Evaluation of Rice Growth Characteristics

Based on Non-destructive Measurements of Leaf Area Index

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Chapter 3 Application of the Evaluation Method to Field Research

Summary

Rice has spread as the dominant staple food in Asia countries, and increase of yield per unit land area is needed. Not only improving rice cultivars but precision farming are strongly recommended, and therefore, gathering information about rice growth characteristics under various environments is considered to be very important for high rice productivity. Especially, leaf area index (LAI), defined as the ratio of leaf area to a given unit of land area, is one of the important biophysical and ecological parameters. Although measurement of LAI dynamics and spatial characteristics is useful to evaluate crop growth and canopy productivity, a laborious work of destructive samplings is commonly necessary. Non-destructive measurement methods with plant canopy analyzers such as LAI-2000 and LAI-2200 (LI-COR) and can be utilized to overcome the disadvantages. However, estimation accuracy of non-destructive measurement is needed to improve. By using frequent measurements and simple mathematical model, evaluation method of rice growth characteristics was developed in this study. This study aims to apply this method to evaluation of genotypic variation and field research in farmers' fields in developing countries.

First, field experiments were conducted for 6 rice cultivars under 5 treatments in 2010 and 2011, and LAI was measured non-destructively one or two times per week with a plant canopy analyzer. Five parameters were calculated by applying non-destructive measurements to four equations such as a logistic equation. By using these parameters, we analyzed cultivar characteristics and the effects of growth environment of LAI dynamics quantitatively. Maximum interception growth rate was considered as

characterizing each cultivar and growth environment because the parameter had no interaction between cultivar and environment. Therefore, this evaluation method is believed to apply to many cultivars and be contributed to investigation of farmers' fields because this method facilitates measuring many plots.

Secondly, experiments were conducted for 5 rice cultivars under 2 fertilizer treatments in 2013 and for 3 cultivars under 3 plant density levels in 2014, and stratified LAI was measured with a plant canopy analyzer. The stratified LAI measurements with a plant canopy analyzer were closely correlated with that by stratified clipping method at every cultivar and treatment. The parameters calculated from the stratified LAI measurements with a plant canopy analyzer and four moment equations numerically represented LAI vertical distribution in each growth stage. The differences in the parameters could also be used to quantify the effect of cultivars, fertilizer treatments and plant density treatments. This evaluation method might help us to understand the effect of canopy structure on photosynthetic ability and dry matter productivity.

This study also parameterized leaf dynamics for a rice diversity research set of germplasm (RDRS) and high yielding cultivars (total 58 cultivars). The significant differences among genotypic groups were observed in relative LAI growth rate and the maximum interception growth rate. High-yielding cultivars released by IRRI had higher values of the maximum interception growth rate, suggesting that the varieties have been improved in terms of canopy development. In contrast, since Takanari and Milyang23 didn't have extreme characteristics in the LAI dynamics, further improvement may be possible.

In farmers' fields in Vientiane province, Lao PDR, we analyzed the LAI dynamics and the relationship between the rice productivity and soil. Because the LAI in the farmers' fields increased almost linearly in this study, a straight-line regression was used for the analysis. The slope of the regression line was defined as LAI growth rate. The rice yield in the farmers' fields was correlated with the maximum LAI. The variability in the maximum LAI was explained by the LAI growth rate but rarely by the effective accumulated temperatures from the estimated transplanting date. The LAI growth rate was associated with the nitrogen and carbon content in the soil. These results suggest that the rice productivity in farmers' fields is governed by the soil fertility through LAI growth, and that LAI monitoring is an effective tool to evaluate the production.

In 77 farmers' paddy fields in the Bakan district, Pursat province, Cambodia, LAI was measured by using a plant canopy analyzer and yield, water status and soil investigations was conducted. The variability in the maximum LAI was mainly explained by that in the LAI growth rate, while the growth period had a significant correlation with the maximum LAI only in the broadcast fields, where earlier planting led to larger LAI. The variability in the LAI was mostly explained by that in the LAI growth rate. The LAI growth rate was affected by water status, planting method (transplanting/broadcasting) and soil condition (C content and C/N ratio), but the effect of N fertilizer was non-significant. These results suggest that the key means to improve rice productivity are earlier broadcasting, water-saving-irrigation methods, effective application of fertilizer and selection of planting methods dependent on the soil fertility.

Synthetic aperture radar (SAR) is proposed as a more suitable method to evaluate rice growth in this area because it is independent from cloud and solar illumination. The relationship between the back scattering coefficient (BSC) in SAR images and LAI of rice. 30 farmers' paddy fields were selected for surveying throughout the growth period in the wet season of 2013, and LAI was measured at 4 time periods before the heading period for each field. X-band SAR images from the COSMO-SkyMed system were used in this study. BSC at 28 of 30 fields was positively correlated with days after transplanting (DAT), and 10 of these results were significant. The increased rate in BSC obtained at the fields where BSC and DAT had a significant correlation, were significantly correlated with LAI growth rate. This finding suggests that if SAR images demonstrate significant increases of BSC against DAT, the increased rate may also represent LAI growth rate, although uncontrollable water levels and weeds occasionally interrupt observation. This study demonstrates the capacity of SAR to evaluate rice production in developing countries.

Although non-destructive measurement was used as replacement of destructive measurement in previous studies, the advantage of non-destructive measurement method was focused in this study. Non-destructive method enables us to measure LAI growth traits easily and to measure the same canopy continuously. By measuring LAI frequently, and applying to simple mathematical model, new evaluation method of rice growth dynamics and canopy structure was developed. Applying this method to various cultivars and rice growth environments reveals genotypic difference of LAI dynamics and variation factor of cultivation environment. In addition to this, I discussed the applicability of SAR to evaluate rice production in developing countries. Combining these methods with another non-destructive measurements might help us to evaluate rice canopy traits efficiently and optimize cultivation management in field level.

Chapter 1

Introduction

1.1 Demand for Rice Production Increase

Oryza sativa L., the most widely grown rice, is the staple food of an estimated 3.5 billion people worldwide (IRRI, 2013). Since the incipience of rice cultivation somewhere in India and/or China (Oka, 1988), rice has spread as the dominant staple food in Asia countries. Indeed, rice production and consumption are among the highest in Asian populations (Mutthaya *et al.*, 2014). Nevertheless, increase of rice production through expansion of rice cultivated area is not promising because farming land is narrowing as a result of urbanization and industrialization. Thus, enhancement of rice production per unit land area is thought to be one of the most important things.

The wet season rainfed lowland is the main rice-producing environment in South and South-east Asia (Schiller, 2006), and here, rice productivity is very low because of limitation of water and soil fertility, flood, weeds, diseases and lodging (Homma *et al.*, 2009; Inamura *et al.*, 2003). Rice productivity per unit land area is mainly determined by growth environment and management (Horie *et al.*, 2003). Therefore, not only improving rice cultivars but precision farming (optimization of cultivation management, water management, fertilizer management and weed management) are strongly recommended to increase rice productivity. In order to optimize cultivation management, gathering information about rice growth characteristics under various environments is necessary.

1.2 Challenges for Quantifying the Rice Growth Characteristics

Information of rice growth characteristics in farmers' fields is limited, and farmers don't always have enough basis to justify the decision making for precision crop management. In crop monitoring for precision farming and yield forecasting, the continuous observation of plant biophysical and ecological status (e.g., leaf area, biomass and nitrogen uptake) is critical (Doraiswamy *et al.*, 2004).

Leaf area index (LAI), defined as the ratio of leaf area to a given unit of land area, is one of the important biophysical and ecological parameters (Vansen *et al*., 2001; Basso *et al*., 2004). LAI represents not only biomass production, but also the most fundamental characteristics of the canopy for subsequent productivity. LAI growth is varied among cultivars and growth environments (Yoshida *et al*., 2007; Setiyono *et al.*, 2008), and monitoring LAI dynamics and spatial characteristic is useful method in evaluating rice growth characteristics under various environments (Maki and Homma, 2014). However, there are few studies of evaluation of LAI dynamics and spatial characteristic by continuous monitoring because a laborious work of destructive samplings is commonly necessary and limited numbers of plants can be used by destructive measurement. Monitoring LAI by remote sensing also has problems of estimation accuracy and resolution (Inoue *et al.*, 2014). These problems have prevented the understanding of environmental response under various environments.

An evaluation of LAI dynamics in various cultivars and/or environments may enable us to distinguish the difference of the growth characteristics and to explore the factors that limit the dry matter production. Thus, parameterization and simulation of LAI dynamics is one of the key methods to quantify the rice growth characteristics in farmers' fields. Relative growth rate and maximum growth rate are the representative parameters of LAI dynamics (Milthorpe and Moorby, 1979; Lizasoa *et al.*, 2003), and therefore these parameters may also represent the effect of cultivars and environments on LAI dynamics.

1.3 Importance of Leaf Area Index (LAI) Measurement by Plant Canopy Analyzer

Methods for LAI measurement can be grouped in two main categories (Jonckheere *et al.*, 2004; Weiss *et al.*, 2004): destructive and non-destructive. Destructive method has disadvantages of requiring a relatively laborious work to collect and measure the samples, and is not suitable for measuring LAI of many cultivars and/or environments. Alternatively, non-destructive measurement methods with plant canopy analyzers such as LAI-2000 (LI-COR), LAI-2200 (LI-COR) and SunScan (Delta-T Devices) can be utilized to overcome the disadvantages. The analyzer also reduces the laboriousness of the destructive measurements for LAI and makes frequent measurements easier.

Several researchers have so far reported indirect measurements of LAI with the plant canopy analyzer for commonbean (*Phaseolus vulgaris* L.), cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), rice (*Oryza spp.*) and soybean [*Glycine max* (L.) Merr.] (Hicks and Lascano, 1995; Dingkuhn *et al*., 1999; Wilhelm *et al*., 2000; de Jesus *et al*., 2001; Stroppiana *et al.*, 2006; Sone *et al.*, 2009). In particular, for rice, Stroppiana *et al.* (2006) and Sone *et al*. (2008) reported that, even in different cultivars and different fertilizer level, LAI-2000 can estimate LAI. Thus, applying frequent and/or stratified measurements by plant canopy analyzer to several equations enables us to estimate parameters such as relative growth rate and maximum growth rate, and to quantify the characteristics of LAI dynamics.

1.4 Application of Synthetic Aperture Radar (SAR)

While application of a plant canopy analyzer is not suitable on a regional scale, satellite based remote sensing is recommended to evaluate wider area. Remote sensing in agricultural research has been widely used to quantify the crop biophysical characteristics (Thenkabail *et al.* 1995; Abou-Ismail *et al*. 2004; Rautiainen 2005). However, it may be difficult to apply such an approach in the monsoon regions of Southeast Asia during the wet season because cloudy conditions often interrupt satellite observation in visible and near-infrared range. (Maki *et al.*, in press). On the other hand, synthetic aperture radar (SAR) can detect the ground surface conditions under any weather condition, and therefore, SAR is more suitable method to evaluate rice growth in the monsoon regions of Southeast Asia (Shao *et al.*, 2001; Zhang *et al.*, 2009). SAR sensors have great potential for the timely assessment of biophysical and ecological variables of rice in Asia (e.g., Le Toan *et al.*, 1997; Ribbes and Le Toan, 1999). Although previous studies investigated the applicability of SAR to estimate LAI (Inoue *et al.*, 2014; Maki *et al.*, 2015), the estimation accuracy has not attained practical level.

1.5 The Objectives of This Study

This study aims to (1) develop a method to quantify the rice growth characteristics by using non-destructive LAI measurement, and (2) to apply the method to evaluation of genotypic variation and field research in farmers' fields.

First, to develop a method to quantify the LAI dynamics by applying several equations, field experiments were conducted for 6 rice cultivars under 5 treatments in 2 years in Kyoto. For the purpose, this study conducted frequent measurements for rice canopy by using plant canopy analyzer and estimated parameters about LAI dynamics by using several equations (Chapter 2-1). Subsequently, to develop a method to quantify the LAI spatial characteristic by moment equations, field experiments were conducted for 3 rice cultivars under 2 fertilizer treatments in 2013 and 3 plant density treatments in 2014. For the purpose, this study conducted stratified measurements by using a plant canopy analyzer and estimated parameters about LAI vertical distribution by using moment equations (Chapter 2-2).

The method developed in Chapter 2-1 was applied to evaluation of genotypic variation (Chapter 3-1) and field research in farmers' fields in Lao PDR (Chapter 3-2) and Cambodia (Chapter 3-3). In Chapter 3-1, I applied the method to 58 cultivars included in *japonica*, *indica* and high-yielding cultivars. In Chapter 3-2, the relationship between the rice productivity and soil was analyzed in farmers' fields in Vientiane province, Lao PDR. Here, rice cultivated under similar management (transplanting, low fertilizer rate and not drought stress). On the contrary, cultivation management is various (transplanting/broadcasting, various fertilizer rate and so on) in Cambodia

(Kodo *et al.*, 2014; Kamoshita *et al.*, 2009). In Chapter 3-3, the effect of cultivation environment and management on LAI growth was investigated in farmers' fields in Pursat province, Cambodia.

Then, applicability of Synthetic Aperture Radar (SAR) to evaluate LAI was discussed based on the results in Chapter 3-2, the relationship between a sequence of SAR images and LAI dynamics of rice was analyzed in farmers' fields in Vientiane province, Lao PDR (Chapter 4).

In Chapter 5, all the results in Chapter 2 - 4 were integrated and I discussed precision crop management thorough quantifying the rice growth characteristics by continuous monitoring of rice and applicability of the method to evaluate in detail and in a wider area by using various non-destructive measurements.

