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Relationship between Leaf Area Index and Yield Components in Farmers' Paddy Fields

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Abstract: Estimation of rice yield components is required to optimize cultivation management in fields. The leaf area index (LAI) can be a parameter for this estimation, but it has not been evaluated in farmers' fields. In this study, we analyzed the relationship between the LAI and yield components using data collected over a five-year period in farmers' fields for the cultivar Hitomebore. Leaf area dynamics (LAD) were parameterized by fitting a growth function to the time-series data of LAI measured using a canopy analyzer. The contribution of LAD to yield components was analyzed using multiple regression. The LAIs at five points during the growing season (effective integrated temperatures of 200, 400, 600, 800, and 1000 °Cd) were calculated using the growth function and the relationship between them and the yield components were analyzed using linear regression. The results of the multiple regression analysis showed that all function parameters significantly affected the yield components at the 5% probability level, with the greatest contribution from the LAI. The LAI at effective integrated temperatures of 400 to 600 °Cd significantly affected most of the yield components. However, the correlation coefficients between the LAI and yield components were not high (R = 0.18–0.61). The LAIs at almost all periods significantly affected the grain number per panicle and 1000-grain weight at the 5% probability level. These results suggest that the LAI could be used for monitoring trends in yield components, while further research on the development of accurate estimation methods is needed.

Keywords: growth function; leaf area dynamics; rice paddies; yield components

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1. Introduction

Rice is one of the staple foods grown in many countries, and its sustainable production is an important issue [1]. Increasing rice yields is important for farming operations. Yield is expressed as the product of yield components, that is, the number of panicles, grains per panicle, grain-filling percentage, and 1000-grain weight [2]; thus, farmers must increase each yield component. Generally, farmers apply cultivation management practices to improve yield components. For example, deep-water management can control the number of panicles and increase the heading rate of all stems [3]. Basal and additional fertilizers have been reported to effectively increase the number of panicles and grain weight [4]. In addition, planting density affects the number of grains [5], while mid-summer drainage improves the grain-filling percentage [6]. The number of panicles is sensitive to water deficiency [7].

It has been previously reported that cultivation management practices to increase yield components can be environmentally damaging [8,9]. Therefore, eco-friendly techniques should be applied [10] or minimal cultivation and management activities should be implemented at the right time in the growing season to achieve the maximum effect with minimum effort, requiring farmers to predict each yield component as early as possible during the growing season. Methods have been proposed to estimate each yield component using the nutritional status and morphological characteristics [11,12]. However, the estimation methods have the problem of low usability because they may require several measurements, including parameters that farmers cannot easily measure. Therefore, a method that can estimate all yield components with a single parameter is expected to be developed but has not been well studied in real farmers' fields.

The leaf area index (LAI), a biophysical parameter, can be measured in farmers' paddy fields. The LAI reflects the environmental factors in the field such as soil nutrient and climate conditions [13,14] and has been indicated to be related to some yield components [15,16]; thus, it might have the potential to be a parameter for yield component estimation. Various methods have been proposed to measure the LAI. The simplest and least expensive method is to estimate it from leaf length or width [17,18]. However, this method requires the estimation equation of the target crop to be obtained and evaluated in advance. In addition, to determine the LAI, all leaves in a unit area need to be measured, which is labor-intensive. A leaf area meter with a scanner can accurately calculate the leaf area by scanning leaves [19], but it also requires scanning all leaves within a unit area to determine the LAI. A plant canopy analyzer with a solar radiation sensor can easily measure the LAI based on the degree of solar radiation intercepted by the plant canopy [20] and has been used for various kinds of plants in past studies [13,21]. Recently, a method for estimating the LAI using unmanned aerial vehicle (UAV)-based remote sensing has been proposed [22]. Although its estimation accuracy was slightly lower than others, this method can quickly observe the entire field.

Although the LAI is one of the biophysical parameters that can be measured in the field, its potential for estimating rice yield components has not been evaluated in farmers' fields. Thus, the objective of the present study was to understand the relationship between LAI and rice yield components. To this end, we measured the LAI irregularly at several points, obtained the growth function using the measured data, and statistically analyzed the relationship between the LAI calculated using the function and yield components. To measure the LAI, a canopy analyzer, which has been used in paddy fields in a past study, was used.

