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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

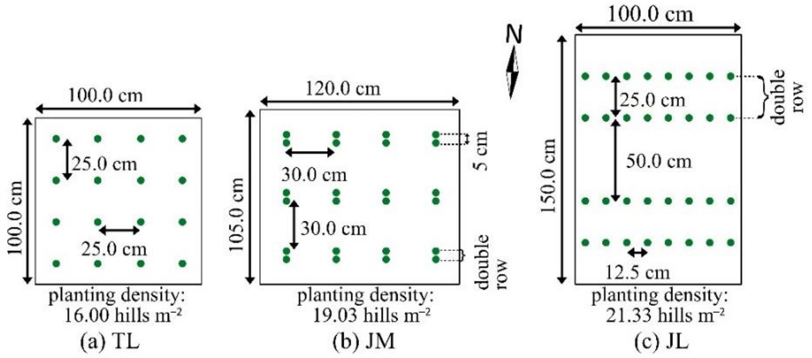
氏名： Name	Taufiq Yuliawan
学位論文題目： Title of Dissertation	Effects of double-row transplanting systems in a rice field on micrometeorological properties and rice production (水田の微気象学的特性とコメの生産に及ぼす複列移植の効果)

学位論文要約：
Dissertation Summary

Rice is a staple food for most Asian countries, particularly Indonesia. Based on the data published by USDA [1], milled rice production in Indonesia has been lower than the consumption levels over the last ten years. Moreover, rice consumption is projected to increase due to the population increase in Indonesia, as reported by the World Bank [2]. This condition is depressed by global warming, which has been reported to decrease rice production in Indonesia (e.g., [3,4]). Therefore, sustainable rice production is a critical food security issue in Indonesia.

To address the issue of rice sufficiency in Indonesia under climate change conditions, the Indonesian government has been promoting the use of double-row transplanting systems, i.e., *Jajar Legowo* (JL) and *Jejer Manten* (JM), to increase rice production. JM has not been promoted nationally, unlike JL, which has been promoted since 2013. These systems have been reported to obtain higher yields of Indica rice cultivars than the standard tile (TL) system, for example Ciherang cultivar by implementing JL [5] and Inpari 10 cultivar by implementing JM [6]. The border effect is considered the reason for the higher yields in JL and JM [7,8]. However, scientific investigations of the border effect in these systems remain limited. Additionally, double-row transplanting systems are not commonly used in Japan. Japanese farmers typically applied a tile transplanting system, for example, 30 cm wide and 15 cm long spacing between plants [9]. Therefore, scientific evidence is needed to support the promotion of JM and JL. This study aimed to check whether JM and JL can increase the yield of a Japonica rice cultivar, Nikomaru, by comparing the growth and production of rice to determine which transplanting system obtained the highest yield. Furthermore, yield components (e.g., number of filled grains) were compared to determine the change in yield components under different transplanting systems. Additionally, comparing the normalized difference vegetation index enriches the results and discussion.

Field experiments were conducted continuously during the summer seasons of 2022 and 2023 in the experimental field at the Faculty of Agriculture, Ehime University, Matsuyama, Japan (33°50' N, 132°47' E). The area of the research plot was 95.0 m^2 in 2022 and 171.0 m^2 in 2023, surrounded by experimental upland plantations (e.g., citrus), greenhouses, screenhouses and workshops. Nikomaru, a Japonica rice cultivar, was manually transplanted with three seedlings per hill, and TL, JM, and JL transplanting systems were applied. The space arrangements and hill densities of those transplanting systems are shown in **Figure 1**.



(a) TL (b) JM (c) JL

Figure 1. Illustration of space arrangement of the transplanting systems used in this study.