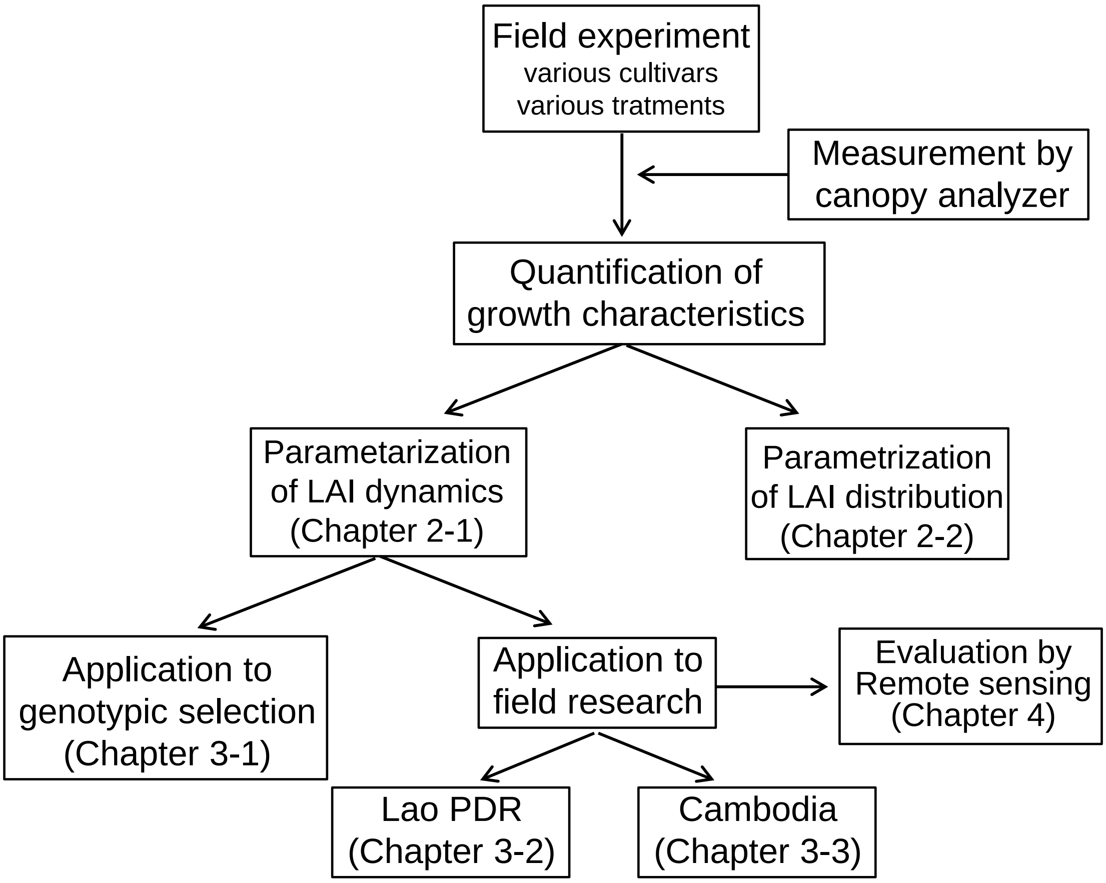


Figure 1. Grand design of this study.

Chapter 2

Parameterization of Leaf Growth Characteristics

Chapter 2-1 Parameterization of Leaf Growth for Rice by Utilizing Plant Canopy Analyzer

2-1.1 Introduction

The efficiency of light capture primarily restricts crop production. Because the efficiency of light capture is primarily determined by leaf growth, monitoring leaf growth is a useful method for evaluating crop growth (Maki and Homma, 2014). The leaf area index (LAI) is a key ecological and biophysical parameter related to leaf growth (GCOS, 2011), and the LAI of rice is different among different cultivars and growth environments (Yoshida *et al.*, 2007; Setiyono *et al.*, 2008). The relative growth rate and maximum growth rate are representative parameters of LAI dynamics (Milthorpe and Moorby, 1979; Lizasoa *et al.*, 2003), and these parameters may therefore also represent the effect of cultivars and environments on leaf growth.

The methods for performing *in situ* LAI measurements can be grouped in two main categories (Jonckheere *et al.*, 2004; Weiss *et al.*, 2004): destructive and non-destructive. Destructive measurement methods involve cutting green leaf blades from plant samples and measure leaf area with an area meter. However, these methods present the disadvantage of requiring relatively laborious work to collect and measure the samples.

Alternatively, non-destructive measurement methods employing plant canopy analyzers such as the LAI-2000 (LI-COR, Inc., Lincoln, NE; LI-COR. 1989, LI-COR. 1992) and SunScan (Delta-T Devices, Cambridge, UK; Potter *et al.*, 1996) instruments can be utilized to overcome the disadvantages of destructive measurement methods. The LAI-2000 is one of the most widely used optical instruments. Researchers have reported indirect measurements of LAI obtained with the LAI-2000 in common bean (*Phaseolus vulgaris* L.), cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.) and soybean [*Glycine max* (L.) Merr.] (Hicks and Lascano, 1995; Dingkuhn *et al.*, 1999; Wilhelm *et al.*, 2000; de Jesus *et al.*, 2001; Stroppiana *et al.*, 2006; Sone *et al.*, 2009). In particular, in rice, Stroppiana *et al.* (2006) and Sone *et al.* (2008) reported that, even among different cultivars and fertilizer levels, the LAI-2000 can be employed to estimate LAI.

The above findings might enable us to easily evaluate leaf growth using the LAI-2000. In this study, we conducted frequent measurements of the rice canopy with the LAI-2000 and estimated parameters by applying several equations to quantify leaf growth. For this purpose, experiments were conducted on 6 rice cultivars under 5 treatments in 2 years. We verified the parameters based on the experimental results and discussed the applicability of this evaluation method to various situations.

2-1.2 Materials and Methods

2-1.2.1 Study Sites and Experimental Design

The field experiment was conducted in experimental fields belonging to Kyoto

University (35°02’N, 135°47’E) and in the Ogura region (34°54’N, 135°46’E) in 2010 and 2011. In the Kyoto University field, three fertilizer treatments were set: a standard fertilizer level (S level), a low fertilizer level (L level) and a no fertilizer level (N level). The fields in the Ogura region were managed under non-fertilizer and non-agrochemical treatment for several years; one field has been managed in this way since 2003 (O_{2003} level) and the other since 2006, although the top-soil of the latter field was converted to the soil of a field where non-fertilized and non-agrochemical treatment has been conducted since 1951 (O_{1951} level). Six cultivars were selected for the experiment to cover diverse characteristics of productivity based on the results of a study conducted in the same field (Matsuyama *et al.*, 2010). Nipponbare and Kasalath are standard cultivars of *japonica* and *indica* rice, respectively (Kojima *et al.*, 2005). Beniasahi and Bei Khe are traditional cultivars of *japonica* and *indica* rice, respectively. Takanari is a high-yielding *indica* cultivar, and B6144F-MR-6-0-0 (B6144F), which was bred for upland cultivation in Indonesia, is also a high-yielding *indica* cultivar (Atlin *et al.*, 2006).

The dates of sowing were 10 May in 2010 and 9 May in 2011. Twenty-four-day-old seedlings were transplanted to the Kyoto University field on 3 June in 2010 and 2 June in 2011, and 27-day-old seedlings were transplanted to the Ogura fields on 7 June in 2010 and 6 June in 2011. In the Kyoto University field, chemical fertilizer with the composition of N-P_2O_5-K_2O = 5-5-5 g m^{-2} was applied as basal fertilization 1 day before transplanting in the S and L level treatments, while fertilization with N-P_2O_5-K_2O = 2.5-2.5-2.5 g m^{-2} was applied twice as top dressing on 22 July and 5 August in 2010 and on 21 July and 3 August in 2011 in the S level treatment. The experiment was conducted with 3 replications; the sizes of the plots were 13.86 m^2 (3.3 m × 4.2 m), 6.75

m^2 (2.7 m × 2.5 m), 11.3 m^2 (2.7 m × 4.2 m) and 6 m^2 (3 m × 2 m) in 2010 and 2011 in the Kyoto University field and in 2010 and 2011 in the Ogura fields, respectively. The planting density was 22.2 plants m^{-2} (0.3 m × 0.15 m) in both the Kyoto University and Ogura fields. Weeds were controlled using agro-chemicals and through hand-weeding in the Kyoto University fields and the Ogura fields, respectively. In the Kyoto University fields, insects and diseases were also controlled with agrochemicals. Although there was no control applied for insects and diseases in the Ogura fields, the damage from these sources appeared to be negligible.

Table 2-1.1 shows the soil nutrient properties of three fields, the Kyoto University field and O_{2003} and O_{1951} in the Ogura region before transplanting in 2010. The Ogura fields exhibited lower nutrient concentrations than the Kyoto University field, except for exchangeable magnesium. Furthermore, O_{1951} presented much lower values in terms of total nitrogen and available phosphorus than O_{2003}.

Fig. 2-1.1 shows the seasonal changes in the mean temperature during the rice growing periods in 2010 and 2011, measured in the Kyoto University field.

Table 2-1.1. Soil nutrient properties of Kyoto fields, O_{2003} level and O_{1951} level. Soil condition includes cation exchange capacity (CEC) (cmol kg^{-1}), nitrogen (mineralizable N) (mg 100 g^{-1}), phosphorus (available P) (mg 100g^{-1}), potassium (exchangeable K) (cmol kg^{-1}), magnesium (exchangeable Mg) (cmol kg^{-1}), and calcium (exchangeable Ca) (cmol kg^{-1}).

	CEC (cmol kg^{-1})	N (mg 100g^{-1})	P (mg 100g^{-1})	K (cmol kg^{-1})	Mg (cmol kg^{-1})	Ca (cmol kg^{-1})	pH
Kyoto	12.11	11.13	298.6	0.43	0.36	2.46	4.7
O_{2003} level	12.08	9.73	103.3	0.19	0.59	1.87	4.9
O_{1951} level	9.56	7.18	42.9	0.12	0.55	1.92	5

CEC, K, Mg and Ca were measured with the ammonium acetate extract method at pH 7.0.
N was determined by a 2-week anaerobic incubation at 30ºC as the amount of NH3-N extracted with 10 % KCl solution.
P was measured by Bray No.2.
pH in 1:1 H_2O.

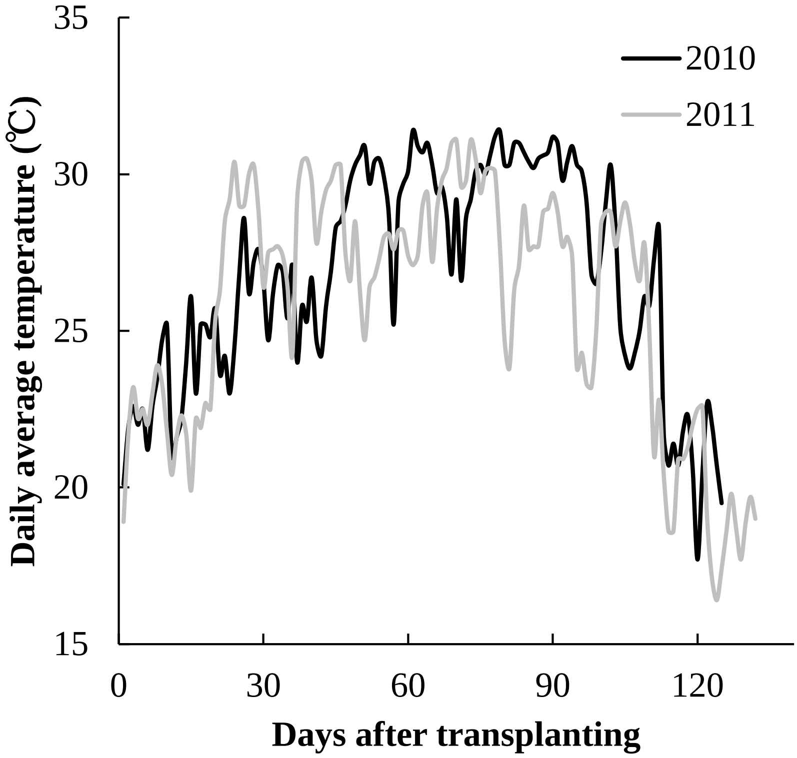


Figure 2-1.1. Difference of daily average temperature during growth period in 2010 and 2011.

2-1.2.2 Measurements

LAI was measured one or two times per week from three weeks after transplanting to maturing with an LAI-2000 (LI-COR, Inc., Lincoln, NE; LAI-2000 measurement). The measurements were conducted under scattered light conditions, such as after sunrise, before sunset or on overcast days, with a single sensor mode in a sequence of two above, four below the canopy at each plot. To reduce the influence of the adjacent plots and the operator, a 90° view-cap was applied to the optical sensor. Diffuse non-light intercepted (DIFN) values obtained from the LAI-2000 were also used in the analysis.

Twenty seedlings were sampled at transplanting for each cultivar. Four plant samples were harvested from each plot at 3 and 6 weeks after transplanting, 9 weeks after transplanting (only for Bei Khe), 2 weeks before heading, during heading, 2 weeks after heading and at maturing (a total of 7 times for Bei Khe and 6 times for the other cultivars). Plant samples were harvested from an area where it was expected that harvesting would not affect the LAI-2000 measurements. The samples were chosen to represent the rice canopy based on the number of tillers among twenty plants in the area of the LAI-2000 measurements. Green leaf blades were separated from the plant samples, and their area was measured using an area meter (LI3080, LI-COR; destructive measurement). The destructive measured leaf area index (LAI_{des}) was calculated by dividing the measured leaf area by the planting area.

