Effects of Planting Pattern on the Interception of Solar Radiation by the Canopy and the Light Extinction Coefficient of the Canopy in Rice Plants Direct-sown in a Submerged Paddy Field

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Abstract: In order to investigate effects of planting pattern on the interception of solar radiation by the canopy and the light extinction coefficient of the canopy in rice, the rice plants direct-sown in a submerged paddy field were grown in six planting patterns (A through F). In plots A, B and C, the planting density was 20.7 hills m\(^{-2}\) (22 cm \(\times\) 22 cm spacing) with five, three and one plant per hill, respectively, and in plots D, E and F, the planting density was 82.6 hills m\(^{-2}\) (11 cm \(\times\) 11 cm spacing), 44.4 hills m\(^{-2}\) (15 cm \(\times\) 15 cm spacing), and 44.4 hills m\(^{-2}\) (7.5 cm \(\times\) 30 cm spacing), respectively, with one plant per hill. At the tillering stage, the greater the tiller number and leaf area index, the larger the interception of solar radiation by the canopy. The tiller number was larger in the plots with one plant per hill, higher plant density and square arrangement of hills. At the early ripening stage, the light extinction coefficient of the canopy was smaller in such plots. The larger the average inclination of leaf blades, the smaller the light extinction coefficient of the canopy. The difference in stem inclination in the canopy might be responsible for the difference in the inclination of leaf blades. In the plots with one plant per hill, higher plant density and square arrangement of hills, stems were more erect. Within the range of planting patterns in our study, both the rate of interception of solar radiation by the canopy and the light-intercepting characteristics were significantly more favorable in the plots with one plant per hill, higher density and a square arrangement of hills.

Key words: Crop growth rate, Direct sowing, Interception of solar radiation, Light-intercepting characteristics, Planting pattern, Rice.

The rate of interception of solar radiation by the canopy and the light-intercepting characteristics of the canopy have significant effects on dry matter production through their effects on photosynthesis. That is, when the leaf area index (LAI) is smaller than the critical value and significant mutual shading does not occur, the dry matter production of the canopy depends on its absorption of solar radiation, which is significantly affected by the LAI (Gardner et al., 1985). When the canopy closes completely, the dry matter production of the canopy is affected to a considerable extent by the absorption of solar radiation by the individual leaves, which depends on the penetration of solar radiation into the canopy (Hayashi, 1972). We know that, in rice, the rate of interception of solar radiation by the canopy varies with the variety, and is closely related with the amount of solar radiation absorbed by the canopy. For example, F\(_1\) hybrid rice produced heavier dry matter as a result of vigorous growth at the tillering stage (Song et al., 1990; Ishihara et al., 1996). We also know that the light extinction coefficient of the canopy varies with the variety. The light extinction coefficient of the canopy tends to be smaller in the currently prevailing rice cultivars than in older cultivars and the yield in the former is higher than that in the latter (Tanaka et al., 1968; Ito and Hayashi, 1969; Hayashi, 1972; Hayami, 1982; Takeda et al., 1984; Saitoh et al., 1990a, b). Planting methods affect the rate of interception of light by the canopy. Heavy basal dressing of nitrogen at planting and topdressing of nitrogen at the tillering stage increase the number of tillers, which should increase the interception of solar radiation by the canopy. The rate of interception of light by the canopy is high during tillering in direct-sown rice, because the tiller number increases greatly as compared with transplanted rice (San-oh et al., 2002). However, to our knowledge, it has not yet been determined whether the planting pattern affects the rate of interception of solar radiation by the canopy, as well as the light-intercepting characteristics of the canopy.