Plant growth parameters, such as plant and canopy heights and the number of tillers, were observed on ten fixed plants, mostly every week. Leaf area index (LAI) was obtained by measuring the leaf area by non-destructive method weekly, and that LAI was adjusted by the LAI obtained by the destructive method conducted on the important growing stages (i.e., initial–max. tiller, max. tiller–before heading, heading–flowering and after flowering–harvest). The samples for the measurements of rice production parameters (e.g., yield and above-ground biomass) were taken on the harvesting day, 110 days after transplanting (DAT). Three hill samples were taken from three sampling areas in each transplanting system. The samples were selected based on the average plant and canopy heights and the number of tillers of ten fixed samples. After being air-dried for ten days, the samples (excluding spikelets) were oven-dried at 80°C for 48 hours (e.g., [10]). Spikelets were treated separately to measure yield components (e.g., number of grains). The yield of brown rice (grain moisture= 15%) was calculated by planting density multiplied by the number of panicles per hill multiplied by the total number of spikelets per panicle multiplied by the percentage of filled grains multiplied by the weight of 1000 grains (brown rice) divided by 1000. The sink capacity per unit area was calculated by the number of grains per unit area multiplied by the weight of 1000 grains divided by 1000. The sink filling rate is assumed to be the same as the percentage of filled grains. A paired t-test with a 5% significance level with the Bonferroni correction (n=3) was applied to compare the averages of plant growth and rice production parameters between the transplanting systems.

Several meteorological sensors were installed on the experimental field to observe the general meteorological conditions of the rice field. Solar radiation above the canopy (*SR*) was measured with a net radiometer CNR4 (Kipp & Zonen, Netherlands) at heights of 1.0 m (June 25–August 1, 2022), 140 cm (August 2–October 8), 120 cm (June 25–September 4, 2023) and 150 cm (September 4– October 6, 2023). Air temperature (T_a) and humidity (RH) at the height of 2.0 m were measured with a temperature and humidity probe HMP155 (Vaisala, Finland) with ventilated systems PVC-02 (Prede, Japan) in 2022 and PVC-04 (Prede, Japan) in 2023. SR, T_a and RH were sampled every second, averaged and recorded every minute by a data logger CR-1000 (Campbell Scientific, USA). Windspeed and rainfall at the height of 2.0 m were measured with an all-in-one weather station ATMOS 41 (METER Group, USA) and recorded every minute by data logger ZL6 (METER Group, USA). The general meteorological conditions (i.e., SR, T_a, RH, u and R) were measured in the middle of the research plot.

A dense canopy often leads to more shading and affects the health of the canopy. In this study, the normalized difference vegetation index (NDVI) was utilized to observe the health of the canopy. NDVI was measured with a multispectral camera Yubaflex (Bizworks, Japan) attached to an unmanned aerial vehicle (UAV) DJI Mavic Pro 2 (Shenzhen DJI Sciences and Technologies, China). This NDVI camera was utilized by previous studies to monitor plant growth, such as cabbage [11] and rice [12] in Japan. NDVI values measured by the camera were calibrated with the NDVI measured by a spectral reflectance sensor (METER Group). NDVI was measured mostly every week from July 22 to September 30, 2023, under clear and stable sky conditions. Supervised classification was conducted to filter NDVI values of the plant body only, avoiding influence from other surfaces, such as soil and water. In addition, a set of upward and downward SRS sensors (METER group, USA) was installed in the TL plot, downward-facing NDVI sensors S2-112-SS (Apogee Instruments, USA) were installed in JM and JL plots, and an upward facing NDVI sensors S2-111-SS (Apogee Instruments, USA) was installed in JM plot. The height of the downward-facing NDVI sensors was installed at 150 cm, and the heights of the upward-facing NDVI sensor were 120 cm (June 25 – September 4, 2023) and 150 cm (September 4 – October 6, 2023), following the height of the CNR4.

JM and JL obtained higher above-ground biomass (W_t) per unit area, which differed significantly in 2022 but not significantly in 2023. This study observed that denser plants in JM and JL obtained lower above-ground biomass per hill but higher above-ground biomass per unit area. When comparing the years, total above-ground biomass was higher in 2022 than in 2023 due to a higher T_a and lower SR in the initial growing stage in 2023. Space and plant arrangements in JM and JL could increase plant density, which could be both an advantage and a disadvantage. The disadvantage of denser plants in JM and JL was that these systems faced more competition for light, resulting in a lower above-ground biomass per hill. However, the denser plants in JM and JL increased above-ground biomass per unit area.