2. Materials and Methods

Figure 1 shows an overview of the research flow in the present study. The study was conducted in rice paddies cultivated by farmers in Sendai City, Miyagi Prefecture, Japan, over a five-year period. The LAI was measured multiple times at the same survey point during the growing season using a canopy analyzer. Harvesting was conducted at the end of the ripening period to examine yield components. The growth function was obtained using the measured LAI, and a multiple comparison test was used to find the significant effect of year and planting method on the function parameters and yield components. Then, to examine the effect of leaf area dynamics on yield components, a multiple regression analysis was applied and the standard partial regression coefficients were determined. Finally, LAIs at various growth stages were calculated using the growth function, and to explore the feasibility of estimating yield components, the relationship between the LAIs and yield components was analyzed using linear regression. Some yield components have been suggested to have a linear relationship with LAI [15], and the authors have also confirmed in a past study that there is a linear relationship between grain yield and LAI in a specific period [23].

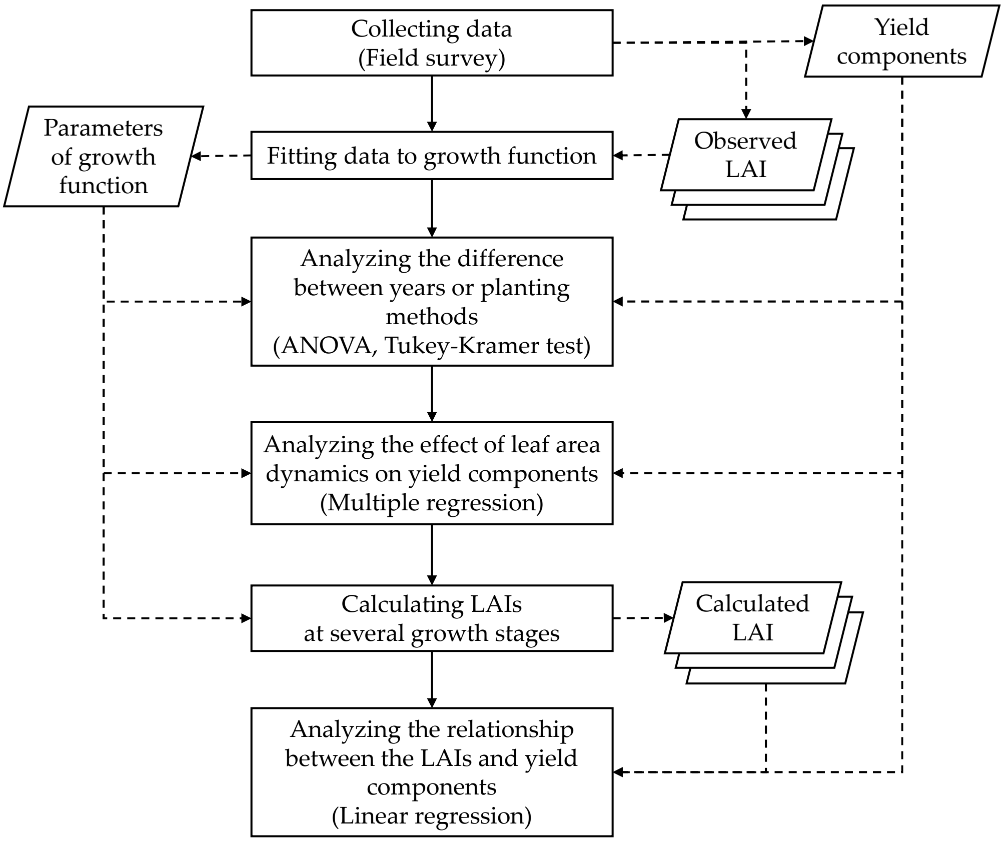

Figure 1. Overview of the research flow. The rectangles, parallelograms, solid arrows, and dashed arrows indicate processing, data, processing flow, and data flow, respectively.

2.1. Research Fields

A five-year field survey was previously conducted from 2016 to 2020 in paddy fields located in the center of the Sendai Plain, about 1 km inland from the coastline, at an elevation of 0 m (Figure 2) [23]. The soil type is classified as gray lowland soil. The area was damaged by the great earthquake in 2011, and crop production was resumed after farmland maintenance was performed. Large-scale agricultural producer cooperatives cultivate and manage these fields. The rice cultivar grown in these fields is Hitomebore, the main cultivar in this region. The field sizes ranged from 0.7 to 1.0 ha. Between 4 and 20 survey points were set in each field at 5–25 m intervals. Table 1 shows the number of fields, survey points, and cultivation histories for each year. The cultivation history varied annually according to the management plan and weather conditions. Figure 3 shows the weather conditions during the growing season over the five years. Weeds and insect pests were managed according to the farmers' customs: herbicides were applied at transplanting, direct sowing, and one month after planting, and insect pest controls were applied at the times of raising seedlings, transplanting, and direct sowing.