Previously, we examined the dry matter production and associated characteristics in a submerged paddy field in the rice plants direct-sown and transplanted in different planting patterns (San-oh et al., 2004). In pattern I, the planting density was 51.3 hills m\(^{-2}\) in a
square hill arrangement with one plant per hill; and in pattern III, the planting density was 17.5 hills m⁻² in a square hill arrangement with three plants per hill. The dry-matter production and the grain yield were greater in pattern I than in pattern III in direct-sown or transplanted plants. The greater dry matter production was due to the higher crop growth rate (CGR) during the period from the tillering to the ripening stage. At the tillering stage, the number of tillers and, therefore, the LAI increased rapidly and the rate of interception of solar radiation by the canopy was greater in pattern I than in pattern III. This difference resulted in the larger CGR in the former plants. After the booting stage, the canopy consisted of more erect stem and, therefore more erect leaves and the light extinction coefficient of the canopy was small. This resulted in the better light-intercepting characteristics of the plants in pattern I than in pattern III, and, as a consequence, a larger CGR in the former than in the latter. These results indicate that planting pattern affects the rate of interception of solar radiation by the canopy and the light-intercepting characteristics of the canopy, and that planting pattern is an important factor in the cultivation of rice, especially in direct-sown rice plants. The planting pattern can be changed by varying hill density, the spatial arrangement of hills, the number of plants per hill and the planting density.

From the results of the previous study (San-oh et al., 2004), we postulated that the higher the hill density, the larger the rate of interception of solar radiation by the canopy at the tillering stage if hills are arranged square. We also postulated that, at planting densities within range that do not cause lodging, the higher the hill density, the smaller the light extinction coefficient of the canopy due to more erect leaves. In this study, in order to confirm those assumptions, we examined the effects of the planting pattern on the rate of interception of solar radiation by the canopy and the light extinction coefficient of the canopy, by varying the hill density as well as the spatial arrangement of hills, the number of plants per hill and the planting density. We also investigated the characteristics affecting the rate of interception of solar radiation and the light extinction coefficient.

### Materials and Methods

#### 1. Materials and cultivation of plants

Rice plants (*Oryza sativa* L. cv. Takanari) were grown in the paddy field of the University Farm (35° 41’ N, 139° 29’ E) in alluvial soil (clay loam) from the Tama River in 2004. Plants were grown in different planting patterns. In plots A, B and C, the planting density was 20.7 hills m⁻² (22 cm × 22 cm spacing) with five, three and one plant per hill, respectively, and in plots D, E and F, the planting density was 82.6 hills m⁻² (11 cm × 11 cm spacing), 44.4 hills m⁻² (15 cm × 15 cm spacing), and 44.4 hills m⁻² (7.5 cm × 30 cm spacing), respectively, with one plant per hill (Table 1). Germinated seeds were planted on May 1 after puddling in the drained field at a density three or five times higher than the desired final density of plants, and at a depth of 1 cm. After the establishment of seedlings on May 21, the plants in each plot were thinned to the designated density and the field was flooded.

As a basal dressing, manure was applied at a rate of approximately 2 kg m⁻² and chemical fertilizer at a rate of 5.0, 5.0 and 5.0 g m⁻² for N, P₂O₅ and K₂O, respectively. Topdressing was applied at a rate of 2.0 g each per m² for N and K₂O on June 30, July 20 and August 19. Heading (50% heading) occurred on August 8. Plants were harvested on October 14. No lodging occurred in any plants. The experiment was designed with three randomly arranged replicates (28 m² for each replicate).

#### 2. Measurement of the rate of light interception by the canopy

The light intensity above the canopy (I₀) and that at the surface of the soil under the canopy (Iₙ) were measured simultaneously with two silicon-photodiode light sensors (320-730 nm) (S-1133; Hamamatsu Photonics Co., Hamamatsu, Japan) under diffuse light conditions. The responses to light intensity of the sensors had been confirmed beforehand to be

| Plot | Hill density (hills m⁻²) | Spatial arrangement of hills | No. of plants per hill | Plant density (plants m⁻²) |
|------|--------------------------|-----------------------------|-----------------------|---------------------------|
| A    | 20.7                     | 22 cm × 22 cm               | 5                     | 103.3                     |
| B    | 20.7                     | 22 cm × 22 cm               | 3                     | 62.0                      |
| C    | 20.7                     | 22 cm × 22 cm               | 1                     | 20.7                      |
| D    | 82.6                     | 11 cm × 11 cm               | 1                     | 82.6                      |
| E    | 44.4                     | 15 cm × 15 cm               | 1                     | 44.4                      |
| F    | 44.4                     | 7.5 cm × 30 cm              | 1                     | 44.4                      |
identical. The light intensity at the surface of the soil relative to that above the canopy was determined as an average of 1 m in length in the inter-row space and in the inter-hill space for one measurement. The rate of interception of light by the canopy (LIC) was calculated from the following equation.

