\textsubscript{2}O\textsubscript{5}, and 15.1 g K\textsubscript{2}O m\textsuperscript{-2} with priority of basal dressing. In this field, grains were harvested with a combine harvester in the mid-September and straws were plowed in the field after harvesting. Irrigation was managed to keep the depth of water at about 3 cm throughout the cultivation period excepting the days for midseason drainage and drainage after 10 days of heading. The amount of water irrigated in F-field was not determined. This irrigation water bring also from Yasu river. Herbicides and pesticides were applied 4-6 times during cultivation.

**Measurement of yields (investigation over the long-term)**

The grain yield in U-field was estimated by a 3.3 m\textsuperscript{2} quadrat sampling during 1980-1998. The yield in the adjacent F-field was similarly estimated until the field was used for building in 1990. The yields in the F-field after this year were deduced from average yields in Rittoko area listed in the statistics of rice production issued by Kinki Department of Agriculture.

**Measurement of nitrogen (investigation on a year)**

To compare the nitrogen economy between U-field and the adjacent F-field, we measured dry weight and total nitrogen contents of rice plants at the full heading stage in 1988. Ammonium and total nitrogen contained in suspended solids in irrigation water were determined to specify exogenous supply of nitrogen to the U-field. Nitrate nitrogen was not determined. This water was collected at the water inlet of each field. Total and ammonium nitrogen contents of soil in both fields were also determined in addition to estimation of nitrogen fixed in the rhizoplane and rhizosphere soils by acetylene reduction method (Hardy et. al., 1968). Total nitrogen of dried plant material, soils, and suspended solids in irrigation water were determined by semimicro-Kjeldahl method. Ammonium contents in soils were determined by the steam distillation after suspending in 10% KCl and those in irrigation water were determined by Nessler's colorimetry. For the measurement of nitrogen fixation by roots and soil, 3 g of fresh roots or 20 g of rhizosphere soil were incubated in Erlenmeyer flask in the presence of air containing 10% of acetylene for 3 days at 30°C. These samples were collected from a soil block, which contained a rice root and hill and produced by a cylindrical root core sampler (12.5 cm in diameter and 15 cm in length). The evolved ethylene was determined by gas chromatography (FID-GC4, Shimadzu).

**Results**

1. **Yearly yields of rice grains**

The average yields of rice grains during 1980-1998, except 1993, the year of abnormal weather, were 382.7 g m\textsuperscript{-2} in the U-field and 480 g m\textsuperscript{-2} in F-fields in Rittoko, indicating that the yields in the U-field have been maintained at 80% of the F-fields for 18 years. Yearly variances in yields were 9.6% in the U-field and 4.0% in the F-fields. The regression lines defined as $Y = aX + b$, where $Y$ represents expected yields of grains, g m\textsuperscript{-2} in a certain year, $X$, years of cultivation and a yearly yield increase g m\textsuperscript{-2}, were found to be $Y = 3.48X + 350.6$ for U-field and $Y = 2.20X + 461.9$ for F-fields. The yields in both fields showed a tendency to increase slightly and the increase in the U-field was statistically significant at 5% level by F-test. In the year of cold summer, 1993, planting in the U-field was delayed almost one month, leading to yield loss of 24%, in contrast to 9.3% yield loss in the F-fields (Fig. 1).

2. **Dry weights and total nitrogen contents of rice plants at the full-heading stage**

In 1988, full heading of rice plants was observed on September 5 in the U-field and on August 15 in the F-field. The top dry weight at the full heading stage was 631.7 g m\textsuperscript{-2} in the U-field and 1212.3 g m\textsuperscript{-2} in the F-field, indicating that dry matter production in the U-field plants was almost half of that in the F-field. Dry weights of each part reflected the plant type of cultivars, and rations of weight of the culm with leaf sheath to the total top dry weights were 55.4% and 43.3% in U-field and F-field plants, respectively. Dry weight ratios of leaves and panicles to the total were 18.5% and 16.5%, respectively, for plants grown in the U-field, and 22.8% and 25.6%, respectively, for those grown in the F-field (Table 1).

The total nitrogen contents of the stand per unit area (m\textsuperscript{2}) at the full heading stage were 5.397 mg in the U-field and 10.889 mg in the F-field, indicating that nitrogen uptake by plants in the U-field was close to half the quantity in the F-field. Nitrogen contents of panicles, leaves, and stems were 37.5%, 34.8% and 23.5%, respectively, of total nitrogen contents in the plants in the U-field, while those in F-field were 59.0%, 21.0% and 12.1%, respectively, well reflecting the total dry weight production in each field (Table 2).