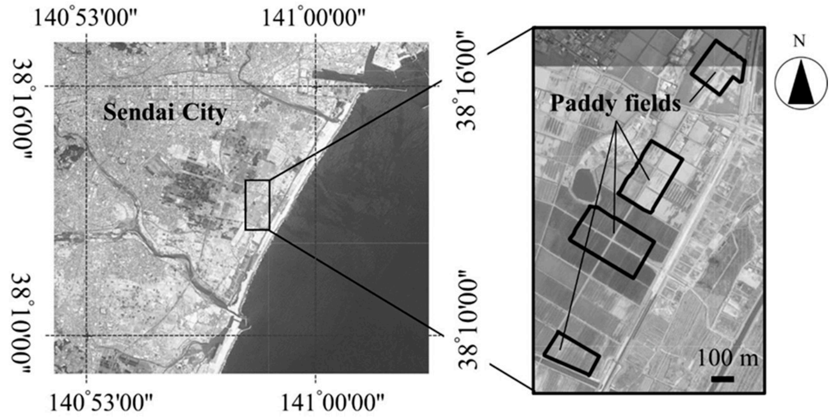

Figure 2. The farmers' paddies are managed by a large-scale agricultural producers' cooperative corporation. This figure was created by modifying an aerial image taken by the Geospatial Information Authority of Japan.

Table 1. Number of survey points per field and cultivation history from 2016 to 2020 [23].

Year	Planting Method ^{d}	Survey Points/Fields	Planting Density (m)	Date of Sowing	Date of Transplanting	Date of Heading	Date of Harvesting	Fertilizer	
								Basal (g m^{-2})	Additional (g m^{-2})
2016	DS	10/1	0.3 × 0.2	24 April	-	8 August	13 September	40 ^{a}	-
	TP	10/1	0.3 × 0.2	8 May	18 May	8August	13 September	40 ^{a}	-
2017	DS	80/4	0.3 × 0.2	7 May	-	11 August	21 September	40 ^{a}	-
	TP	80/4	0.3 × 0.2	25 April	15 May	11 August	21 September	40 ^{a}	-
2018	DS	80/4	0.3 × 0.2	7 May	-	10 August	18 September	40 ^{a}	-
	TP	40/2	0.3 × 0.2	29 April	19 May	10 August	18 September	40 ^{a}	5 ^{b}
2019	DS	48/4	0.3 × 0.2	4 May	-	8 August	25 September	40 ^{c}	-
	TP	48/4	0.3 × 0.2	16 April	16 May	8 August	12, 17 September	40 ^{c}	-
	TPd	48/4	0.3 × 0.2	22 April	12 May	8 August	17 September	40 ^{c}	-
2020	TP	16/4	0.3 × 0.2	12, 14 April	14 May	4 August	11 September	40 ^{c}	-

^{a} Hitomebore senyouhiryou 2gouR (Central Chemical Co, Ltd., Tokyo, Japan). ^{b} Minakuchi NK (Central Chemical Co, Ltd., Tokyo, Japan). ^{c} Miyagimai-ippatsu 204 (Katakura and Co-op Agri Corporation, Tokyo, Japan). ^{d} DS, TP, and TPd indicate plants whose seeds were directly sown into the fields, plants transplanted by a machine after growing in a seedling box, and plants transplanted by a machine after growing in a seedling box with a high seed density, respectively.

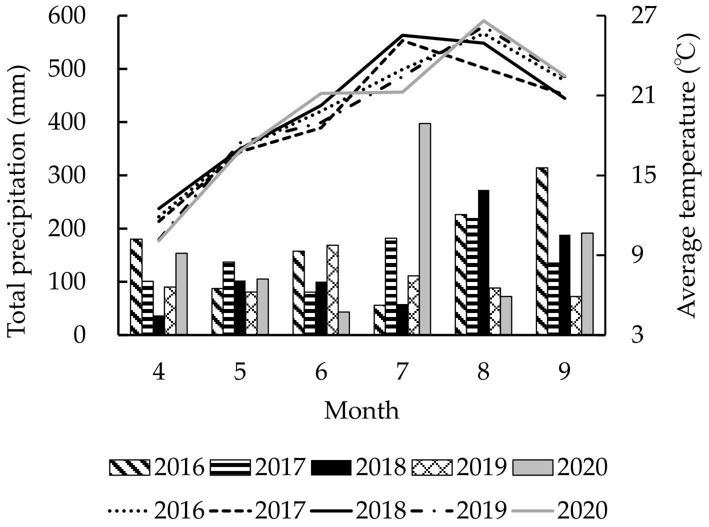

Figure 3. Total precipitation and average temperature recorded at the Automated Meteorological Data Acquisition System (AMeDAS) observatory close to the research fields from 2016 to 2020.