2-1.2.3 Parameter Estimation for Leaf Growth

The LAI and DIFN values obtained from the LAI-2000 measurements were analyzed to characterize their dynamics. Parameters describing these dynamics were obtained by applying the following 4 mathematical growth models, in which the independent variable was the effective accumulated temperature (T; ºC d; base temperature of 10 ºC). Transplanting date was defined as T = 0.

First, LAI dynamics during the early growth stage were approximated using the following exponential function (Milthorpe and Moorby, 1989; Lafarge and Tardieu, 2002):

$$LAI = \alpha\, e^{\beta T} \qquad (1)$$

where α and β are regression coefficients: α corresponds the initial LAI value at T = 0 ($iLAI_{exp}$); and β (ºC^{-1}) is the parameter referred to as the relative leaf growth rate (RGR). The LAI values which were recorded until T reached 700 (T < 700; approximately until 6 weeks after transplanting) were used to estimate the parameters.

Second, LAI dynamics during the middle growth stage were approximated with the following linear function (Milthorpe and Moorby, 1989; Lafarge and Tardieu, 2002):

$$LAI = A\, T + B \qquad (2)$$

where A and B are regression coefficients: A is the parameter for the LAI growth rate (LGR); and B corresponds the initial LAI value at T = 0. LAI values recorded during 400 < T < (T at heading) - 120 (approximately from 4 weeks after transplanting until 1 week before heading) were used to estimate the parameters.

Third, LAI dynamics from transplanting until heading were approximated using a logistic curve with an asymptotic line of y = γ (Fig. 2-1.2; Milthorpe and Moorby, 1989; Chen *et al.*, 2014) :

$$LAI = \gamma / (1 + \delta\, e^{-\varepsilon T}) \qquad (3)$$

where γ, δ and ε are regression coefficients: γ is the parameter representing the maximum LAI (MLAI); γ / (1 + δ) corresponds the initial LAI value at T = 0 ($iLAI_{log}$); and $\gamma\ \delta$ / 4 (ºC^{-1}) is the parameter representing the maximum LAI growth rate (MLGR). LAI until heading was used to the estimate parameters.

Fourth, the dynamics of diffusive light interception, defined as (1-DIFN), were also approximated using a similar type of logistic curve to the employed for LAI dynamics, but asymptotic line was y = 1 (Milthorpe and Moorby, 1989):

$$1\text{-DIFN} = 1 / (1 + \zeta\ e^{-\eta T}) \qquad (4)$$

where ζ and η are regression coefficients: 1 / (1 + η) corresponds to the initial value of (1-DIFN) at T = 0; and ζ / 4 (ºC^{-1}) represents the maximum interception growth rate (MIGR). DIFN until heading was used to estimate the parameters.

In addition to Eq. 4, the effective accumulated temperature when the rate of intercepted light (1 – DIFN) exceeded 0.7 ($T_{0.7}$) was obtained through linear interpolation of (1 – DIFN) against T. $T_{0.7}$ represents the effective accumulated temperature required to achieve full coverage of the canopy.

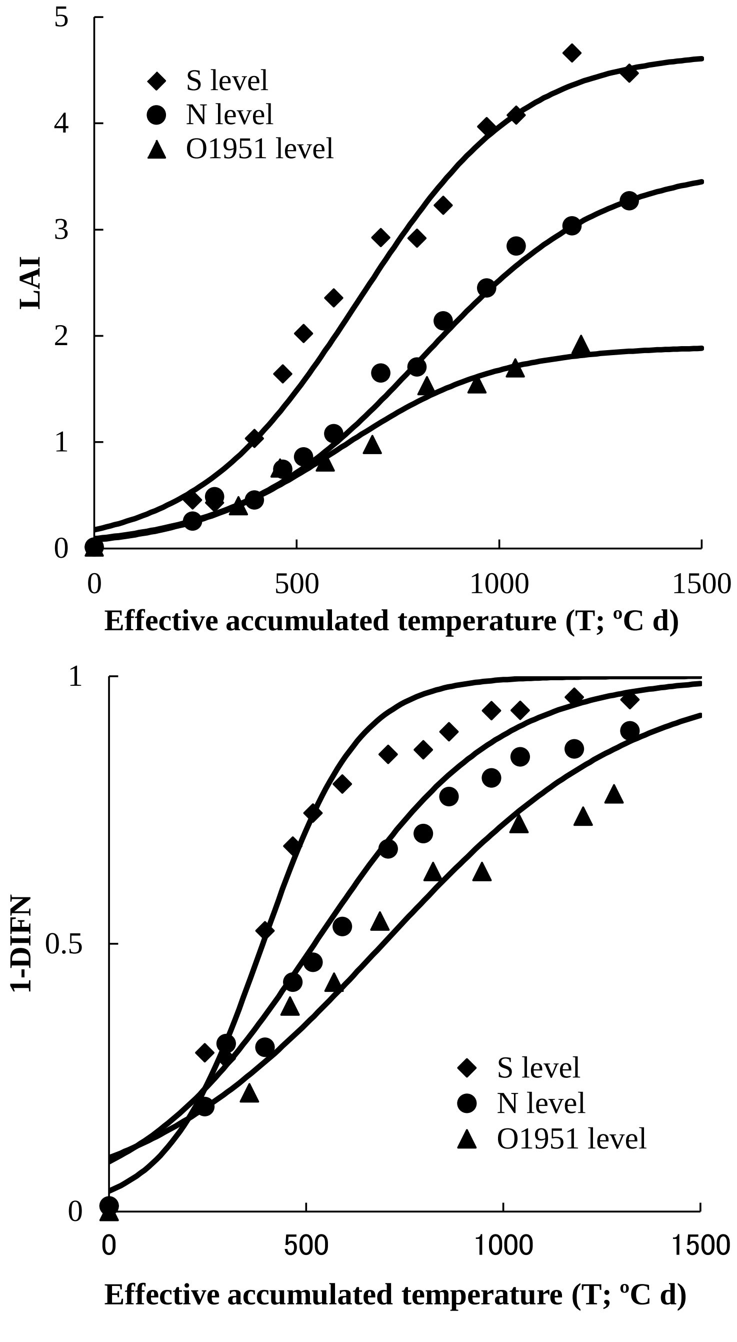


Figure 2-1.2. Relationship between effective accumulated temperature (T; ºC d) and (a) LAI and light interception (1- DIFN) for Nipponbare at S, N and O_{1951} level. Solid lines are regression logistic curves.

2-1.2.4 Statistical Analysis

The experimental plots were arranged by split plot and randomized complete block design with 3 replications in Kyoto University fields, where main treatments were fertilizer levels and sub treatments were cultivars. Randomized complete block design for cultivars was arranged with 3 replications to each field (O_{2003} and O_{1951}) in Ogura region.

The parameters in Eq. (1), (3) and (4) were estimated by using the modified Gauss-Newton iterative procedure for non-linear least squares method. The parameters in Eq. (2) were estimated by linear least square method. 3-way analysis of variance (ANOVA) was applied for the parameters to test main effects and their interactions:

$$\text{Parameters} = \text{Year (Y)} + \text{Cultivar (C)} + \text{Treatment (T)} + Y \times C + C \times T + T \times Y + Y \times C \times T \quad (5)$$

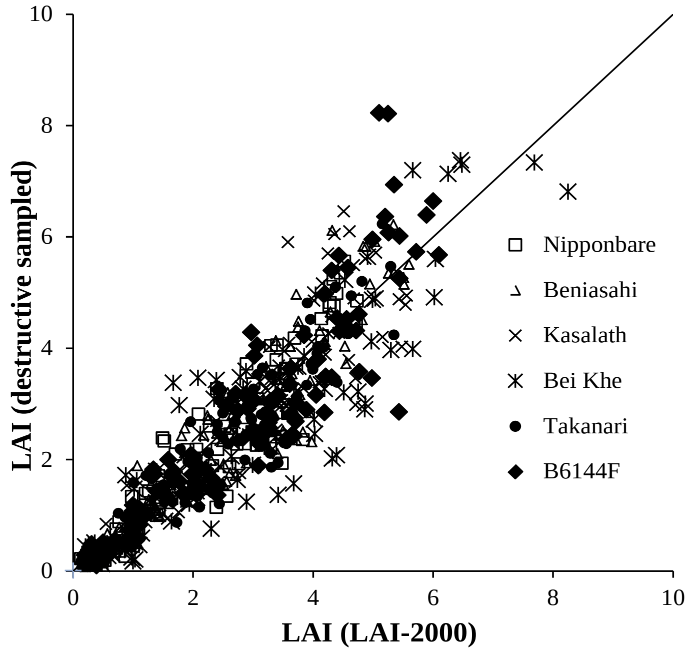
All the analyses were carried out using GLM procedure of SAS.

2-1.3 Results

2-1.3.1 Validation of LAI by LAI-2000 Measurement

Fig. 2-1.3a shows the relationship between the LAI determined based on LAI-2000 measurements and the LAI_{des} determined through destructive measurements at 3 weeks after transplanting, 6 weeks after transplanting, 9 weeks after transplanting (only for Bei Khe), 2 weeks before heading and at heading. The LAI values determined using the LAI-2000 agreed well with the LAI_{des} until heading (R^2 = 0.86, Slope = 1.001, Intercept = -0.165). However, the LAI values determined through LAI-2000 measurements after heading (at 2 weeks after heading) were significantly higher than LAI_{des} obtained through destructive measurements (Fig. 2-1.3b).

(a)



(b)

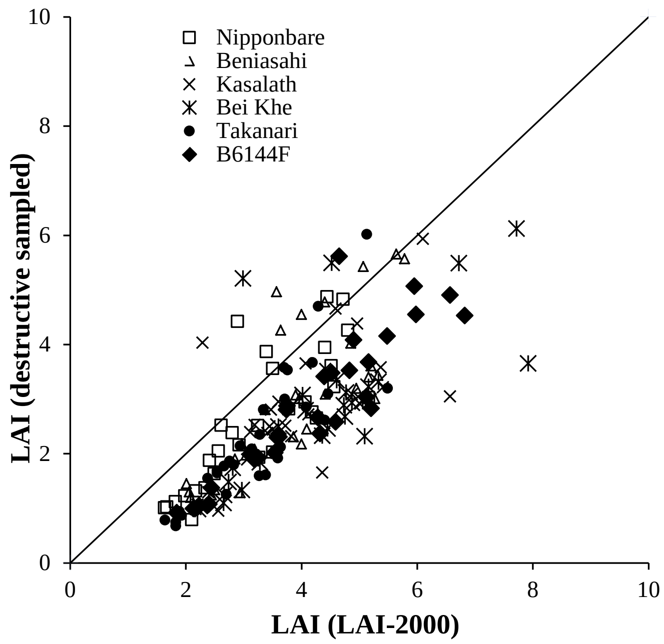


Figure 2-1.3. Difference in LAI between LAI-2000 measurements and destructive measurements. Destructive measurements were measured at (a) 3 weeks after transplanting, 6 weeks after transplanting, 9 weeks after transplanting (only for Bei Khe), 2 weeks before heading, heading and (b) 2 weeks after transplanting.

2-1.3.2 Parameter Estimation

Table 2-1.2. Analysis of variance of nine parameters. RLGR represents the relative early LAI growth rate calculated with Eq. (1) (°C^{-1}). $iLAI_{exp}$ represents initial LAI at T = 0 calculated with Eq. (1). MLAI represents the maximum LAI calculated with Eq. (3). MLGR represents the maximum LAI growth rate calculated with Eq. (3) (°C^{-1}). $iLAI_{log}$ represents initial LAI at T = 0 calculated with Eq. (3). MIGR represents the maximum interception growth rate (°C^{-1}) calculated with Eq. (4). LGR represents the LAI growth rate calculated with Eq. (2) (°C^{-1}); $T_{0.7}$ represents the effective accumulated temperature when the interception reaches 0.7 (°C).

	RGR ($\times 10^{-3}$)	$iLAI_{exp}$	MLAI	MLGR ($\times 10^{-3}$)	$iLAI_{log}$	MIGR ($\times 10^{-3}$)	LAI at heading	LGR ($\times 10^{-3}$)	$T_{0.7}$ (°C)
Year									
2010	9.65	0.013	3.81	6.44	0.110	1.70	3.60	3.92	595
2011	7.93	0.032	3.70	5.44	0.110	1.51	3.36	3.50	672
Cultivar									
Nipponbare	8.34d	0.022bc	3.58bc	4.97c	0.109	1.33c	3.04c	3.60b	688d
Beniasahi	8.75bc	0.020c	3.63bc	5.33c	0.115	1.49bc	3.54b	3.11c	666cd
Kasalath	9.28a	0.022b	3.69bc	7.98a	0.064	2.00a	3.66b	4.88a	549a
Bei Khe	8.95b	0.024b	4.21a	5.39c	0.171	1.56bc	4.25a	3.20c	619b
Takanari	8.85bc	0.021bc	3.38c	5.58b	0.088	1.48bc	2.83c	3.84b	655bcd
B6144F	8.58cd	0.027a	4.02ab	6.39b	0.113	1.76ab	3.57b	3.65b	626bc
Treatment									
S level	9.90a	0.029a	4.97a	8.12a	0.162a	2.44a	5.63a	4.78a	438a
L level	9.86a	0.031a	4.26b	8.52a	0.117b	2.28a	4.26b	3.82bc	437a
N level	8.45b	0.022b	3.61c	4.52c	0.099c	1.21b	3.12c	3.58c	672b
O_{2003} level	8.31b	0.016c	3.52c	5.37b	0.090cd	1.31b	2.73d	4.01b	677b
O_{1951} level	7.43c	0.015c	2.43d	3.19d	0.082d	0.78c	1.67e	2.38d	945c
Year	<0.01	<0.01	ns	<0.01	ns	<0.01	ns	<0.01	<0.01
Cultivar	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Treatment	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Y × C	<0.01	<0.01	ns	ns	ns	ns	<0.01	ns	<0.05
Y × T	<0.01	<0.01	<0.05	<0.01	<0.01	ns	ns	ns	<0.01
C × T	ns	<0.05	ns	<0.01	<0.01	ns	<0.05	<0.05	ns
Y × C × T	ns	ns	ns	ns	<0.01	ns	ns	ns	ns

The increase in the LAI until 6 weeks after transplanting was approximated with an exponential curve (Eq. (1)) (R^2 = 0.73 - 1.00, 0.91 on average), while the increase in the LAI until heading was approximated with a logistic curve (Eq. (3)) (R^2 = 0.90 – 0.99, 0.96 on average), and the dynamics of light interception until heading were also approximated with a logistic curve (Eq. (4)) (R^2 = 0.79 - 1.00, 0.95 on average). The results of ANOVA and the least squares means of representative parameters in Eq. (1) to (4), together with the LAI at heading (destructive measurement) and $T_{0.7}$, are shown in Table 2-1.2 All of the parameters were significantly lower at the O_{1951} level.