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LIC = (1 - \frac{I_b}{I_o}) \times 100
\]

3. Measurement of light extinction coefficients and inclinations of leaf blades and stems

The relative light intensities within the canopy were measured at 10-cm intervals from the surface of the soil were measured with the above-mentioned light sensors. Four or six neighboring hills with average numbers of panicles were selected from each replicate to examine the canopy structure. Plants in each 10-cm layer of the canopy were collected and separated into leaf blade, leaf sheath plus stem, and panicle. Leaf area was measured with the automatic area meter (AAM-8; Hayashi Denko Co., Tokyo, Japan). The light extinction coefficient was calculated from the cumulative leaf area index and the relative light intensity inside the canopy (Monsi und Saeki, 1953). Two hills in plots A, B and C, and four hills in plots D, E and F, with average numbers of panicles, were selected from each replicate for measurements of inclinations of leaves and stems. The angle of inclination from the horizontal was measured for each leaf at the center of the leaf blade and for each stem at the center of the neck node of a panicle, with a protractor.

4. Measurement of dry weight

Eight hills with average numbers of stems were selected from each replicate for measurements of dry weight and leaf area. Plants were separated into leaves, leaf sheaths plus stems and panicles and dried in a ventilated oven at 80°C for more than four days.

5. Measurement of yield

Plants in an area of 2 m\(^2\) for each replicate were harvested for determinations of yield per unit area. Yield was determined for brown rice. Grains that were more than 1.8 mm thick were selected as fully ripened by sieving.

Results

1. Number of tillers, LAI and rate of interception of solar radiation by the canopy

The number of tillers per square meter increased rapidly in all plots at the tillering stage in June, and the number peaked in late June, gradually decreasing until heading (Fig. 1A). The increase in the number of tillers was largest in plot D and was smallest in plants in plot C. When the tiller number was maximal, the differences in the number of tillers among plots were small although the numbers in plots D and C were the highest and lowest, respectively. Among the plots with different hill densities, but with the same number of
plants per hill (D, E and C), the number of tillers was largest in plot D, with the highest hill density. Among plants with different numbers of plants per hill at the same hill density (A, B and C), the increase of the number of tillers was larger in plots A and B than in plot C. When we compared the plants in the different arrangements of hills, with the same number of plants per hill and the same hill density (E and F), the number of tillers increased more rapidly in plot E with a square arrangement of hills than in plot F with a row arrangement of hill.

LAI increased in all plots until heading, and gradually decreased after that (Fig. 1B). Differences in LAI were almost the same as in those of tiller number, although LAI tended to decrease rapidly in plots A and B compared with in the other plots after heading (Fig. 1B).

The rate of interception of solar radiation by the canopy increased rapidly at the tillering stage in all plots, and it continued to increase slowly until the tiller number reached a maximum (Fig. 2). The rate of interception of solar radiation by the canopy was the highest in plot D and the lowest in plots C and F during the tillering stage. On July 10, when the rate of interception of solar radiation by the canopy exceeded 80% in all plots, there was no significant difference among plots, in the rate of interception of solar radiation by the canopy. Among the plots with different hill densities but the same number of plants per hill (D, E and C), the rate of interception of solar radiation by the canopy increased more rapidly in plot D, with a higher hill density, than in plots C and E. Among the plots with different numbers of plants per hill and the same hill density (A, B and C), the rate of interception of solar radiation by the canopy increased more rapidly in plots A and B, with larger numbers of plants, than in plot C. Between the plots with different arrangements of hills but the same number of plants per hill and the same hill density (E and F), the rate of interception of solar radiation by the canopy increased more rapidly in plot E with a square arrangement of hills than in plot F with a row arrangement of hills.

There were close relationships between the average number of tillers and the average rate of interception of solar radiation by the canopy (Fig. 3), and between the average LAI and the average rate of interception of solar radiation by the canopy (data not shown) from June 14 to August 9.