2.2. Measurements

The yield components were determined by the following procedure [24]. At each survey point, the rice and weeds growing in a circular area (0.82 m^2) were harvested when 80% of the grains had a bright yellow color. The number of panicles was counted, and the grain-filling percentage was determined by selecting grains that sank in saltwater with a specific gravity of 1.06; sunken grains were defined as ripened grains. These grains were then dried in a ventilated dryer at 80 °C for five days, and the dry grain and weed weights were measured using an electronic balance. The dry grain weight was not adjusted for moisture content. Finally, the 1000-grain weight was calculated using the measured data. Weeds from the same area were also harvested and dried.

The LAI was measured using a plant canopy analyzer LAI-2200 (LI-COR, Inc., Lincoln, NE, USA), as previously described [23]. The measurement error has been reported as 29% for rice cultivars [13]. A LAI-2200 sensor was used to calculate the LAI value from two measurements in the upper part of the canopy and four measurements in the lower part [13]. These measurements were performed twice at each survey point, and the two measurements were averaged for each point. A cap at an opening angle of 90° was mounted on the sensor of the plant canopy analyzer to limit the observation direction and avoid the influence of light blockage by the operator. We conducted measurements from mid-June to mid-August (heading stage) each year, six times in 2016, eight in 2017, fourteen in 2018, three to seven in 2019, and seven in 2020.

The data of the survey points where the dry matter weight of weeds exceeded 10 gm^{-2} were excluded because the LAI was overestimated using the canopy analyzer.

2.3. Parametrization of Leaf Area Dynamics

A growth function was used to parameterize leaf area dynamics. A typical growth function is a logistic function, as expressed in Equation (1) [25]:

$$\mathrm{LAI} = \mathrm{LAI}_{\mathrm{max}}/\{1 + \mathrm{a} \times \exp(-\mathrm{b} \times \mathrm{T})\} \tag{1}$$

where $\mathrm{LAI}_{\mathrm{max}}$ ($m^2\ m^{-2}$) and T (°Cd) represent the maximum LAI value during the growing period and the effective integrated temperature (base temperature of 10 °C), respectively, and the variables a and b are parameters that characterize the shape of the logistic curve. The coefficients of a typical logistic function do not represent physical quantities, so it is difficult to interpret their meanings intuitively. Therefore, we adopted the growth function reported by Yin et al. [26] with the explanatory variables replaced with the effective integrated temperature. Equation (2) is as follows:

$$\mathrm{LAI} = \mathrm{LAI}_{\mathrm{max}} \times \{1 + (\mathrm{T_e} - \mathrm{T})/(\mathrm{T_e} - \mathrm{T_m})\} \times (\mathrm{T}/\mathrm{T_e})^{\{\mathrm{Te}/(\mathrm{Te}-\mathrm{Tm})\}} \tag{2}$$

where $\mathrm{T_m}$ (°Cd) and $\mathrm{T_e}$ (°Cd) are the effective integrated temperature at the inflection points of the growth rate and the end of growth, respectively. Equation (2) was fitted to the time series of measured LAIs using the non-linear least-squares method. The effective integrated temperature at LAI measurement was calculated from the transplanting or sowing date using daily air temperature data recorded at the Automated Meteorological Data Acquisition System (AMeDAS) observatory close to the research fields.

2.4. Statistical Analysis

An analysis of variance (ANOVA) was applied to the yield components and estimated parameters to test the effects of the year and planting method. Multiple comparisons between years or planting methods were performed using the Tukey–Kramer test. For both analyses, *p*-values less than 0.05 were judged as statistically significant differences.

The photosynthetic products after heading and parts of those accumulated before heading are translocated to the harvest part; thus, the extent to which the leaves receive sunlight during the growing season is important for dry matter production [2,27]. Therefore, leaf area dynamics may be related to dry matter production. A multiple regression analysis then was conducted using Equation (3) to examine the effect of the parameters in Equation (2), which characterizes the leaf area dynamics, on yield components. The extent of the growing period's effects on the values of the yield components differed across components; thus, the contribution of each parameter was expected to vary.

$$\begin{aligned}\text{Yield component} &= a \times \mathrm{LAI_{max}} + b \times T_m + c \times T_e + d \times \mathrm{LAI_{max}} \times T_m \\ &+ e \times \mathrm{LAI_{max}} \times T_e + f \times T_m \times T_e + g \times \mathrm{LAI_{max}} \times T_m \times T_e + \text{Intercept}\end{aligned} \tag{3}$$

where yield component indicates the panicle number, grain number per panicle, grain-filling percentage, or 1000-grain weight and $\mathrm{LAI_{max}}$, T_m, and T_e indicate the parameters defined in Equation (2). These values were standardized with the average of 0 and variance of 1. The letters a, b, c, d, e, f, and g denote standardized partial regression coefficients.