β (m^2 m^{-2} C^{-1}) in Eq. (1), indicating the relative leaf growth rate (RGR), ranged from 6.00×10^{-3} (B6144F at the O_{1951} level in 2010) to 11.32×10^{-3} (Kasalath at the S level in 2011). RGR showed a significant interaction between the year and cultivar and between the year and treatment. RGR was significantly higher under the basal fertilizer treatment. RGR also showed significantly higher values in the *indica* cultivars than in Nipponbare (standard *japonica* cultivar) (Table 2-1.2). α in Eq. (1), indicating the initial LAI value at T = 0 ($iLAI_{exp}$), ranged from 0.009 (Takanari at the O_{1951} level in 2010) to 0.067 (Kasalath at S level in 2011).

γ (m^2 m^{-2}) in Eq. (3), indicating the maximum LAI (MLAI), ranged from 1.78 (Takanari at the O_{1951} level in 2010) to 6.60 (Bei Khe at the S level in 2010). MLAI showed a significant interaction only between the year and treatment. MLAI at the S level was significantly higher than in the other treatments. γ δ/ 4 in Eq. (3), indicating the maximum LAI growth rate (MLGR), ranged from 3.4×10^{-3} (Bei Khe at the O_{1951} level in 2011) to 13.1×10^{-3} (Kasalath at the L level in 2010). MLGR showed a significant interaction between the year and treatment and between the cultivar and treatment. MLGR was significantly higher under basal fertilizer treatment. MLGR also showed higher values in the Kasalath and high-yielding cultivars than among the other cultivars. γ / (1 + δ), indicating the initial LAI value at T = 0 ($iLAI_{log}$), ranged from

0.006 (Nipponbare at O_{1951} level in 2010) to 0.283 (Bei Khe at S level in 2010).

$\zeta / 4$ in Eq (4), the maximum interception growth rate (MIGR), ranged from 0.64×10^{-3} (Beniasahi at the O_{1951} level in 2010) to 3.3×10^{-3} (Kasalath at the S level in 2010). The interaction was not significant for MIGR. MIGR values were higher under basal fertilizer treatment. MIGR also showed higher values in Kasalath and B6144F than in Nipponbare.

2-1.3.3 Relationships between Parameters

ANOVA showed that the significance of the effect of year, cultivar, treatment and their interactions was consistent between the MLAI and LAI_{des} determined at heading through destructive measurements, as was that between MLGR and LGR (LAI growth rate; A in Eq. (2)) and between MIGR and $T_{0.7}$ (Table 2-1.2). MLAI was significantly correlated with the LAI determined at heading through destructive measurements (R^2 = 0.701) (Fig. 2-1.4). However, the slope of this line was significantly different from 1, and the intercept was significantly different from 0. When the LAI determined at heading through destructive measurements was higher, MLAI tended to be underestimated, while when the LAI determined at heading through destructive measurements was lower, MLAI tended to be overestimated. MLGR was closely related to LGR, except for at the L level (R^2 = 0.64) (Fig. 2-1.5). At the L level, MLGR was higher than LGR. MIGR was significantly inversely proportional to $T_{0.7}$ (R^2 = 0.685) (Fig. 2-1.6). Both $iLAI_{exp}$ and $iLAI_{log}$ were not significantly correlated with the actual LAI at transplanting (data not shown).

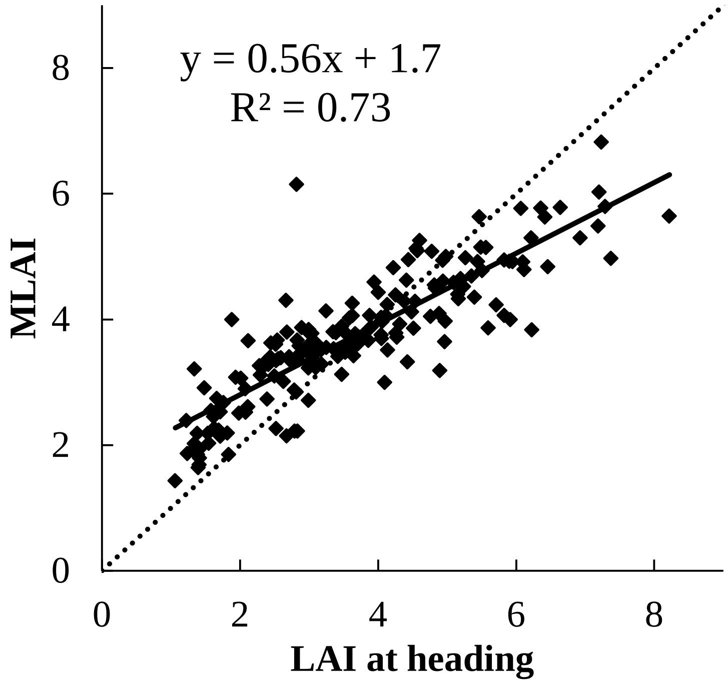


Figure 2-1.4. Relationship between MLAI (maximum LAI calculated by Eq. (3)) and LAI at heading by destructive measurement. Dotted line represents 1 : 1 line. A straight line is the regression line (y = 0.56 x + 1.7, R^2 = 0.74).

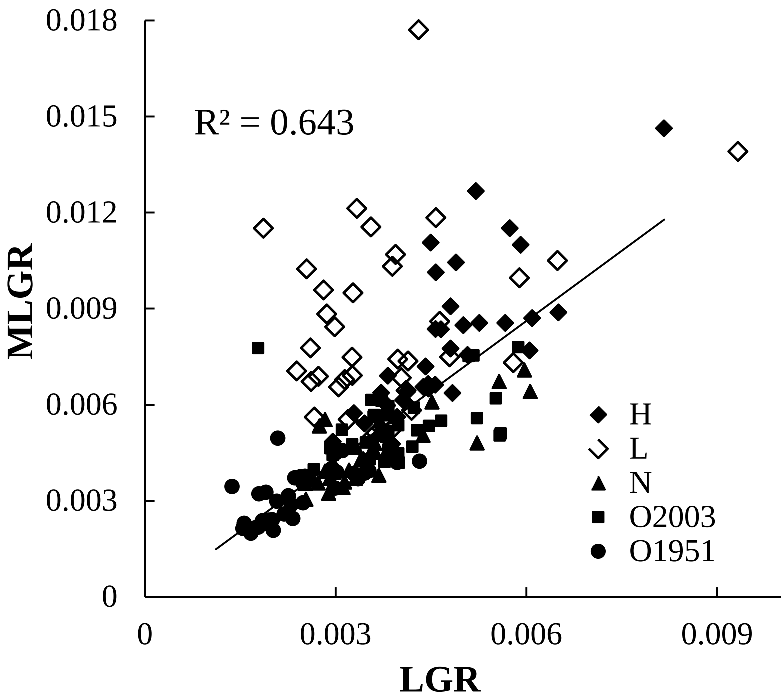


Figure 2-1.5. Relationship between LGR (LAI growth rate) and MLGR (maximum LAI growth rate). H; the plot at standard high fertlizer level, L; represents low fertilizer level, N; represents no fertilizer level.

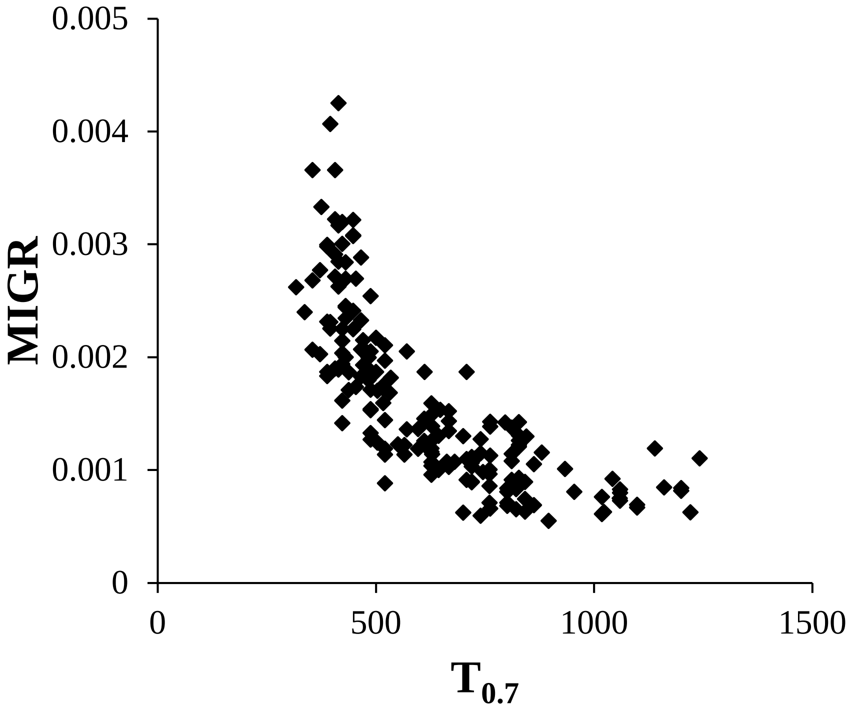


Figure 2-1.6. Relationship between MIGR (maximum interception growth rate) and $T_{0.7}$ (effective accumulated temperature when (1-DIFN) exceeded 0.7).

2-1.4 Discussion

In this study, a dynamic analysis of leaf growth was conducted using LAI and DIFN values obtained with a plant canopy analyzer, the LAI-2000 (LI-COR, Inc., Lincoln, NE). Fig. 2-1.3 shows that the LAI determined from the LAI-2000 measurements was consistent with the LAI_{des} determined through destructive measurements until heading under the experimental conditions, and the measurement error was 28.8 %. This measurement error is similar to that obtained in previous results (Stroppiana *et al.*, 2006, Sone *et al.*, 2008). Frequent measurements followed by approximation using functions are considered to decrease error variance. The results of curve fitting to Eq.

(1) – (4) also indicated that the parameters of these equations may be sufficiently representative to quantitate the dynamics of leaf growth numerically and to characterize each cultivar and treatment well in each stage.

The values of the representative parameters in Eq. (1) – (4) were lower at the O_{1951} level compared with the other treatments (Table 2-1.2). The lower values may represent lower nitrogen and phosphorus concentrations in soil solutions during the growth period at the O_{1951} level (Hara *et al.*, 2013). Basal fertilizer application at the L level increased the parameter values compared with those recorded at the N level. Additional top dressing of fertilizer at the S level did not increase the growth rate but did significantly increase MLAI compared with the L level. The results indicated that the basal fertilizer application enhanced leaf growth, and the additional fertilizer mainly extended the period of enhancement, leading to a higher LAI.

All of the parameters also varied among the cultivars. *Indica* cultivars tend to develop the LAI earlier than *japonica* cultivars (Dinkugn *et al.*, 1999). In this study, the parameters of Nipponbare and Beniasahi (*japonica* cultivars) also showed lower values in growth rate and maximum LAI, while Kasalath (*indica* cultivar) exhibited a higher growth rate and Bei Khe (*indica* cultivar) exhibited a higher maximum LAI. The interactions between the cultivars and environments (years or treatments) for MLAI and MIGR were not significant (Table 2-1.2). This result shows that these parameters calculated from logistic curves are more stable for evaluating the ability of cultivars or growth environments than LAI at heading and $T_{0.7}$.

MLAI was not significantly different between years. This result may have arisen because the maximum LAI is decided mostly by the effective accumulated temperature until heading, which was similar between years. In contrast, three parameters, RGR, MLGR and MIGR, varied between years, suggesting that growth rates are determined not only by the effective accumulated temperature but also by solar radiation and temperature dynamics. Analyses of leaf growth in multi-year and multi-site studies will be needed to quantify the effect of weather conditions more precisely.

Logistic regression was considered to be appropriate for estimating leaf growth, as the coefficient of determination (R^2) of the logistic regression was high (Eq. (3); ave. 0.96, Eq. (4); ave. 0.95). Three parameters, MLAI, MLGR and MIGR, were calculated through logistic regression in this study. MLAI was correlated with the LAI determined at heading through destructive measurements, but the regression line of the relationship was not 1:1. This result indicates that when a logistic line is used, the maximum LAI can be estimated relatively, but not absolutely. MLGR was closely associated with LGR, except for at the L level. At the L level, the R^2 value for the logistic regression was much higher than that for a straight line, and MLGR was therefore believed to be a more suitable parameter for evaluating leaf growth at extreme conditions, such as the L level, where only basal fertilizer was applied. MIGR showed nearly the same values under conditions where $T_{0.7}$ was more than 800 ºC, and thus, MIGR might not be sufficient for evaluating interception growth under extremely poor soil conditions, such as the O_{1951} level.