Table 2. Light extinction coefficients of the canopy (K) at the early ripening stage.

| Plot | K     |
|------|-------|
| A    | 0.53 b* |
| B    | 0.55 b  |
| C    | 0.69 a  |
| D    | 0.42 c  |
| E    | 0.38 c  |
| F    | 0.50 b  |

Light extinction coefficients are given for canopy layers higher than 60 cm above the ground. *Means followed by different letters are significantly different at the 5% level by Tukey’s test (n=3).
2. Structure of the canopy and the light extinction coefficient

At the early ripening stage, we examined the canopy structure and light-intercepting characteristics of the canopy layers more than 60 cm above the ground. There were no differences in the stratified distribution of each organ among plants (data not shown). There were close linear correlations between the relative light intensity within the canopy and the cumulative LAI, in all plots (Fig. 4). The average light extinction coefficient of the canopy, as indicated by the slope of each regression line, was smallest in plots D and E and largest in plot C (Table 2). Among the plots with different hill densities but the same number of plants per hill (plots D, E and C), the light extinction coefficient was smaller in plots A and B with a larger number of plants than for in plot C. Among the plots with different arrangements of hills but the same number of plants per hill and the same hill density (E and F), we found that the light extinction coefficient of the canopy was smaller for in plot E with the square arrangement of hills than in plot F with a row arrangement of hills.

There was a close correlation between the average inclination of five leaf blades and the light extinction coefficient at the early ripening stage, although the differences in the inclination among plots were small (Fig. 5). The inclination angle of stems from the horizontal was affected by the planting patterns in the same manner as that of leaf blades among, but there were no distinct differences among plots in the leaf angle from the stem axis (data not shown).

3. Crop growth rate (CGR) and correlations of the CGR with the average interception of solar radiation and the light extinction coefficient

The CGR from June 14 to August 9 was the highest in plot D and lowest in plot F (Table 3). Among the plots with different hill densities but the same number of plants per hill (D, E and C), the CGR was higher in plot D than in plots C and E with a lower hill density. There was no difference in the CGR among the plots with different hill densities but the same number of plants per hill at the same hill density (A, B and C). Between the plots with different arrangements of hills but with the same number of plants per hill at the same hill density (E and F), we found that the CGR was higher in plot E.

### Table 3. Crop growth rates (CGRs).

| Plot | June 14-August 9 | August 9-October 14 |
|------|------------------|---------------------|
| A    | 21.7 b*          | 12.1 bc             |
| B    | 21.4 b           | 11.1 c              |
| C    | 21.9 b           | 8.9 d               |
| D    | 23.1 a           | 14.1 a              |
| E    | 21.4 b           | 13.2 ab             |
| F    | 19.7 c           | 10.8 cd             |

* Means followed by different letters are significantly different at the 5% level by Tukey’s test (n=3).
than in plot F. The CGR from August 9 to October 14 was the highest in plots D and E and lowest in plot C. Among the plots with different hill densities, but the same number of plants per hill (D, E and C), the CGR was higher in plots D and E than in plot C. Among the plots with different numbers of plants per hill but the same hill density (A, B and C), the CGR was higher in plots A and B than in plot C. Between the plots with different arrangements of hills but the same number of plants per hill and the same hill density (E and F), the CGR was higher in plot E with a square arrangement than in plot F with a row arrangement.

A close positive relationship was observed between the CGR and the average rate of interception of solar radiation by the canopy from June 14 to August 9, although the CGR in plot C was higher than that expected from the low value of the average rate of interception of solar radiation by the canopy (Fig. 6). A close negative relationship was observed between the CGR and the light extinction coefficient from August 9 to October 14 (Fig. 7).

4. **Dry matter production and grain yield**

The dry weight of aboveground parts at harvest was greatest in plots D and E and the smallest in plot C (Table 4). The dry weight tended to be smaller in plot F than in plots A and B although the difference was not significant. There was no significant difference in the harvest index. Consequently, the grain yield was the highest in plots D and E and lowest in plots C and F.

Table 4. Dry matter accumulation, grain yield and harvest index.

| Plot | Dry weight (g m⁻²) | Yield (g m⁻²) | Harvest index (%) |
|------|-------------------|---------------|-------------------|
| A    | 2007 b            | 886 b         | 44.6 a            |
| B    | 1944 b            | 887 bc        | 43.2 a            |
| C    | 1788 c            | 834 c         | 45.1 a            |
| D    | 2293 a            | 929 a         | 42.1 a            |
| E    | 2094 ab           | 919 a         | 43.8 a            |
| F    | 1845 b            | 825 c         | 43.9 a            |

Dry weights of aboveground parts were determined at harvest. Yields of brown rice with a grain thickness of more than 1.8 mm per unit area are shown. Yields are given for a water content of 14.5%. The harvest index was calculated by dividing the dry weight of brown rice by the dry weight of aboveground parts. Means followed by different letters are significantly different at the 5% level by Tukey’s test (n=3).