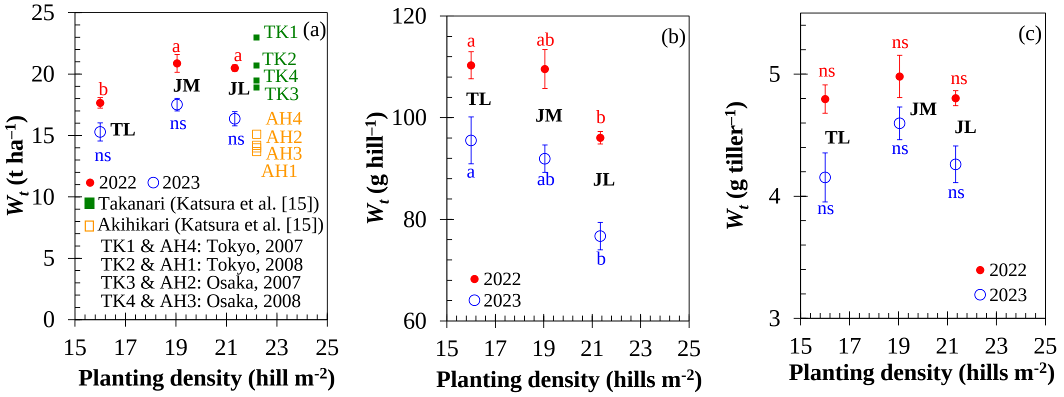


Figure 2. Comparison of total above-ground biomass (a) per unit area, (b) per hill and (c) per tiller of the harvested samples in 2022 and 2023. The bars in the markers indicate the standard deviation. The letters above and below the markers indicate the significance of the data. The same letters are not significantly different, and ns indicates not significant. The data of TL, JM and JL shown in this figure have been published in Yuliawan et al. [13,14], and the total above-ground biomass of Takanari and Akihikari cultivars is from Katsura et al. [15].

JM obtained the highest yield, followed by JL and TL, as shown in **Figure 2a**. The yields of Nikomaru obtained in this study are comparable to the yield obtained in the previous study by Morita et al. [9] in Fukuoka 2005 and 2007 and Maeda [16] in Okayama, 2005–2007. As shown in **Figure 2**, yield increased throughout the planting density, reached its maximum value, and decreased under a very high planting density. In contrast, W_g per hill decreased throughout the planting density. Higher planting density obtained lower W_g per hill because the competition for light, and probably also nutrition, increased throughout the increase of planting density. However, an increase in planting density could increase the yield due to a higher number of hills per unit area than the sparse planting density.

TL obtained the highest number of grains per hill, followed by JM and JL. However, the denser plants in JM and JL increased the number of grains per unit area. JM achieved the highest sink capacity per unit area, followed by JL and TL. Denser plants in JM and JL compared to TL resulted in fewer tillers and sink capacity per hill than in TL. However, JM and JL obtained higher sink capacity per unit area due to a higher planting density than TL. A higher sink capacity per hill in TL than JM and JL is a disadvantage for TL. As shown in **Figure 4**, JM obtained the highest percentage of filled grains and the highest number of filled grains per unit area, followed by JL and TL. Higher sink capacity per hill in a standard tile transplanting system often leads to a lower sink filling rate, as reported by previous research [17] for other Japonica cultivars.