The present study indicated that leaf growth of rice could be well explained by exponential and logistic functions, although estimation of initial LAI were not accurate. Birch (1999) and Yin *et al.* (2003) proposed a generalized logistic sigmoid growth equation and a beta growth function to describe plant growth, respectively. Application of such functions will be considered in a further study.

2-1.5 Conclusion

In this study, the dynamics of leaf growth were represented numerically by the parameters in several mathematical growth models, for which the data obtained by frequent measurement of plant canopy analyzer were used. Especially, MLAI and MIGR were considered as characterizing each cultivar and growth environment because these two parameters had no interaction between cultivar and environment. The difference in leaf growth among cultivars or environments is easily quantified by this method, which will be utilized at many occasions. Therefore, this method is believed to apply to many cultivars and is expected to be contributed to evaluation of growth environments because this method facilitates measuring many plots.

Chapter 2-2 Continuous Monitoring of Vertical Distribution of LAI in Rice by Using Plant Canopy Analyzer

2-2.1 Introduction

Crop canopy structure depends on the genetic characteristics and its physiological and biochemical processes, as well as its planting pattern and growth status (Guo *et al.*, 2015). Canopy structure directly influences the light distribution and leaf physiological characteristics in crop canopies (Yu *et al.*, 1997; Stewart *et al.*, 2003). Leaves and the other photosynthetic organs in crop canopies serve both as solar energy collectors and as exchangers of the plant community (Campbell and Norman, 1989). Especially, leaf area index (LAI) [m^2 m^{-2}] is one of the most important parameters in climatic, ecological and agronomical research studies (Stroppiana *et al.*, 2006), so monitoring the LAI vertical distribution is a meaningful method to analyze the canopy photosynthesis and biomass productivity.

Since Monsi and Saeki (1953) first applied the Beer-Lambert law describing random distribution of light to predict light transmission in the plant canopy, several studies have investigated the vertical distribution for crops such as maize (*Zea mays* L.), rice (*Oryza spp*.) and soybean [*Glycine max* (L.) Merr.] (Sinoquet *et al.*, 1991: Shiratsuchi *et al.*, 2006: Blad and Baker, 1972). Monitoring and quantification of dynamics of LAI vertical distribution are considered to be a key approach to analyze the crop growth dynamics and the light energy use (Hirose and Werger, 1987). However, a big effort and a laborious work of destructive samplings are commonly necessary to conduct destructive measurement of LAI vertical distribution (stratified clipping method), limiting the sequential information.

Non-destructive measurement methods with a plant canopy analyzer can be utilized to overcome the disadvantages. Actually, in rice, Stroppiana *et al.* (2006) and Sone *et al.* (2008) reported that, even among different cultivars and fertilizer levels, the plant canopy analyzer can be employed to estimate LAI. Chapter 2-1 measured LAI frequently by plant canopy analyzer and then parameterized the LAI dynamics by using mathematical functions. By using a plant canopy analyzer, continuous monitoring of LAI vertical distribution is expected to be simplified and non-destructively.

In this study, we used a plant canopy analyzer, LI-COR LAI-2200, which is a non-destructive and non-laborious equipment to conduct non-destructive stratified measurements and then, the statistical moment equations were applied to obtain 4 parameters for evaluation of LAI vertical distribution. For this purpose, field experiments were conducted for 5 rice cultivars under 2 fertilizer treatments in 2013 and for 3 cultivars under 3 plant density treatments in 2014.

2-2.2 Materials and Methods

2-2.2.1 Study Sites and Experimental Design

The field experiments were conducted in the paddy fields at the experimental farm belonging to Graduate School of Agriculture, Kyoto University (35°02’N, 135°47’E, 65 m altitude) in 2013 and 2014.

In 2013, five cultivars were selected for the experiment to cover diverse characteristics of canopy structure. Shennong265 is erect panicle type of *japonica* cultivars. Nipponbare and Kasalath are standard cultivars of *japonica* and *indica* rice, respectively (Kojima *et al.*, 2005). Takanari is a high yielding *indica* cultivars. Kamenoo is traditional cultivars of *japonica*. Twenty-nine-day-old seedlings were transplanted on 6 June. Each plot was 12.15 (4.5 × 2.7) m^2, and planting density was 22.2 plants per m2 (0.3 m × 0.15 m) with one plant per hill. Two fertilizer treatments, low nitrogen fertilizer (LN) level (N: P_2O_5: K_2O = 3: 2.3: 2.5) and high nitrogen fertilizer (HN) level (N: P_2O_5: K_2O = 17: 14.4: 16.1) were set. Tall cultivars of Kamenoo and Kasalath were grown only LN level to avoid lodging.

In 2014, three cultivars, Nippobare, Takanari and Shennong265 were grown. Chemical fertilizers were applied (N: P_2O_5: K_2O = 20: 16.6: 19). Three plant density treatments, high plant density (HD) level (44.4 plant m^{-2}), normal plant density (ND) level (22.2 plant m^{-2}) and low plant density (LD) level (16.7 plant m^{-2}) were set. Twenty-eight-day-old seedlings were transplanted on 5 June. Each plot was 10 m^2 (2.4 × 4.2 m).

In 2013 and 2014, the randomized block design was established with 3 replications, and water, weeds, insects and disease were controlled as required to avoid yield loss.

2-2.2.2 Measurements

LAI was measured one or two times a week from two weeks after transplanting to heading by a plant canopy analyzer (LI-COR LAI-2200) every 10 cm vertical height in each plot. The measurements were conducted under scattered light conditions, such as after sunrise, before sunset or overcast days, with a single sensor mode in a sequence of two above, four below canopy at each plot. To reduce the influence of the adjacent plots and the operator, a 90° view-cap was applied to the optical sensor.

Stratified clipping was conducted for two hills at panicle initiation stage and heading stage with one replication in order to validate LAI-2200 stratified measurements. The depth of each stratum was fixed at 10cm. Plant samples were harvested from an area where it was expected that harvesting would not affect the LAI-2200 measurements. The samples were chosen to represent the rice canopy based on the number of tillers among 12 plants in the area of the LAI-2200 measurements. Rice plant sample of each stratum was separated into green leaf blades and stems (culms, panicles and dead tissues). Leaf area (LA) was measured by green leaf blades by using an area meter (LI3080, LI-COR). The leaf area index (LAI) was calculated by dividing the measured leaf area was by the planting area.

2-2.2.3 Data Analysis

LAI vertical distribution was analyzed by calculating 4 parameters in this study. The four parameters (a_1, a_2, a_3, a_4) describing LAI vertical distribution were obtained by the following five statistical moment equations.

$$a_1 = \sum_{i=1}^{k} h_i \ LAI_i \qquad (1)$$

where a_1 represents the mean of LAI vertical distribution, i represents each stratum, h_i represents relative height of ith stratum and LAI_i represents relative LAI of ith stratum.

$$m_r = \sum_{i=1}^{k} (h_i - a_1)^r \, LAI_i \qquad (2)$$

m_r represents r-th moment.

$$a_2 = m_2 \qquad (3)$$

a_2 represents the variance of LAI vertical distribution

$$a_3 = m_3 /(m_2)^{3/2} \qquad (4)$$

a_3 represents the skewness of LAI vertical distribution.

$$a_4 = m_4 / m_2^{\ 2} \qquad (5)$$

a_4 represents the kurtosis of LAI vertical distribution.

The experimental plots were arranged by split plot and randomized complete block design with 3 replications in Kyoto University fields, where main treatments were fertilizer levels in 2013 and plant density treatments in 2014 and sub treatments were cultivars. 3-way analysis of variance (ANOVA) was applied for the parameters to test main effects and their interactions (Eq. (6); 2013, Eq. (7); 2014):

Parameters = Period (P) + Cultivar (C) + Fertilizer (F) + Y × C + C × F + F × Y + Y × C × F (6)

Parameters = P + C + Density (D) + P × C + C × D + D × P + P × C × D (7)

2-2.3 Results

2-2.3.1 Validation of Stratified LAI Using LAI-2200 Measurements

Fig. 2-2.1 shows the relationship between the LAI readings of a plant canopy analyzer in the non-destructive stratified measurements and the LAI determined by stratified clipping method of more than 10 cm above the measuring point at panicle initiation (PI) stage and heading stage in 2013 and 2014 ((a) PI, 2013; (b) Heading, 2013; (c) PI, 2014; (d) Heading, 2014). The LAI determined using the LAI-2200 stratified measurement agreed well with the LAI by stratified clipping method of more than 10 cm above the measuring point at both stages and years ($R^2 < 0.85$) (Fig. 2-2.1). Among cultivars, treatments and periods, the measurement error was not so much different, and RMSE and rRMSE between LAI by LAI-2200 and LAI by stratified clipping method of all plots were 0.614 and 0.216, respectively (Table 2-2.1).

Table 2-2.1. Differences in root mean square error (RMSE) and relative root mean square error (rRMSE) between LAI by LAI-2200 and LAI by stratified clipping method among years, periods, cultivars, fertilizer treatments and plant density treatments.

		RMSE	rRMSE
All		0.614	0.216
Year			
	2013	0.518	0.219
	2014	0.637	0.202
Cultivars			
	Shennong265	0.473	0.220
	Nipponbare	0.702	0.196
	Takanari	0.694	0.230
	Kasalath[1)]	0.441	0.161
	Kamenoo[1)]	0.515	0.299
Fertilizer			
	High	0.629	0.166
	Low	0.547	0.292
Plant density			
	High	0.656	0.220
	Middle	0.594	0.216
	Low	0.656	0.227
Periods			
	PI	0.552	0.228
	Heading	0.676	0.206

1) only in low nitrogen fertilizer level in 2013.

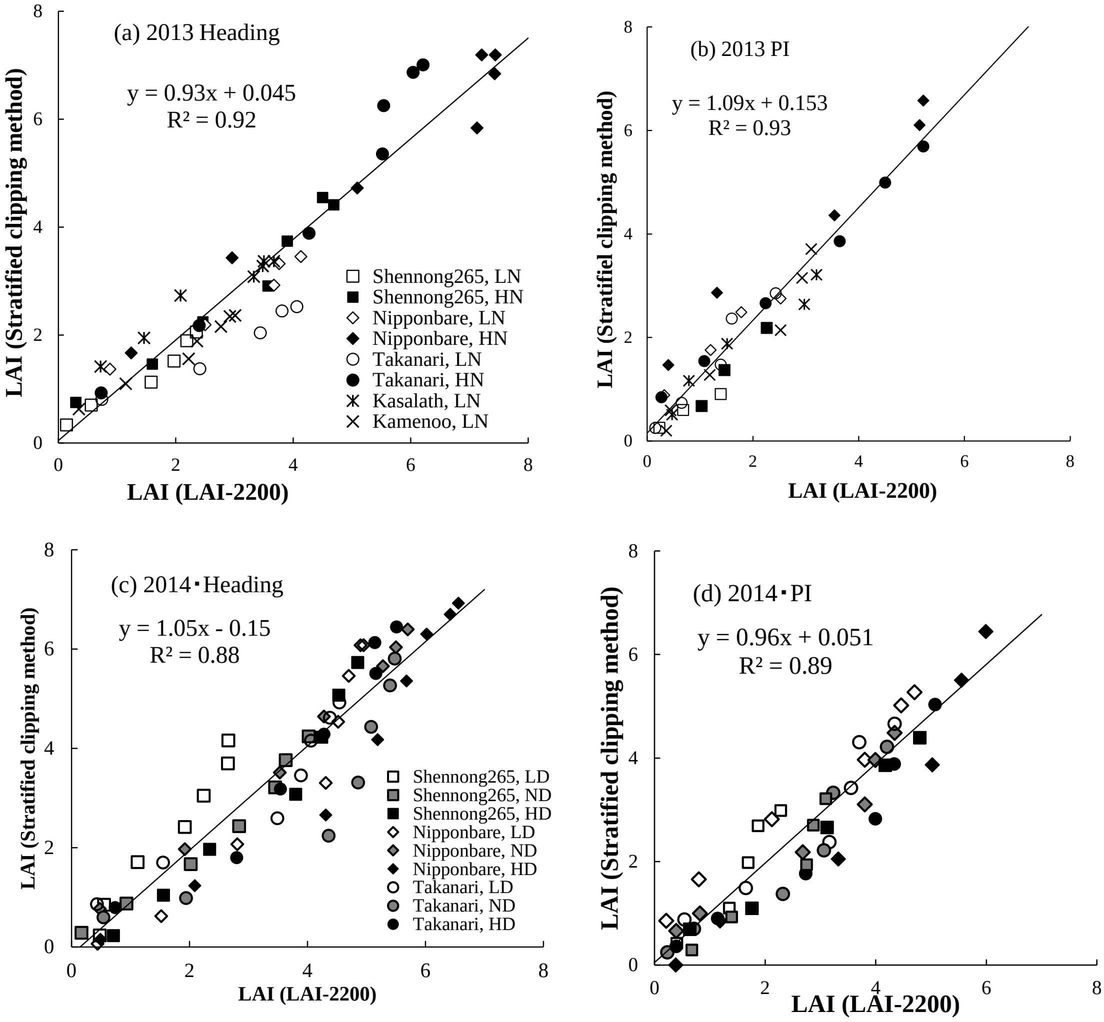


Figure 2-2.1. The relationship between the LAI readings of plant canopy analyzer in the non-destructive stratified measurements and the LAI determined by stratified clipping method of more than 10 cm above the measuring point (a) at heading stage in 2013, (b) at panicle initiation (PI) in 2013, (c) at heading stage in 2014 and (d) at PI in 2014. (a), (b): Low and High represents fertilizer level. (c), (d): Low, Normal and High represents plant density level. The solid line is the regression line.