Discussion

In a previous study (San-oh et al., 2004), we examined the dry-matter production and associated characteristics of rice plants direct-sown and transplanted in planting patterns I and III in a submerged paddy field (see Introduction). Light interception by the canopy was greater at the tillering stage and the light extinction coefficient of the canopy was smaller after the booting stage in planting pattern I than in planting pattern III in both direct-sown and transplanted plants. These characteristics increased the production of dry matter in the former planting pattern than in the latter planting pattern.

Based on the results of the previous research (San-oh et al., 2004), we postulated that the higher the hill density, the higher the rate of interception of solar radiation at the tillering stage and that the higher the hill density, the smaller the light extinction coefficient because of more erect stems and, therefore, more erect leaves if no lodging occurred. We examined this assumption in detail by changing the hill density, the spatial arrangement of hills, the number of plants per hill and the plant density. We also investigated the characteristics affecting the rate of interception of solar radiation and the light extinction coefficient.

There were significant differences among plots with different planting patterns, in the rate of interception of solar radiation by the canopy the light extinction coefficient of the canopy, and the CGR. As we postulated, the rate of interception of solar radiation was larger in plants grown at a higher density of hills when the number of plants per hill was the same (compare plots D, E and C) (Fig. 2). We also found that the rate of interception of solar radiation was higher in the plots with a larger number of plants per hill when the hill density was the same (compare plots A, B and C) and in the plot with a square arrangement of hills than in those with a row arrangement of hills when the number of plants per hill and the hill density...
were unchanged (compare plots E and F). The light extinction coefficient of the canopy was smaller in plants grown at a higher hill density when the number of plants per hill was unchanged (compare plots D, E and C) (Table 2). This was also as we expected. In addition, the light extinction coefficient of the canopy was smaller in the plots with larger numbers of plants per hill than in those with a row arrangement of hills (compare plots E and F).

We found that there was a close linear relationship between the average rate of interception of solar radiation by the canopy and the CGR, irrespective of the planting pattern, during the period from June 14 to August 9; the larger the average rate of interception of solar radiation by the canopy, the higher the CGR (Fig. 6). The canopy had already closed completely and the rate of interception of solar radiation exceeded 80% before heading. A close linear relationship was also observed between the light extinction coefficient of the canopy at the early ripening stage and the CGR during the period from heading to harvest time, irrespective of the planting pattern; the smaller the light extinction coefficient of the canopy, the higher the CGR (Fig. 7). The same correlation of CGR with the interceptions of solar radiation, and light extinction coefficient of the canopy were observed in 2001 in both the transplanted and direct sown plants in planting pattern I and III (data not shown). These results indicate that the planting pattern has a significant effect on dry-matter production and this effect is mainly caused by the change in the rate of interception of solar radiation by the canopy and the light extinction coefficient of the canopy.

Here, we like to consider these relationships in detail. The CGR in plot C was higher than expected from the low value of the average rate of interception of solar radiation by the canopy (Fig. 6). The larger CGR in plot C resulted from the larger NAR (data not shown). The leaf arrangement effective for receiving solar radiation and/or the higher activity of leaf photosynthesis might be responsible for the larger net assimilation rate (NAR) in the plants growing at the low density of plants. The larger the mean LAI the larger the CGR in plots D and E (data not shown). The reduction of LAI after heading was small in the plots with one plant per hill (C, D, E and F) than in the plots with three or five plants per hill (A and B) (Fig. 1). In addition to the contribution of LAI to CGR, the effects of the leaf photosynthesis during senescence on dry matter production might be also included in the differences in CGR among plants (San-oh et al., 2006).