3. **Seasonal changes in ammonium nitrogen and suspended solids in irrigation water**

Ammonium nitrogen contents in water irrigated into the U-field in 1988 were found to be relatively high during the early stage of rice growth, from early May to mid-June, but markedly decreased thereafter (Fig. 2). Total nitrogen annually introduced into this field as ammonium nitrogen was calculated to be 1.4 g m\textsuperscript{-2} on the basis of average concentration of ammonium nitro-
gen and volume of irrigated water. The dry weight of suspended solids in irrigated water during mid-May to early September was in the range of 3 to 6 mg L\(^{-1}\) (Fig. 3). Based on the seasonal change and total volume of irrigation water, the total amount of suspended solid brought into the U-field was calculated to be about 16 g m\(^{-2}\). Assuming that nitrogen content of the suspended solids was comparable to that of the mud in irrigation canal, 0.2% (Kawamura and Nakajima, 1979), the total nitrogen introduced into the U-field with suspended solids was calculated to be 32 mg m\(^{-2}\).

4. **Seasonal changes of total and ammonium nitrogen in paddy soils**

Soils in the F-field and U-field were determined for their total and ammonium nitrogen during the rice
growth season, from mid-May through mid-September, 1988. The total nitrogen contents of soils from F-field were estimated to be in the range of 1.5—1.8 mg g⁻¹ and those of soils from U-field were in the range of 1.1—1.38 mg g⁻¹. Average contents calculated from 6 measurements during the season were 1.6 mg g⁻¹ and 1.2 mg g⁻¹ for F-field and U-field soils, respectively (Fig. 4). The contents of soil ammonium nitrogen in the U-field increased gradually from 4 mg in mid-May to 9.5 mg 100 g⁻¹ in early August and then decreased to 4.5 mg 100 g⁻¹ in mid-September, while those in F-field soils decreased gradually from 11 mg in mid-May to 1.5 mg 100 g⁻¹ in mid-September with a significant increase in early August (8 mg 100 g⁻¹). In both fields, however, average contents were 6.0 mg 100 g⁻¹ (Fig. 5).

5. Nitrogen fixation in rhizosphere
Nitrogen fixation in rhizosphere was determined 5 times during early June to late September. Average ethylene quantities produced in the presence of roots were 0.68 × 10⁹ and 0.25 × 10⁹ nmol g⁻¹ root day⁻¹ in the U-field and F-field plants, respectively, indicating that capability to fix nitrogen of plant roots grown in the U-field was 2.7 times as high as that of plants grown in the F-field. Reducing activity of ethylene by plant roots at the heading stage was markedly higher in those grown in the U-field than those grown in the F-field. The average ethylene production in soil estimated during the same season was 0.65 nmol for the U-field and 0.26 nmol g⁻¹ soil day⁻¹ for F-field. Thus the nitrogen fixation per unit soil in the U-field was calculated to be 2.5 times as high as that in the F-field. The nitrogen fixation in rhizos-
Table 3. Seasonal change in nitrogen fixation capability of roots and soils in the unfertilized and fertilized paddy fields as determined in 1988 by acetylene reducing activities\*.

<table>
<thead>
<tr>
<th>Fields</th>
<th>Ethylene evolved (10^3 nmol g^-1 roots day^-1)</th>
<th>June 23</th>
<th>July 21</th>
<th>Aug. 18</th>
<th>Sept. 15</th>
<th>Sept. 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfertilized</td>
<td></td>
<td>0.44±0.16</td>
<td>0.65±0.13</td>
<td>2.12±0.13</td>
<td>0.19±0.04</td>
<td>0.11±0.03</td>
</tr>
<tr>
<td>Fertilized</td>
<td></td>
<td>0.19±0.09</td>
<td>0.27±0.09</td>
<td>0.24±0.09</td>
<td>0.32±0.08</td>
<td>0.17±0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fields</th>
<th>Ethylene evolved (nmol g^-1 soil^-1 day^-1)</th>
<th>June 23</th>
<th>July 21</th>
<th>Aug. 18</th>
<th>Sept. 15</th>
<th>Sept. 30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unfertilized</td>
<td></td>
<td>0.21±0.03</td>
<td>0.95±0.26</td>
<td>0.07±0.02</td>
<td>1.35±0.61</td>
<td>0.06±0.01</td>
</tr>
<tr>
<td>Fertilized</td>
<td></td>
<td>0.40±0.11</td>
<td>0.26±0.04</td>
<td>0.44±0.05</td>
<td>0.12±0.01</td>
<td>0.06±0.01</td>
</tr>
</tbody>
</table>

* Acetylene-reducing activities were measured by the method of Hardy et al. 1968.
** Three grams of roots harvested from both fields were incubated at 30°C for 3 days in the presence of 10% of acetylene and ethylene evolved was determined by FID-GC.
*** Twenty grams of rhizosphere soils were incubated under the same conditions and ethylene was determined. ± indicates standard deviation.