2-2.3.2 Parameter Estimation for Leaf Area Distribution

Fig. 2-2.2 shows the result of the periodical change of every 10 cm stratified LAI with plant growth for Shennong265 and Nipponbare at high fertilizer level in 2013. LAI of erect panicle type of rice (Shennong265) showed relatively vertically-uniform distribution until heading, while those of Nipponbare and Takanari showed non-uniform distribution: higher stratum had larger LAI. At heading stage, the tendency became more clear (Fig. 2-2.3).

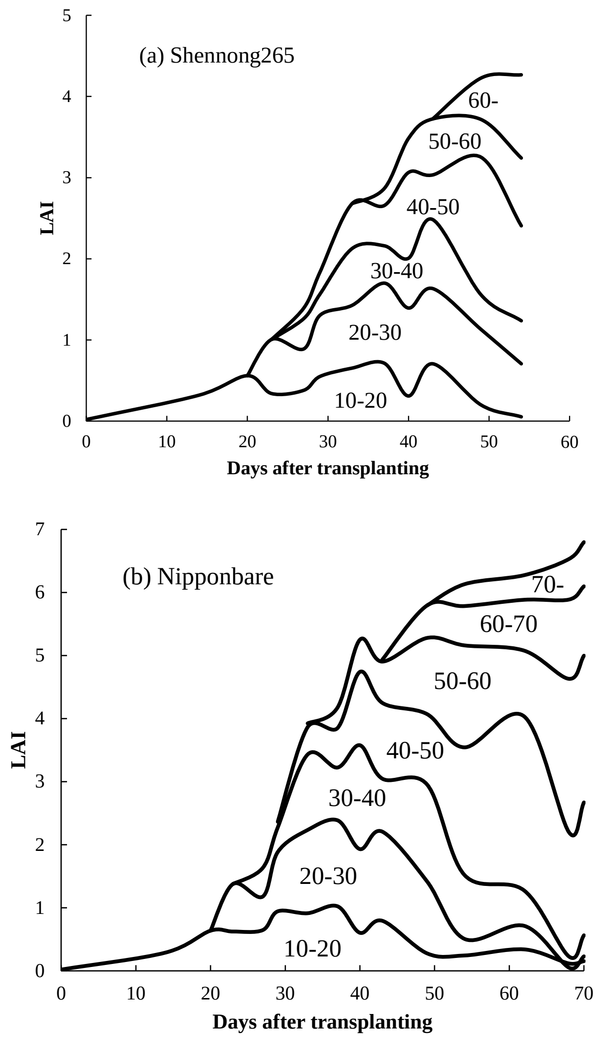


Figure 2-2.2. The periodical change of LAI vertical distribution with plant growth (Smooth lines of scatter plots by Microsoft Excel 2010). (a): Shennong265 at high fertilizer treatment in 2013. (b): Nipponbare at high fertilizer treatment in 2013.

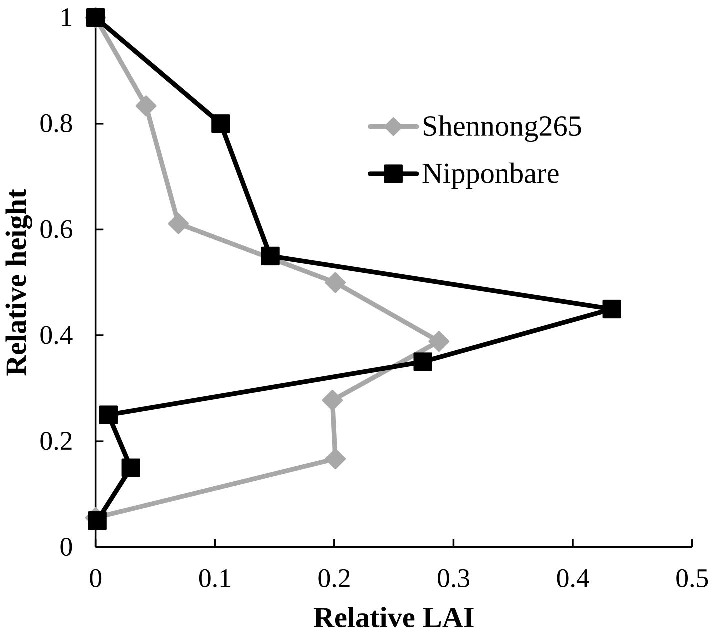


Figure 2-2.3. The LAI vertical distribution for Shennong265 and Nipponbare at heading stage at high fertilizer treatment in 2013. The height and LAI were showed by relative values: the canopy height = 1 and the total LAI = 1.

In this study, four parameters (a_1 – a_4) related to LAI vertical distribution were calculated from the statistical moment equations (Eq. (1) – (5)). These results stand in Table 2-2.2. a_1, the mean of LAI vertical distribution, ranged from 0.295 (Shennong265 at LN level at 2 weeks before heading) to 0.559 (Takanari at HN level at heading). a_2, the variance of LAI vertical distribution, ranged from 0.023 (Nipponbare at HN level at heading) to 0.100 (Shennong265 at HN level at 2 weeks before heading). a_3, the skewness of LAI vertical distribution, ranged from -0.072 (Shennong265 at LN level at 2 weeks before heading) to 0.016 (Shennong265 at ND level at 1 week before heading). a_4, the kurtosis of LAI vertical distribution, ranged from 1.55 (Nipponbare at LN level at 1 week before heading) to 4.28 (Takanari at ND level at heading). a_1 and a_2 showed the high correlation with a_3 and a_4, respectively (Table 2-2.3). a_2 also showed significant correlation with both a_1 and a_3, but the correlation coefficient was lower (Table 2-2.3).

Table 2-2.2. The differences of parameter (a_1, a_2, a_3 and a_4) values among periods, cultivars and cultivation treatments. PI: panicle initiation; 2BH: 2 weeks before heading; 1BH: 1 week before heading; LN: low nitrogen fertilizer level; HN: high nitrogen fertilizer level; LD.

a_1	Cultivar	Treatment	PI	2BH	1BH	Heading
2013	Shennong265	LN	0.328	0.295	0.32	0.363
	Shennong265	HN	0.35	0.394	0.404	0.406
	Nipponbare	LN	0.375	0.379	0.463	0.415
	Nipponbare	HN	0.412	0.432	0.446	0.448
	Takanari	LN	0.318	0.371	0.458	0.453
	Takanari	HN	0.323	0.455	0.48	0.559
	Kasalath	LN	0.344	0.345	0.391	0.424
	Kamenoo	LN	0.393	0.374	0.374	0.407
2014	Shennong265	LD	0.428	0.388	0.413	0.394
	Shennong265	ND	0.432	0.446	0.438	0.409
	Shennong265	HD	0.452	0.481	0.448	0.441
	Nipponbare	LD	0.396	0.463	0.455	0.470
	Nipponbare	ND	0.416	0.434	0.417	0.492
	Nipponbare	HD	0.362	0.443	0.488	0.476
	Takanari	LD	0.400	0.415	0.440	0.455
	Takanari	ND	0.424	0.388	0.439	0.447
	Takanari	HD	0.434	0.384	0.464	0.453

a_2	Cultivar	Treatment	PI	2BH	1BH	Heading
2013	Shennong265	LN	0.051	0.050	0.045	0.033
	Shennong265	HN	0.051	0.100	0.034	0.031
	Nipponbare	LN	0.044	0.038	0.051	0.027
	Nipponbare	HN	0.043	0.029	0.033	0.023
	Takanari	LN	0.049	0.043	0.043	0.036
	Takanari	HN	0.039	0.037	0.037	0.029
	Kasalath	LN	0.043	0.029	0.033	0.044
	Kamenoo	LN	0.060	0.051	0.036	0.047
2014	Shennong265	LD	0.052	0.039	0.041	0.035
	Shennong265	ND	0.046	0.042	0.033	0.034
	Shennong265	HD	0.044	0.039	0.031	0.032
	Nipponbare	LD	0.035	0.030	0.034	0.028
	Nipponbare	ND	0.029	0.027	0.032	0.028
	Nipponbare	HD	0.028	0.030	0.036	0.030
	Takanari	LD	0.031	0.036	0.034	0.028
	Takanari	ND	0.033	0.025	0.032	0.028
	Takanari	HD	0.030	0.028	0.036	0.030

a_3	Cultivar	Treatment	PI	2BH	1BH	Heading
2013	Shennong265	LN	-0.063	-0.072	-0.065	-0.035
	Shennong265	HN	-0.054	-0.013	-0.003	-0.011
	Nipponbare	LN	-0.037	-0.012	0.002	-0.012
	Nipponbare	HN	-0.020	-0.002	-0.016	-0.026
	Takanari	LN	-0.038	-0.063	-0.004	0.000
	Takanari	HN	-0.044	-0.002	-0.016	0.006
	Kasalath	LN	-0.080	-0.030	-0.036	-0.012
	Kamenoo	LN	-0.021	-0.041	-0.018	-0.013
2014	Shennong265	LD	-0.009	-0.008	-0.007	-0.019
	Shennong265	ND	-0.018	-0.017	0.016	-0.003
	Shennong265	HD	-0.019	-0.004	0.003	-0.009
	Nipponbare	LD	-0.030	-0.011	0.008	-0.002
	Nipponbare	ND	-0.027	0.003	-0.008	0.000
	Nipponbare	HD	-0.023	-0.007	0.010	0.003
	Takanari	LD	-0.005	-0.017	-0.016	-0.007
	Takanari	ND	-0.018	-0.023	-0.012	-0.008
	Takanari	HD	-0.015	-0.022	-0.012	0.006

a_4	Cultivar	Treatment	PI	2BH	1BH	Heading
2013	Shennong265	LN	2.67	2.38	2.67	3.41
	Shennong265	HN	2.48	1.71	3.00	3.24
	Nipponbare	LN	2.59	2.26	1.55	3.43
	Nipponbare	HN	2.32	3.56	3.21	4.03
	Takanari	LN	2.65	3.08	2.08	2.85
	Takanari	HN	2.96	2.77	2.88	4.21
	Kasalath	LN	3.55	3.05	3.32	2.42
	Kamenoo	LN	2.12	2.36	2.79	2.42
2014	Shennong265	LD	2.26	2.43	2.70	3.01
	Shennong265	ND	2.43	2.41	2.90	3.11
	Shennong265	HD	2.49	2.95	3.30	2.86
	Nipponbare	LD	3.30	3.14	3.14	3.47
	Nipponbare	ND	3.54	3.75	3.54	2.76
	Nipponbare	HD	3.47	3.29	3.25	3.53
	Takanari	LD	3.78	2.79	3.05	3.55
	Takanari	ND	3.19	3.90	3.15	4.28
	Takanari	HD	3.15	3.56	2.86	3.51

Table 2-2.3. Correlation coefficient between parameters calculated from the statistical moment equations (Eq. (1), (3), (4) and (5)) (n = 68). a_1, a_2, a_3 and a_4 represents the mean, variance, skewness and kurtosis of LAI vertical distribution, respectively.

	a_1	a_2	a_3	a_4
a_1	1			
a_2	-0.383**	1		
a_3	0.789**	-0.386**	1	
a_4	0.234	-0.833**	0.167	1

The results of ANOVA and the least squares means of the representative parameters are shown in Table 2-2.4. All parameters, a_1, a_2, a_3 and a_4, significantly changed with plant growth periods. Both in 2013 and 2014, a_1, a_3 and a_4 became higher and a_2 became lower with plant growth. a_1 in fertilizer treatment was significantly higher, and that in Shennong265 was significantly lower than in Nipponbare both in 2013 and 2014. a_2 in Shennong265 was significantly higher than in Nipponbare and Takanari both in 2013 and 2014. a_3 in Shennong265 was significantly lower than in Nipponbare and Takanari in 2013. a_4 in Shennong265 was significantly lower than in Nipponbare and Takanari, and that in high fertilizer treatment was significantly higher.

a_1 showed a significant interaction between the period and cultivar in both 2013 and 2014. a_1 in Shennong265 was more constant with plant growth than in Nipponbare and Takanari. a_2 and a_4 also showed a significant interaction between the period and cultivar only in 2014. a_2 and a_4 in Shennong265 were more variable with plant growth than in Nipponbare and Takanari. a_3 showed a significant interaction between cultivar and fertilizer in 2013. a_3 in Shennong265 and Takanari was higher at high fertilizer treatment, while that in Nipponbare at high fertilizer treatment was almost same as at low fertilizer treatment.