The leaf area index (LAI) affects the rate of interception of solar radiation by the canopy (Gardner et al., 1985). In rice plants, the number of tillers affects LAI and, therefore, plants with a larger number of tillers intercept a larger amount of solar radiation (Hayashi, 1972; San-oh et al., 2004). In the present study, plants with a larger average number of tillers intercepted a larger amount of solar radiation from June 14 to August 9 (Fig. 3). There are some reports on the effects of planting pattern on the number of tillers. At the tillering stage, the number of tillers per square meter increased as the number of plants per hill increased (Tsunoda et al., 1971; Nakano et al., 1994) and in plants grown at a higher hill density (Ehara et al., 1998). However, the number of tillers was larger in the plots with a row arrangement than a square arrangement of hills at a density of 40 to 50 hills per m$^2$ at the panicle formation stage, although the number was almost the same at heading (Akita and Tanaka, 1992). The number of tillers was higher (i) in the plots with a higher hill density when the number of plants per hill was the same (compare plots D, E and C); (ii) in plants grown with a larger number of plants per hill at the same hill density (compare plots A, B and C); and (iii) in the plots with a square arrangement of hills as compared to a row arrangement of hills, when the number of plants per hill and the hill density were the same (compare plots E and F) (Fig. 1). The effects of hill density and the number of plants per hill on the number of tillers observed in the present study, were the same as those reported previously. However, the effects of the spatial arrangement on the number of tillers in the present study differed from the previous study, probably due to the difference in cultivars used for the study. In the present study, the hill density, the number of plants per
hill, the spatial arrangement of hills and the planting density were chosen within ranges in which lodging does not occur (Table 1). Within the chosen ranges, the number of tillers increased rapidly in plots with one plant per hill, a higher hill density and a square arrangement of hills. Thus, the rate of interception of solar radiation by the canopy of those plants was higher.

There have been a few studies on the effects of planting patterns on the inclination of leaf blades and the light extinction coefficient of the canopy. The canopy of plants grown with higher hill densities has a lower light extinction coefficient (Murata et al., 1966). We also found that the light extinction coefficient of the canopy was smaller in plots with a higher hill density when the number of plants per hill was the same (compare plots D, E and C) (Table 2). In cv. Dontokoi, the leaf inclination angles from horizontal was also larger in the plots with one plant per hill than in the plots with three plants per hill (San-oh et al., 2003). However, there have been few comparative studies on the light extinction coefficient of the canopy among the plots with different numbers of plants per hill at the same hill density and among the plots with different arrangements of hills and the same number of plants per hill at the same hill density. We found that the light extinction coefficient of the canopy was smaller in the plots with larger numbers of plants per hill at the same hill density (compare plots A, B and C). We also found that the light extinction coefficient of the canopy was smaller with the square arrangement of hills than with the linear arrangement of hills (compare plots E and F).

The light extinction coefficient of the canopy is affected by leaf inclination, the extent of shading by panicles and the pattern of distribution of leaves and panicles in the canopy (Saitoh et al., 1990a; b; Xu et al., 1997). Large differences in terms of the distribution of leaves and panicles among planting patterns were not observed (data not shown). We found that the larger the inclination of leaf blades, the smaller the light extinction coefficient of the canopy (Fig. 5). There were no differences in the leaf angle from stem axis (data not shown). Our results indicate that a difference in stem inclination in the canopy might be responsible for a difference in the inclination of leaf blades. The planting pattern with one plant per hill, a higher hill density and a square arrangement of hills might result in more erect stems.

We found a close relationship between the average rate of interception of solar radiation from June 14 to August 9 and the light extinction coefficient at the early ripening stage (Fig. 8). A smaller light extinction coefficient was accompanied by a larger average rate of interception of solar radiation by the canopy. As discussed above, the rate of interception of solar radiation by the canopy was higher in the plots in which the stem number increased rapidly. In turn, a canopy with a larger number of stems might result in an increase in the inclination of stems, even though the light extinction coefficient of the canopy tended to be smaller with one plant per hill at a higher hill density, even at the same level of interception of solar radiation, namely, even at with the same number of stems.

The choice of planting pattern is important when rice is cultivated by direct sowing. The lodging resistance of rice plants has been improved by breeding. To increase the dry matter production and grain yield of these new lodging-resistant cultivars, it is important to reevaluate the effects of the planting pattern on dry matter production, to improve the rate of interception of solar radiation by the canopy, and to optimize the light-intercepting characteristics of the canopy via modifications in the planting pattern.

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** In Japanese with English summary.
*** In Japanese.
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