To investigate the predictability of the yield components based on leaf area measurements, a linear regression analysis was conducted using Equation (4):

$$\text{Yield component} = h \times \mathrm{LAI}(T) + \text{Intercept} \tag{4}$$

where LAI(T) is the LAI at the effective integrated temperature (T), which was calculated using Equation (2) with the estimated parameters. T values of 200, 400, 600, 800, and 1000, represent the start, middle, and end of tillering period, panicle formation period, and heading period, respectively. The letter h is the regression coefficient. For Equations (3) and (4), the explanatory variables with a p-value less than 0.05 were judged to have a statistically significant effect. R (Ver. 4.0.5) software was used for statistical analysis.

3. Results

The yield components obtained from the yield survey and the growth function parameters estimated using Equation (2) are listed in Table 2. The average number of panicles for all data was 376.0 $\mathrm{m^{-2}}$. There was a significant difference in the number of panicles between years but no significant difference between planting methods. The average number of grains per panicle for all the plants was 66.6, with significant differences between years and planting methods. The average grain-filling percentage was 80.0%; there were significant differences between years and planting methods, while that of densely sown transplanted plants was significantly lower (66.6%). The average 1000-grain weight was 24.2 g; significant differences existed between the years and planting methods, but the variation was small. The average dry grain weight was 413.7 g $\mathrm{m^{-2}}$; there was a significant difference between years, with the grain weight being significantly greater in 2020 than in all the other years. All parameters in Equation (2) significantly differed among the years, planting methods, and their interactions. The mean $\mathrm{LAI_{max}}$ was 2.9 $\mathrm{m^2\ m^{-2}}$. There were significant differences in $\mathrm{LAI_{max}}$ between years and planting methods. The average values of T_m and T_e were 633.1 °Cd and 983.0 °Cd, respectively; the standard deviation of T_m was larger than that of T_e.

The standardized partial regression coefficients obtained via multiple regression analysis using Equation (3) are listed in Table 3. All variables, except for the interaction between the three parameters, had a significant effect on the number of panicles. The values of the coefficients were positive, with $\mathrm{LAI_{max}}$ being the highest. $\mathrm{LAI_{max}}$, T_m, and the interaction between T_e and T_m had a significant effect on the number of grains per panicle; the values of the standard partial regression coefficients of $\mathrm{LAI_{max}}$ and T_m were positive, whereas those of the interaction between T_e and T_m were negative. All variables except T_e had a significant effect on the grain-filling percentage; the standardized partial regression coefficients of $\mathrm{LAI_{max}}$, T_m, and the interaction of the three parameters were negative, whereas those of the other variables were positive. $\mathrm{LAI_{max}}$, T_e, and T_m significantly affected the 1000-grain weight; the standardized partial regression coefficient of $\mathrm{LAI_{max}}$ was positive, whereas those of T_m and T_e were negative.

Table 2. Analysis of variance of yield components and parameters of the growth function. The numbers in parentheses indicate the standard deviations. Different letters a, b, and c indicate significant differences at the 5% probability level.

	Panicle Number (m^{-2})	Grain Number Per Panicle	Grain-Filling Percentage (%)	1000-Grain Weight (g)	Dry Grain Weight of the Ripened Grain (g m^{-2})	LAI_{max} (m^2 m^{-2})	T_m (°Cd)	T_e (°Cd)
All	376.0 (91.3)	66.6 (10.9)	80.0 (13.1)	24.1 (0.8)	413.7 (113.3)	2.9 (0.9)	633.1 (134.7)	983.0 (84.0)
Year (Y)								
2016	420.5 (60.3) ab	53.7 (6.9) a	77.0 (6.9) ab	23.9 (0.8) ab	371.1 (60.9) ab	3.1 (0.7) a	698.5 (71.5) ab	951.3 (55.5) ab
2017	321.9 (61.1) c	63.5 (6.7) b	82.2 (8.8) a	24.0 (0.6) ab	378.3 (113.7) a	2.3 (0.6) b	641.6 (75.7) a	971.7 (74.5) ab
2018	454.3 (89.3) a	73.0 (10.6) c	80.3 (9.8) a	24.1 (0.9) a	452.7 (91.2) b	2.9 (0.4) a	740.7 (72.1) b	1019.5 (45.2) c
2019	356.8 (72.2) d	65.1 (12.8) b	74.0 (18.8) b	24.2 (0.7) a	398.9 (110.7) a	3.8 (1.1) c	536.1 (139.8) c	954.4 (111.2) a
2020	382.3 (54.5) bd	69.8 (6.7) bc	95.5 (1.3) c	23.5 (0.3) b	567.9 (72.8) c	3.3 (0.3) ac	373.8 (68.0) d	1029.5 (86.4) bc
Planting Method (P)								
DS	380.9 (116.9) a	64.1 (8.2) a	74.4 (7.9) a	23.7 (0.6) a	344.9 (81.2) a	2.4 (0.6) a	735.3 (64.5) a	1024.2 (74.6) a
TP	375.1 (54.0) a	69.2 (11.6) b	89.2 (5.6) b	24.4 (0.7) b	504.2 (72.7) b	3.2 (0.6) b	551.5 (109.2) b	947.4 (70.4) b
TPd	353.9 (64.6) a	67.8 (15.7) ab	66.6 (26.5) c	24.5 (0.7) b	361.3 (123.6) a	4.5 (1.2) c	459.8 (73.3) c	926.1 (81.7) b
Y	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
P	not significant	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Y × P	<0.001	<0.001	not significant	<0.001	<0.001	<0.001	<0.001	<0.001