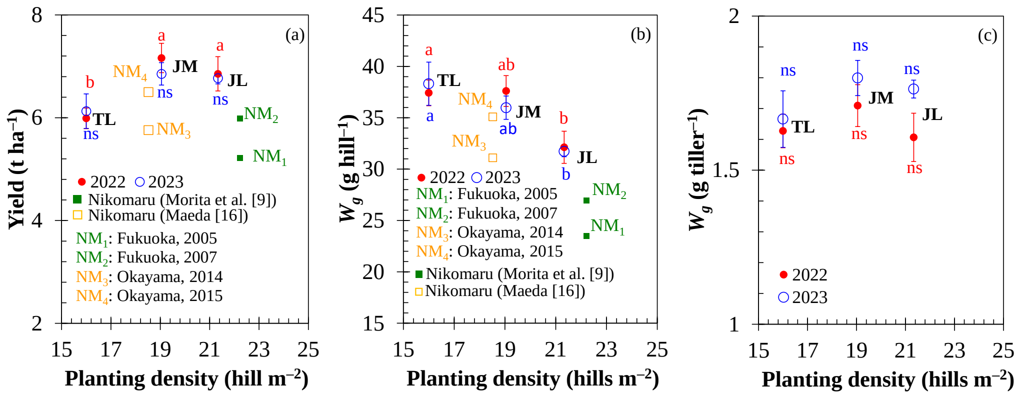


Figure 3. Comparison of (a) yield, weight of grain (b) per hill and (c) per tiller of harvested sample in 2022 and 2023. The bars in the markers indicate the standard deviation. The letters above and below the markers indicate the significance of the data. The same letters indicate no significant difference, and ns indicates not significant. The data of TL, JM and JL shown in this figure have been published in Yuliawan et al. [13,14], NM$_1$ and NM$_2$ are from Maeda [16] and NM$_3$ and NM$_4$ are from Morita et al. [9].

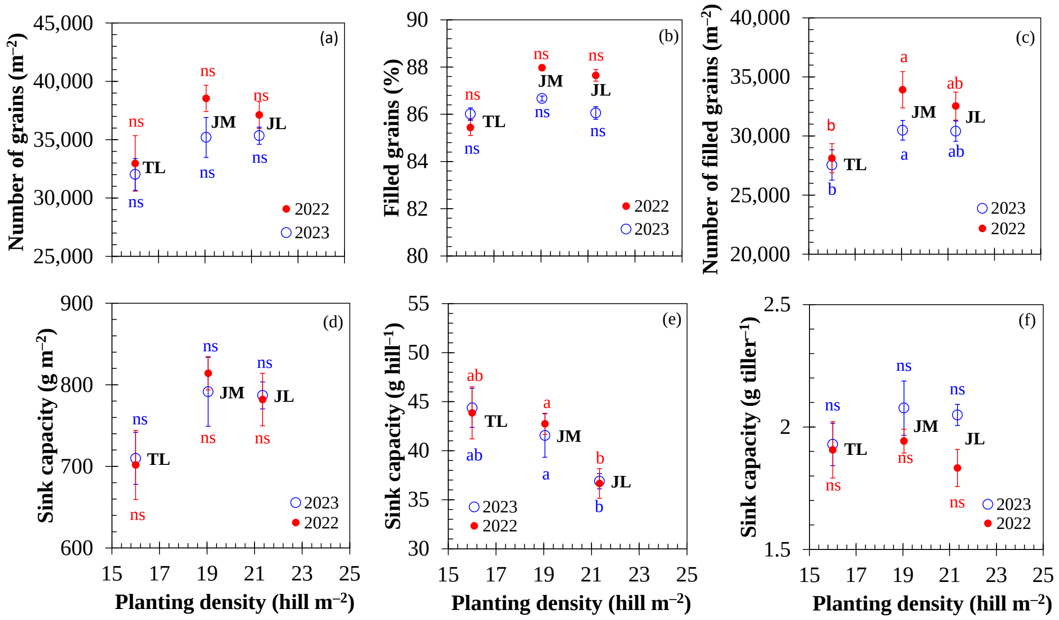


Figure 4. Comparison of (a) number of grains per unit area, (b) percentage of filled grains, (c) number of filled grains per unit area, sink capacity (d) per unit area, (e) per hill and (f) per tiller of the harvested samples in 2022 and 2023. The bars in the markers indicate the standard deviation. The letters above and below the markers indicate the significance of the data. The same letters indicate no significant difference, and ns indicates not significant. The data shown in this figure have been published in Yuliawan et al. [13,14].