Discussion

Grain yield in the U-field was found to be kept at 80% of that in the F-field located adjacent to the field for almost a half century. This is surprising in view of the result that 22 g nitrogen must be absorbed by rice plants for producing 1000 g of grains (Onikura et al., 1975). In 1988, nitrogen contents in rice plants during the growing season reached the maximum at the full heading stage and the values per m² determined in this study were 5.4 g for plants grown in the U-field and 10.9 g for those grown in the F-field. The grain yields per m² was 383 g and 480 g for the U-field and F-fields, respectively. Based on nitrogen contents in plants at the full heading stage, it was deduced that 22.7 g nitrogen was absorbed by rice plants in the F-field to produce 1000 g of grains, which is similar to the value reported by Onikura et al., (1975). Since 14.8 g of nitrogen per m² had been supplied as inorganic basal dressing in the F-field, the most nitrogen essential for maintaining grain production should be derived from chemical fertilizers. On the contrary, 14.1 g of nitrogen was calculated to be absorbed by rice plants to produce 1000 g grains in the U-field, indicating that grain production per absorbed nitrogen in the U-field was around 50% higher than those in F-fields.

These results suggest that rice plants growing under extremely limited nitrogen supply are capable of producing grains efficiently utilizing the nitrogen in irrigation water and soils. However, at least 5.4 g of nitrogen per m² must be supplied annually to secure grain production in the U-field. Since no inorganic or organic fertilizers have been applied to the U-field for almost 50 years, and all weeds (including winter weeds) were removed from this field by hand, the possible source of nitrogen was thought to be the irrigation water and nitrogen fixation in the rice plant rhizosphere (Yoshida and Rosabel, 1973; Castro and Yoshida 1977).

Quantitative analysis of nitrogen in irrigation water demonstrated that 1.4 g ammonium nitrogen and 32 mg of total nitrogen per m² were supplied annually from irrigated water and solids suspended in the water, respectively. This value is very close to 1.1 g m⁻² reported for unfertilized paddy fields in south-east Asian countries (Wetselaar, 1981).

The rest of nitrogen required for grain production might be supplied by the biological nitrogen fixation in rice plant rhizosphere. Measurement of acetylene reducing activity of the plant roots showed that 7.18×10⁷ nmol of acetylene was reduced per m² per year. Assuming that the ratio of acetylene reduction to nitrogen fixation is 3:1 (Hardy et al., 1968), the amount of nitrogen fixed annually in the F-field was calculated to be 0.68 g m⁻². Wetselaar (1981) reported that biological nitrogen fixation including microbial activity was in the range of 1.8–10.0 g m⁻² in U-field in south-east Asian countries and suggested that biological nitrogen fixation is an important source for nitrogen economy.

In general, total nitrogen in paddy soil had not been taken into account in the calculation of nitrogen economy because only inorganic form of nitrogen is utilized by rice plants. Total nitrogen in the soil, therefore, could not necessarily be an index for grain productivity. Thus the productivity of fields depends on the amount of ammonium ion released from soils. Based on quantitative analysis of KCl-soluble ammonium nitrogen, ammonium nitrogen released from soil in the U-field was summed up to 9 g m⁻², provided the depth of plow layer was 15 cm.
Total nitrogen of U-field soil decreased slightly during the rapid growth of rice plants, suggesting that inorganic nitrogen released from the soil was efficiently consumed for the plant growth. Total nitrogen in the soil was recovered to the level of mid-June by the time the grains started ripening in mid-September. In general, the content of Cl-soluble ammonium nitrogen parallels with the total nitrogen contents of soils. The total nitrogen contents in the soil in the U-field has been kept constant every year at the time of planting (Fig. 4), suggesting that this nitrogen economy supports the almost constant grain production in the U-field without application of fertilizer nitrogen. Assuming that nitrogen derived from irrigation water and biological fixation was immediately utilized by rice plants, 3.4 g of nitrogen out of 5.4 g per m² required for grain production had to be derived from the soil.

Although there has to be some other source of nitrogen for the U-field to balance the entire nitrogen economy, the major supply would come from irrigation water, biological fixation and soil sources mentioned above. Simplified calculation of contribution of each source to total nitrogen economy indication that 26%, 12%, and 62% of nitrogen were supplied from irrigation water, biological fixation and soil complex, respectively.

Acknowledgment

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References


*In Japanese with English summary or abstract.
**In Japanese.
***Translated from Japanese title by the present author.