Table 3. Standardized partial regression coefficients of the multiple regression analysis.

Component	Intercept	a	b	c	d	e	f	g
Panicle number	0.03	0.50	0.25	0.13	0.19	0.22	0.24	−0.06
	not significant	<0.001	<0.001	<0.05	<0.01	<0.001	<0.001	not significant
Grain number per panicle	0.04	0.30	0.17	0.02	0.04	−0.11	−0.13	0.09
	not significant	<0.001	<0.01	not significant	not significant	not significant	<0.05	not significant
Grain-filling percentage	0.19	−0.19	−0.56	0.00	0.41	0.22	0.10	−0.18
	<0.001	<0.001	<0.001	not significant	<0.001	<0.001	<0.05	<0.01
1000-grain weight	0.11	0.22	−0.13	−0.14	0.30	0.09	0.06	0.06
	not significant	<0.001	<0.05	<0.05	<0.001	not significant	not significant	not significant

Figure 4 shows the relationship between the calculated LAI and the observed yield components, and the regression equation with significant coefficients is shown in the figure. In Figure 4, densely sown transplanted plants were not described. For directly sown plants, the LAI calculated with T = 400 was significantly related to all yield components except panicle number at the 5% probability level. For transplanted plants, LAIs calculated with T = 600 and 800 were significantly related to all yield components at the 5% probability level. For the 1000-grain weight of both directly sown plants and transplanted plants, the absolute value of the slope of regression equation became small as T increased.