JM obtained the highest normalized difference vegetation index (NDVI), followed by JL and TL, as shown in **Figure 5**. Although the differences in NDVI values are insignificant between the transplanting systems, JM achieved a higher NDVI throughout the growing stage. These results correlate to the LAI variations, where JM obtained the highest LAI, followed by JL and TL. As described by Kriegler et al. [18], NDVI could monitor the health of the canopy besides monitoring the canopy density. Moreover, healthy vegetation absorbs much visible light and reflects and emits more near-infrared spectrum than unhealthy vegetation [19]. Thus, higher NDVI values indicate healthier vegetation, which can absorb more solar radiation for photosynthetic activity. Previous studies have reported a strong relationship between NDVI and absorbed solar radiation [20]. The higher NDVI obtained by JM and JL than TL is considered a reason for better solar radiation absorption in those double-row transplanting systems. Although the data is not shown in this document, JM and JL obtained a higher intercepted solar radiation, particularly after the flag leaf extensions stage. This condition was caused by a higher LAI and supported by the healthier canopy, as shown by NDVI values in **Figure 5**. Furthermore, after analyzing correlations between NDVI and sink filling rate and yield, this study found that the average NDVI during the flag leaf extension to milking stages had the highest coefficient of determination (**Figures 5c** and **5d**). The average NDVI during the flag leaf extension to milking stages was strongly correlated with the sink filling rate (**Figure 5d**) and yield (**Figure 5c**). Healthier canopies supported the absorption of solar radiation during the grain-filling periods, resulting in a higher sink filling rate in JM and JL than in TL. Additionally, the average NDVI throughout the season was strongly correlated with the above-ground biomass, as shown in **Figure 5b**.

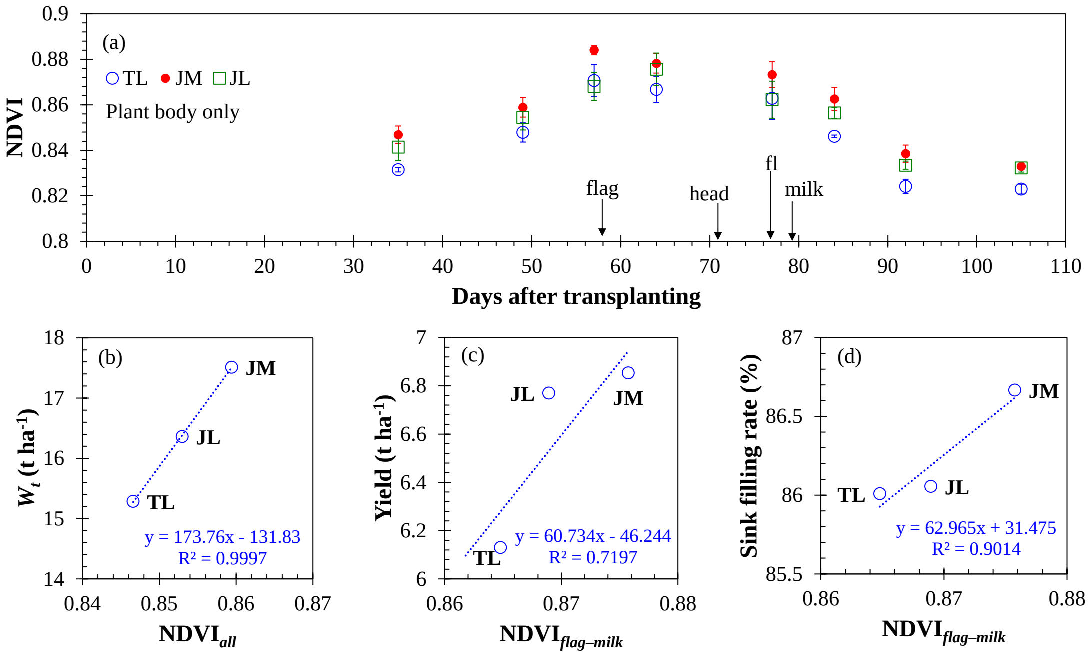


Figure 5. Weekly variations of (a) normalized difference vegetation index (NDVI), relationships between (b) the average of NDVI throughout the season and total above-ground biomass, (c) the average of NDVI during the grain filling stage (flag leaf extension–milking, NDVI$_{flag–milk}$) and yield, and (d) NDVI$_{flag–milk}$ and sink filling rate. The bars in the markers indicate the standard deviation. The notes of flag, head, fl, and milk denote important phenological events, which are flag leaf extension, heading, flowering (100%), and milking (100%) stages, respectively. The data shown in this figure have been published in Yuliawan et al. [13,14].