Table 2-2.4. The result of analysis of variance (ANOVA) of four parameters calculated by the statistical moment equations.

	a_1	a_2	a_3	a_4
Period				
PI	0.351a	0.046a	-0.043	2.61a
2WBH	0.388b	0.050a	-0.028	2.63a
1WBH	0.429b	0.040ab	-0.017	2.57a
Heading	0.441c	0.030b	-0.007	3.53b
Cultivar				
Shennong265	0.358a	0.050a	-0.039a	2.70
Takanari	0.427b	0.039b	-0.015b	2.94
Nipponbare	0.421b	0.036b	-0.016b	2.87
Fertilizer				
Low	0.378	0.043	-0.033	2.64
High	0.426	0.041	-0.014	3.03
Period	**	*	**	**
Cultivar	**	*	**	ns
Fertilizer	**	ns	**	*
P×C	**	ns	ns	ns
P×F	ns	ns	ns	ns
C×F	ns	ns	*	ns
P×C×F	ns	ns	ns	ns

	a_1	a_2	a_3	a_4
Period				
PI	0.416a	0.036a	-0.018a	3.07
2WBH	0.427ab	0.033ab	-0.012ab	3.13
1WBH	0.445bc	0.033ab	-0.002bc	3.10
Heading	0.499cd	0.031b	-0.004b	3.34
Cultivar				
Shennong265	0.431a	0.039a	-0.006	2.74a
Takanari	0.422a	0.031b	-0.012	3.40b
Nipponbare	0.450b	0.030b	-0.007	3.35b
Density				
Low	0.426	0.036a	-0.010	3.05
Normal	0.432	0.032b	-0.010	3.25
High	0.444	0.033ab	-0.005	3.18
Period	**	*	**	ns
Cultivar	**	**	ns	**
Density	ns	*	ns	ns
P×C	**	*	ns	*
P×D	ns	ns	ns	ns
C×D	ns	ns	ns	ns
P×C×D	ns	ns	ns	ns

2-2.4 Discussion

In this study, analysis of LAI vertical distribution was conducted using the LAI readings of an LAI-2200 (LI-COR, Inc., Lincoln, NE) in the non-destructive stratified measurements. Fig. 2-2.1 shows that the LAI by LAI-2200 were closely correlated with the LAI by stratified clipping method at every treatment and cultivar, suggesting that the LAI vertical distribution can be evaluated by the LAI readings of the LAI-2200 stratified measurement. The measurement error (rRMSE) between LAI by LAI-2200 and LAI by stratified clipping method of all plots was 22.8 %, and this measurement error is similar to that obtained in the previous measurements for rice canopy (Stroppiana *et al.*, 2006; Sone *et al.*, 2008; Hirooka *et al.*, 2015). The measurement error is not so much different among years, periods, cultivars fertilizer levels and plant density levels (Table 2-2.1). Every 10 cm LAI-2200 stratified measurements followed by parameterization using statistical moment equations is considered to decrease the error variance.

Statistical moment equations were used to analyze the difference of LAI vertical distribution in this study. The moment equations represent the mean densities and spatial covariance (Bolker *et al.*, 1999), and might predict spatial characteristics under different treatments by using stratified LAI measurements. In this study, the skewness and kurtosis of LAI vertical distribution were closely associated with the mean and variance of LAI vertical distribution, respectively. This result shows that the mean and skewness are the parameters which represent the center of LAI vertical distribution and the variance and kurtosis are the parameters which represent the uniformity of LAI vertical distribution.

All parameters (a_1, a_2, a_3 and a_4) varied with each growth stage, and thus, these parameters numerically showed the periodical change of LAI vertical distribution. Previous studies also reported that rice canopy structure such as LAI vertical distribution and extinction coefficient changed with plant growth (Saitoh *et al.*, 1990; Ando *et al.*, 2002). Both in 2013 and 2014, the center of LAI vertical distribution becomes higher and the uniformity of LAI vertical distribution became lower with plant growth. Thus, the characteristics of LAI vertical distribution changes with plant growth, and continuous monitoring of LAI vertical distribution is considered to be important to analyze the processes of dry matter production.

Shennong265, erect panicle type of rice, has the significantly different characteristics of LAI vertical distribution from Nipponbare and Takanari in this study. According to previous studies, erect panicle type of rice has high leaf photosynthetic capacity (Urairi *et al.*, under submission), and achieves very high yield under high nitrogen conditions (Zhang *et al.*, 2002). However, little is known about the leaf canopy structure of the erect panicle type of rice in spite of its importance in determining the rice productivity. In Shennong265, the center of LAI vertical distribution is lower and the uniformity of LAI vertical distribution is higher. Quantification of these characteristics might help us to understand the factor of the high productivity of the erect panicle type of rice. This evaluation method of LAI vertical distribution is also believed to be applicable to many cultivars because this method facilitates the non-destructive stratified measurements in many plots.

Cultivation management such as fertilizer and planting density treatments also affected LAI vertical distribution in this study. Three parameters (a_1, a_3 and a_4) show the significant difference between fertilizer levels, and one parameter (a_2) show the significant difference among plant density levels. These results are agreement well with previous studies, in which high nitrogen fertilizer increases the leaf biomass of uppermost layers (Stobbs, 1975), and plant density affected canopy structure (Hirose *et al.*, 1988). Further study of the effect of another cultivation management such as planting method (transplanting/direct seeding) and water environment on LAI vertical distribution might be needed.

2-2.5 Conclusion

The non-destructive stratified measurements with a plant canopy analyzer (Li-COR LAI-2200) and parameterization using the statistical moment equations reveal that the characteristics of the LAI vertical distribution varied with growth periods, cultivars and cultivation managements. This method also show the interaction between cultivar and period. These results suggest that the non-destructive stratified measurements and the statistical moments evaluated in this method quantitatively provide the information of the LAI vertical distribution. The information might help us to analyze the effect of canopy structure on photosynthetic ability and dry matter productivity.

Chapter 3

Application of the Evaluation Method to Field Research

Chapter 3-1 Analysis of Genotypic Variation of Leaf Canopy Dynamics in Rice by Using Plant Canopy Analyzer

3-1.1 Introduction

Leaf canopy dynamics is one of the important characteristics in rice (*Oryza sativa* L.) because it determines the dry matter productivity. Relative leaf growth rate and maximum leaf growth rate are calculated by approximating by exponential curve and logistic curve (Milthope and Moorby, 1979). Frequent measurements and then approximation by these functions may enable us to evaluate the leaf canopy dynamics. There are disadvantages of the destructive measurement which are to require a relatively laborious work to collect and measure the samples. This is one of the reasons why genotypic variation of leaf canopy dynamics has not been fully undertood (de Jesus *et al*., 2001). Recently, plant canopy analyzer such as LAI-2000 (LI-COR, Inc., Lincoln, NE; LI-COR. 1992, LI-COR. 2004) and Sunscan (Delta-T Devices, Cambrodge, UK; Potter *et al.*, 1996) have been utilized, and we can conduct non-destructive measurement of leaf area index (LAI). We don't need a laborious work and much time in this method. Especially, LAI-2000 is a suitable equipment for evaluating LAI of rice cultivars under various environments (Yamamoto *et al.*, 1995, Wilhelm *et al.*, 2000, Sone et al., 2009). It is suggested in Chapter 2-2 that the difference of leaf canopy dynamics among many cultivars can be evaluated quantitatively.

We used global rice core collection (RDRS : Rice Diversity Research Set of germplasm ; Kojima *et al*. 2005), which have various phenotypes. RDRS consists of 69 cultivars included in Nipponbare and Kasalath. RDRS is expected to be used not only to analyze the genotypic variance but also as genetic resources such as experimental and breeding materials (Kojima *et al.*, 2005). Previous studies investigated yield components, photosynthetic rate and stomatal conductance of RDRS (Takahashi *et al*., 2007, Ohsumi *et al*. 2007a, Ohsumi *et al.* 2007b, Kanemura *et al*. 2007).

The objective of this study is to evaluate cultivar variance of leaf canopy dynamics by measuring LAI and light transmittance by LAI-2000. According to Chapter 2-1, relative growth rate of LAI, maximum interception growth rate and the days to 80 % coverage were calculated from LAI-2000 frequent measurements. In this chapter, extinction coefficient and LAI at heading were also used to evaluate the characteristics of the leaf canopy. Principle components analysis was conducted, and we discuss about the difference of leaf canopy dynamics among genotypic groups.

3-1.2 Materials and Methods

3-1.2.1 Study Sites and Experimental Design

The field experiment was conducted in the experimental fields belonging to Kyoto University (35°02’N, 135°47’E) in 2007, 2008 and 2009. We used 54 of 69 RDRS cultivars. The rest of 15 cultivars cannot be maturing in Kyoto because of temperature and day length. In addition to these cultivars, we used 4 cultivars, Takanari, IR72, IR55423-01 (APO), B6144F-MR-6-0-0 (B6144F), which are high yielding cultivars. The dates of sowing were 7 May in 2007 and 2008, and 30 April in 2009. Twenty-four-day-old seedlings were transplanted to the Kyoto University field on 31 April in 2007 and Twenty-one-day-old seedlings were transplanted on 28 May in 2008 and on 21 May in 2009. The planting density was 22.2 plants per m^2 (0.3 m × 0.15 m). Chemical fertilizer in the form of N-P_2O_5-K_2O = 5-5-5 g m^{-2} was applied as basal fertilization. The sizes of the plots were 7 × 8 plants in 2007 and 2009, and 7 × 11 plants in 2008. Weeds were controlled using agro-chemicals and through hand-weeding, and insects and diseases were also controlled with agrochemicals.

3-1.2.2 Measurements

LAI was measured one time per week from three weeks after transplanting to maturing in each plot with an LAI-2000 (LI-COR, Inc., Lincoln, NE; LAI-2000 measurement). The measurements were conducted under scattered light conditions, such as after sunrise, before sunset or on overcast days, with a single sensor mode in a sequence of two above, four below the canopy at each plot. To reduce the influence of the adjacent plots and the operator, a 90° view-cap was applied to the optical sensor. Diffuse non-light intercepted (DIFN) values obtained from the LAI-2000 were also used in the analysis. In this study, (1-DIFN) was defined as light interception rate. Four plant samples were harvested from each plot at heading. Green leaf blades were separated from the plant samples, and their area was measured using an area meter (LI3080, LI-COR; destructive measurement). At maturing, eight plants were harvested to measure the yield.

3-1.2.3 Analysis Method

Four high-yielding cultivars and Milyang23 were defined as high yield varieties (HYV). According to Kojima *et al.* (2005), 53 cultivars were divided into the three groups (I1 (aus *indica*), I2 (The rest of *indica*), J (*japonica*)).

LAI dynamics during the early growth stage were approximated using the following exponential function.

$$LAI = a\ e^{\alpha\ DAT} \qquad (1)$$

where a and α are regression coefficients: a corresponds the initial LAI value at DAT = 0; and α ($^{o}C^{-1}$) is the parameter referred to as the relative leaf growth rate (RGR). DAT represents days after transplanting. The LAI values until 6 weeks after transplanting were used to estimate the parameters.

Second, the dynamics of diffusive light interception, defined as (1-DIFN), were approximated using a similar type of logistic curve to the employed for LAI dynamics, but asymptotic line was y = 1.

$$1\text{-}DIFN = 1 / (1 + c\ e^{-\gamma T}) \qquad (2)$$

Thirdly, by using LAI and DIFN from 3 weeks after transplanting to heading, extinction coefficient (K) was calculated.

$$DIFN = e^{-K\ LAI} \qquad (3)$$

In addition to α (day^{-1}), γ / 4 (day^{-1}) and K, two parameters (days to 80 % coverage, LAI at heading) were analyzed. We evaluated the genotypic variation of 5 parameters, and conducted principle components analysis. We used one-way analysis of variance to evaluate the difference among genotypic groups, and if significant, a Tukey-Kramer test to compare the mean values of 5 parametrs.

3-1.3 Results

Averaged yield from 2007 to 2009 ranged from 109.3 g m^{-2} (Khan Mac Kho (J)) to 666.6 g m^{-2} (B6144F (HYV)) (Table 3-1.1). Table 3-1.1 shows the top 5 and bottom 5 of 5 parameters related to leaf canopy. α ranged from 0.064 (Qingyu (I2)) to 0.197 (Ratul (I1), γ ranged from 0.054 (Jena035 (I1)) to 52.0 (Dianyu1(J)). Many of I1 cultivars were included in top 5 and bottom 5 of each parameter, and it is suggested that I1 has much variation than the other groups. α of *indica* cultivars had much variation, and that of I1 was significantly higher than J.（Fig. 3-1.1 (a) ; Table 3-2.2）. γ of *indica* cultivars also had much variation， and γ of HYV was significantly higher than that of J, and higher than that of any other groups (Fig. 3-1.1 (b); Table 3-1.2). Especially, γ of B6144F, IR72 and APO were very high (Table 3-1.1). Variance of $DAT_{0.8}$ was not so much difference among cultivar groups, and that of I1 was significantly lower than that of HYV (Fig. 3-1.1 (c); Table 3-1.2). Both the variance and values of K and LAI at heading were not significantly different among genotypic groups (Fig. 3-1.1 (d), (e); Table 3-1.2).

Table 3-1.1. Top 5 and Bottom 5 cultivars of yield and parameters related to leaf growth.

	Yield	α	γ	$DAT_{0.8}$	K	LAI at heading
Top						
1	B6144F (HYV)	Ratul (I1)	APO (HYV)	Jena 035 (I1)	Padi Perak (J)	Padi Kuning (I2)
2	Takanari (HYV)	Lebed (I1)	ARC 7291 (I1)	Jaguary (J)	Milyang 23 (HYV)	Nepal 555 (I1)
3	IR72 (HYV)	Co 13 (I2)	B6144F (HYV)	Padi Kuning (I2)	Rexmont (J)	Jarjan (I1)
4	APO (HYV)	Tupa 121-3 (I1)	IR72 (HYV)	ARC 7291 (I1)	Basilanon (I1)	B6144F (HYV)
5	Milyang 23 (HYV)	Basilanon (I1)	Deng Pao Zhai (I2)	Asu (I2)	Shwe Nang Gyi (I2)	Kasalath (I1)
Bottom						
1	Khau Mac Kho (J)	Qingyu (I2)	Kalo Dhan (I1)	Dianyu 1 (J)	Dianyu 1 (J)	Tadukan (I2)
2	Jaguary (J)	Jhona 2 (I1)	Dianyu 1 (J)	Milyang 23 (I2)	Kasalath (I1)	Local Basmati (I1)
3	Khao Nok (J)	Rexmont (J)	Ryou Suisan Koumai (I2)	Rexmont (J)	APO (HYV)	ARC 7291 (I1)
4	ARC 11094 (I1)	B6144F (HYV)	ARC 7047 (I1)	Nipponbare (J)	Lebed (I1)	Co 13 (I2)
5	Calotoc (I1)	Jaguary (J)	Bei Khe (I2)	IR72 (HYV)	Ratul (I1)	Dianyu 1 (J)

Table 3-1.2. The difference of yield, five leaf canopy parameters and principle components among genotypic groups.