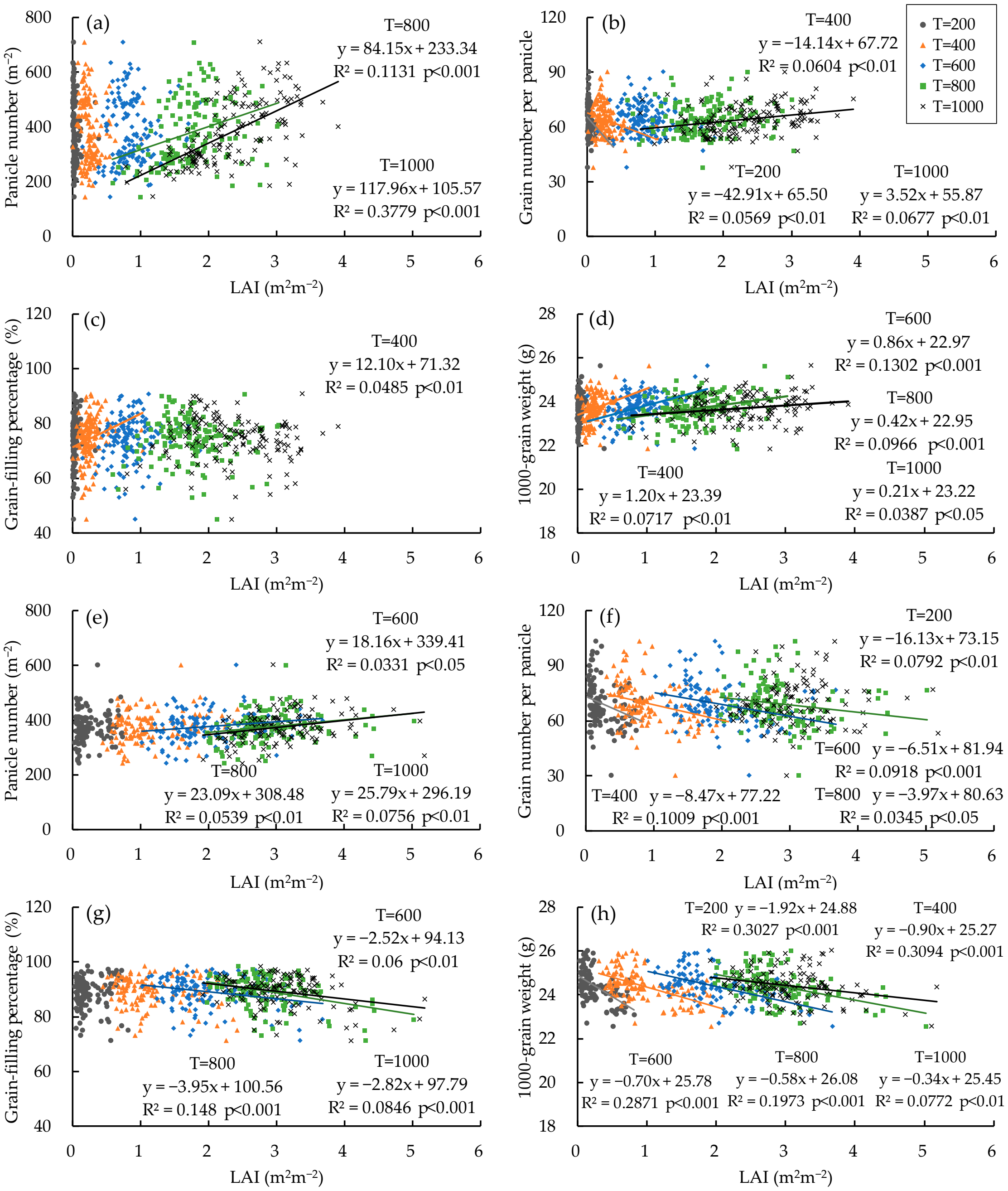

Figure 4. Relationship between the LAI estimated using Equation (2) at the effective integrated temperatures (T) of 200, 400, 600, 800, and 1000 °Cd and the observed yield components. (**a**–**d**) show the relationship for directly sown plants, and (**e**–**h**) show that for transplanted plants.

4. Discussion

Target values of the yield components have been proposed for Hitomebore [28], the rice cultivar used in this study. When the adjustments for moisture content and conversion to brown rice weight were applied to the average yield obtained in the present study, the adjusted weight was lower than the target values. The number of panicles was more than 20% lower than the target, whereas the differences in grains per panicle and grain-filling percentage were less than 7% of the target. Therefore, the low yield in the farmers' fields was largely due to the low number of panicles. One reason for this low number may be that the planting density was lower than the conventional value. Significant inter-annual differences in the number of panicles may have been influenced by factors that vary from year to year, such as field soil conditions, weather, and water management practices. There were significant differences in all components between years, suggesting that it would be difficult to consistently achieve the target value every year in farmers' fields.

Significant differences were observed between the planting methods in yield components, except for panicle number. For the densely sown transplanted plants, the grain-filling percentage was significantly lower (66.6%). Excessive increases in the LAI led to lower grain-filling percentages [29]. The LAI_{max} of 4.5 in densely sown transplanted plants was significantly higher than in other methods but not excessively high compared to previous reports for Hitomebore [30]. Densely sown rice plants were transplanted to four fields, one of which contained survey points with significantly lower grain-filling percentages. This field was only used in 2019 in this study, so the trends in yield and components for other years are unknown. The survey data in this study did not reveal the reason for the low grain-filling percentages.

The average value of the RMSE when fitting Equation (2) to the observed LAIs was 0.19, suggesting that the leaf area dynamics were well represented using the growth function. All the parameters estimated using Equation (2) showed significant interannual differences. The average LAI_{max} was 2.9, lower than that reported in previous studies for the same cultivar [30] and could be caused by the low panicle number previously mentioned. For paddy rice, the period when the LAI reached its maximum coincides with the heading stage [31], and the effective integrated temperature from germination to heading is almost the same for all genotypes [2]. The standard deviation of T_m was larger than that of T_e (84 °Cd), showing that growth curves of various shapes occurred even though the T_e values were similar. These results indicate that leaf area dynamics reflect environmental differences in the fields from year to year and site to site because they are affected by weather conditions, such as solar radiation, rainfall, and soil characteristics [14].