The study found that JM obtained the highest yield, followed by JL and TL. Higher plant competition for light in JM and JL caused a lower tiller number and above-ground biomass (W_t) per hill than in TL. However, due to denser plants, JM and JL obtained a higher number of tillers, W_t, leaf area index (LAI) and sink capacity per unit area than TL. Moreover, JM obtained the highest sink filling rate, followed by JL and TL. Additionally, JM obtained the highest normalized difference vegetation index (NDVI), followed by JL and TL. NDVI during flag leaf extension to the milking stage was highly correlated to the sink filling rate ($R = 0.949$) and yield ($R = 0.849$), and the averaged NDVI of the whole growing season was strongly correlated to W_t ($R = 0.999$). The synergistic effect of higher sink capacity and sink filling rate, supported by higher NDVI, led to higher yields in JM and JL than in TL.

This study checked the applicability of double-row transplanting systems introduced by the Indonesian government to a Japonica rice cultivar, Nikomaru, which has an erect canopy shape similar to the canopy shape of common Indica rice cultivars transplanted in Indonesia. The double-row transplanting systems used in this study need to be checked by applying those systems to other Japonica rice cultivars, such as Hinohikari or Himenorin, which have different canopy shapes compared to Nikomaru. This study suggests that studies comparing the yield of Japonica rice cultivars by applying JM and JL are highly recommended to be conducted.

The findings of this study strongly recommend for the promotion of JM by the Indonesian government, similar to the national promotion of JL. Currently, JL has been selected by the Indonesian government as the most recommended transplanting system for rice due to its ability to yield higher than TL. However, the introduction of JM could not only increase the yield but also reduce the number of seedlings per unit area, making it a more economical choice for farmers than applying JL. This study recommends further research to compare the yield and cost-effectiveness of JM and JL.

Besides increasing rice yield, Applying JM and JL can make field management easier because of their wider space than the space in TL. The wide space between double rows in JL and JM and between the columns in JM gives enough space for the farmer to do field management (e.g., pesticide spraying) more easily and safely. One of the issues of rice farming in Japan is the difficulties in field management. Farmers in Japan are dominated by the older generation, which is not physically strong enough like the younger generation. So, a wider space between plants could probably increase the farmer's safety and plants' safety in case a work accident occurs while old-generation farmers are doing field management. This study suggests conducting a study to compare the ergonomic aspect of the application of JM and JL in rice fields for older farmers who are doing field management.

The sun inclination angles in Japan differ from those in Indonesia. In Japan, these angles vary significantly between months, unlike in Indonesia. This study was limited to applying JM and JL only in an east-west transplanting direction. Therefore, further research is needed to assess the application of JM and JL in Japan, considering the changing sun inclination angles. This study recommends such research to ensure the successful adaptation of these systems to local conditions, such as changing the transplanting direction from an east-west direction to a north-south direction.

Figure 6. *Jajar Legowo* (JL) transplanter used by the farmer to mark the hills to help farmers transplant rice manually. Source: Taufiq [21].

Lastly, the unsolved challenge for JM and JL is the rice transplant method because the space arrangement differs from the standard transplanting system. Currently, Indonesian farmers mark the hills by drawing lines on the rice field to apply JM and JL, as shown in **Figure 6**. In Indonesia, the use of transplanting machines for JL and JM still needs to be improved due to a lack of resources. Japan, a country with expertise and resources in developing agricultural machinery, particularly rice transplanting machines, is in an excellent position to help. This study suggests that research on developing a machine for transplanting rice using JM and JL is necessary, and it can be facilitated by collaborating with Japan.

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(Note) The Summary should be about 10％ of the entire dissertation and may include illustrations