The results of a multiple regression analysis showed that all variables significantly affected the yield components. All parameters had standardized partial regression coefficients for both positive and negative values. This agreed with the negative relationship between yield components. For the yield components, the standardized partial regression coefficients of LAI_{max} were positive and higher than those of the other parameters, except for the grain-filling percentage. Therefore, an increase in the LAI_{max} is needed to improve the yield components. Additional fertilization and adjustments to the planting density have been reported to increase the LAI [32]. T_m had a significant effect on all yield components. Its contribution to the yield components was the second largest among the three parameters, indicating that T_m is also an important factor for yield component formation. The standardized partial regression coefficients of T_m were positive for panicle number and grains per panicle and negative for grain-filling percentage and the 1000-grain weight. While the standardized partial regression coefficient of T_m was negative for the grain-filling percentage, that of the interaction of LAI_{max} and T_m was positive; hence, the standardized partial regression coefficient of the interaction of T_e and T_m was negative. T_m significantly increased the number of grains per panicle; these results show that the contribution of T_m to the yield components may vary in a more complex manner than the other parameters. This may be due to the fact that the periods that are important for formation of each yield component are different [2]. For the 1000-grain weight, the standardized partial regression coefficients of LAI_{max} and T_m tended to be smaller than those of the other components. This result is consistent with the 1000-grain weight being a stable trait with respect to environmental variability [33].

For directly sown plants, the LAI in the early stage of tillering ($T = 400$ °Cd) significantly affected all yield components except for panicle number, while the correlation coefficients were low. The results of cross-validation of Equation (4) with grouping by year showed that the RMSEs were 8.0 grains, 7.7%, and 0.6 g for the grain number per panicle, grain-filling percentage, and 1000-grain weight, respectively. A T of 400 °Cd occurs before the T_m, at which the leaf area growth rate reaches a maximum value (Table 2), indicating a sufficient amount of time to modify cultivation management practices for the target values of yield components set by farmers if accurate estimation is possible. For transplanted plants, the LAI in the middle of the tillering period (T = 600 °Cd) significantly affected all yield components, while the correlation coefficients were low. The results of cross-validation of Equation (4) with grouping by year showed that the RMSEs were 53.1 m^{-2}, 11.1 grains, 5.4%, and 0.6 g for the panicle number, grain number per panicle, grain-filling percentage, and 1000-grain weight, respectively. A T of 600 °Cd occurs somewhat after the T_m (Table 2), indicating a limited time to modify cultivation management practices to improve yield components. However, an advantage of this is that the yield can be approximated if all yield components can be estimated accurately. According to the changes in regression equations in Figure 4b,d,f,h, farmers should consider the LAI value at the early growth stage. The LAI might have the potential to be an indicator to monitor the effectiveness of the cultivation management.

Many rice cultivars have been bred from Koshihikari, and Hitomebore is one of them. There is expected to be a correlation between LAI and yield components similar to that in the present study for these cultivars, while the regression equation may not be similar for the cultivars whose physical traits have been improved in breeding processes. In the present study, data were collected over five years and in multiple fields and points to consider a variety of growing environments, but further research would be needed to determine the relationships in regions with significantly different weather and soil conditions. In addition, the yield in the present study was not very high; an analysis of higher-yield cases, where a strong negative correlation might be observed, should be studied in future research.

To control rice yield components effectively by cultivation management, simple estimation methods are required. To explore the potential of estimating yield components using a single parameter, we examined the relationship between the LAI and yield components. The results showed that although the LAI significantly affected all yield components, the estimation using only LAI had limited accuracy and required the use of additional parameters or advanced methods such as machine learning. Recently, UAV-based remote sensing has been proposed to estimate the LAI [22], because it can estimate not only the LAI but also the leaf color and height from the aerial images. This may improve the accuracy with relatively little additional work. The LAI changes spatially within a field; thus, modifying cultivation management practices based on the LAI measured at a specific point may not be suitable for the entire field. UAV-based remote sensing can also contribute to resolving this problem. Future research will consider analyzing the possibility of controlling yield components, including examining data collection methods, the analytical methods, and the relationships among yield components.

5. Conclusions

A simple method for yield component estimation of rice is useful for farmers to conduct cultivation management practices. To explore the feasibility of rice yield component estimation using only the LAI, we investigated the relationship between the LAI and yield components based on a field survey. The results showed that using the growth function is effective in numerical analyses of leaf area dynamics. The results also highlighted that the LAI at effective integrated temperatures from 400 to 600 °Cd affected rice yield components, but these estimation accuracies were not high. The RMSEs for the panicle number, grain number per panicle, grain-filling percentage, and 1000-grain weight were 53.1 m^{-2} (for transplanted plants), 8.0–11.1 grains, 5.4–7.7%, and 0.6 g, respectively. In future research, the applicability of this method for rice grown in other environments and improvements to the estimation accuracy will be studied.

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