Groups	HYV	J	I1	I2
Yield	603.6±43.4 a	297.6±29.6 c	386.4±20.2 b	426.9±22.9 b
α	0.121±0.014 ab	0.097±0.009 b	0.130±0.007 a	0.114±0.007 ab
γ	0.098±0.006 a	0.081±0.003 b	0.084±0.003 ab	0.082±0.003 ab
$DAT_{0.8}$	42.1±2.00 b	39.8±1.2 b	35.6±0.9 a	36.9±1.1 ab
K	0.78±0.03 ns	0.80±0.02	0.80±0.01	0.80±0.02
LAI at heading	5.3±0.4 ns	4.5±0.3	5.4±0.2	4.8±0.2
Com. №1	0.21±0.55 ns	0.40±0.34	-0.28±0.26	0.01±0.29
Com. №2	1.16±0.43 a	-0.40±0.27 b	0.16±0.20 ab	-0.24±0.23 b

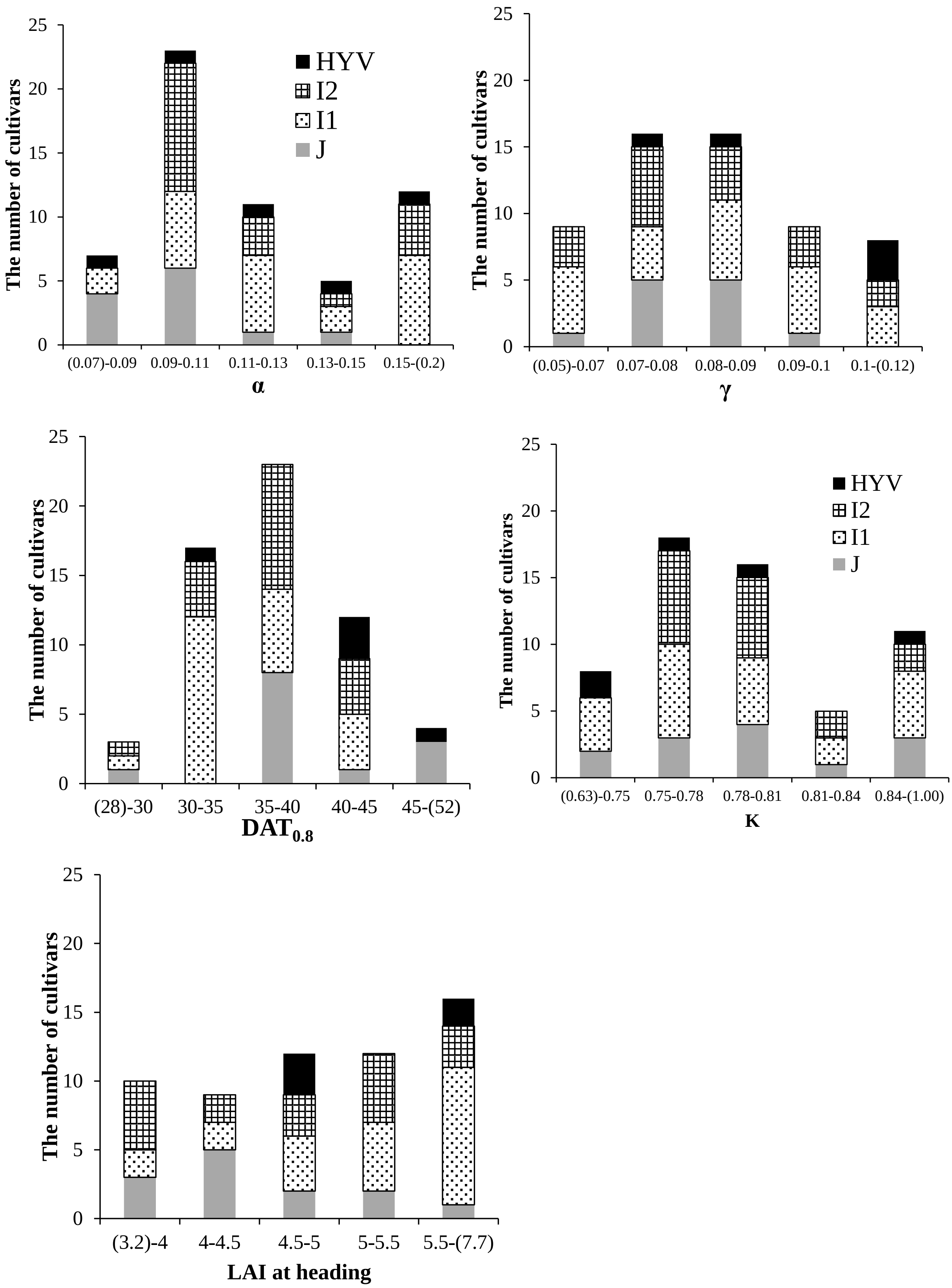


Figure 3-1.1. The difference of parameters related to leaf growth among cultivars. (a) relative early LAI growth rate (α); (b) maximum ntercption growth rate (γ); (c) the days to 80 % coverage ($DAT_{0.8}$); (d) extinction coefficient (K); (e) LAI at heading.

Principle components analysis was conducted by using 5 indices. Contribution ratio of the first components was 30.03 %, and factor loadings of $DAT_{0.8}$ and K was higher, and that of LAI at heading was negative values (Table 3-1.3). On the other hand, contribution ratio of the second components was 26.85 %, and factor loadings of α, γ and LAI at heading was higher values. While there was not a big difference of the first components among genotypic groups, the second components of HYV and I1 was higher, and that of J was lower (Fig. 3-1.2).

Table 3-1.3. The factor loadings and contribution rate of principle components analysis of each parameter.

Eigenvector	First com.	Second com.
α	0.24	0.51
γ	0.11	0.69
$DAT_{0.8}$	0.71	0.03
K	0.51	-0.04
LAI at heading	-0.40	0.51
Contribution	30.03%	26.85%

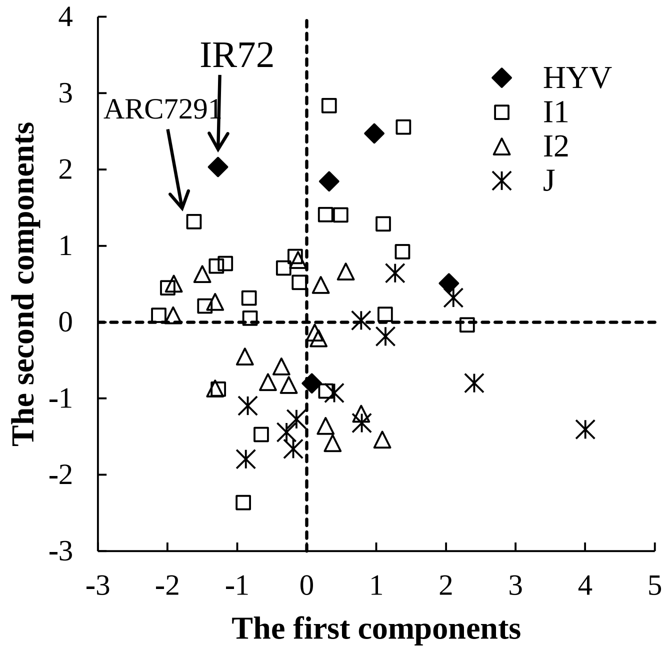


Figure 3-1.3. Distribution of cultivars from the result of principle component analysis (Table 3-1.3) by using 5 indices related to leaf growth dynamics.

3-1.4 Discussion

In this study, leaf growth analysis of RDRS and high-yielding varieties was conducted by using the measurements of plant canopy analyzer, LAI-2000 (LI-COR, Inc., Lincoln, NE). Estimation accuracy of LAI-2000 is considered to be relatively high, but it is reported that the measurement error is approximately 30 % (Wilhelm *et al*., 2000, Stroppiana *et al*. 2006, Sone *et al*. 2008). Measuring frequently and then approximation of the functions are thought to decrease the measurement error. In Chapter 2-1, it is suggested that, by one-week-interval non-destructive measurements, leaf canopy dynamics can be parameterized accurately.

Previous studies investigated the genotypic variation of photosynthetic, stomatal conductance and water use efficiency of RDRS (Ohsumi *et al*. 2007a, Ohsumi *et al.* 2007b, Kanemura *et al*. 2007, Matsunami *et al*. 2012), but leaf canopy dynamics of RDRS was not still analyzed. Takahashi *et al*. (2007) reported that LAI at heading of I1 was significantly higher than that of J. The result in this study also show that LAI at heading of I1 was higher than that of J, but not significantly. This may be because fertilizer level and plant density of Takahashi *et al*. (2007) was higher than those of this study. Extinction coefficient (K) of this study was relatively higher than that of previous studies, but agreement well with that of Dinkuhn *et al*. (1999), which was calculated from LAI and DIFN measured by LAI-2000. In addition to this, this study evaluated the genotypic variation of leaf canopy dynamics. Further study of the interaction between cultivar and environment is needed because not only cultivars but also nutrient condition and temperature affects the dynamics of leaf canopy of rice.

The result of principle components analysis show that in the first components, factor loadings of $DAT_{0.8}$ and K were higher and that of LAI at heading was negative. It is suggested that the cultivars which had higher first components shows higher K, and had horizontal leaf, but days to covering is longer and lower LAI at heading. On the other hand, in the second components, factor loadings of α, γ and LAI at heading were higher, suggesting that the cultivars which had higher second components show higher early LAI growth rate, maximum interception rate and LAI at heading. It is concluded in these results that the second components represent LAI growth from early to middle period, and the first components represent the later growth. Therefore, the cultivars which show higher leaf growth rate is considered to be located in the second quadrant.

Indeed, ARC7291 (I1) and IR72 (HYV) were located in the second quadrant. There was significant difference of the values of the second component among genotypic groups, and HYV show much higher values of the second quadrant.

High-yielding varieties released by IRRI had higher values of the maximum interception growth rate, suggesting that the varieties have been improved in terms of canopy development. In contrast, since Takanari and Milyang23 didn't have such a characteristic, the varieties have not been improved the leaf canopy dynamics. These two cultivars have high LNC and photosynthetic rate (Kanemura *et al.*, 2007), and the varieties might have been improved in terms of photosynthetic rate. Therefore, by using RIL (recombinant inbred line) and CSSL (chromosome segment substitution lines), further improvement may be possible.

In this study, the data until heading stage was analyzed. Decreasing rate after heading stage is considered to be one of the important factors to understand the dynamics of leaf canopy (Yoshida *et al*. 2007). The measurement error of LAI-2000 after heading stage was much higher (Chapter 2-1). LAI decreasing rate can be measured theoretically because the area except for leaf canopy is constant after panicle stage. Therefore, further study of leaf dynamics after heading stage might be needed.

Chapter 3-2 Evaluation of the Dynamics of the LAI of Rice in Farmer's Fields in Vientiane Province, Lao PDR

3-2.1 Introduction

Rice is by far the most important crop in the Lao People's Democratic Republic (Lao PDR), and here, approximately 70 % of the total calorie supply in diets comes from rice (Maclean *et al.*, 2002). The wet season lowland is the main rice-producing environment (Schiller, 2006). The production constraints in the lowland paddy fields in Lao PDR are poor soil fertility, drought, flooding and diseases, contributing to the low rice yield (Schiller *et al.*, 2001). To increase the yield in farmers' fields, improved rice varieties (Fukai *et al.*, 1999), soil fertility management (Bell and Seng, 2003) and weed management (Inamura *et al.*, 2003) are recommended. In particular, poor soil fertility is the fundamental problem in the rice production (Wade *et al.*, 1999; Inthavong *et al.*, 2011), and, therefore, understanding the relationship between the soil fertility and rice growth and production is thought to be very important. Although several studies have investigated the rice production and soil properties in farmers' fields (Inamura *et al.*, 2003; Asai *et al.*, 2009; Saito *et al.*, 2009), information about the growth of rice plants is limited.

The leaf area index (LAI) is an important trait that is related to canopy photosynthetic rate and dry matter production during growth periods (Vaesen *et al.*, 2001). An evaluation of the dynamics of LAI may enable us to quantify the growth of rice plants and to explore the factors that limit the dry matter production in farmers' fields.

The objective of this study was (1) to evaluate the dynamics of LAI and (2) to analyze the relationship between the rice productivity and soil in farmers' fields in Vientiane province, Lao PDR.

3-2.2 Materials and Methods

3-2.2.1 Study Sites

This study was conducted in 2013 in farmers' fields in Vientiane province, Lao PDR. 66 farmers' paddy fields from 33 places were selected in this area for surveying throughout the growth period (Fig. 3-2.1). Altitude of the 33 places is from 168 m – 178 m. The longitude and latitude of the study sites were recorded by the Global Positioning System (GPSMAP 62SJ, GARMIN). The rice plants of the investigated farmers' fields varied in cultivation methods (direct seeding/transplanting, fertilizer, planting density and cultivar). Preliminary interviews with farmers suggested that transplanting, non-fertilization, 25 hill m^{-2} of planting density and traditional cultivation were the majority.

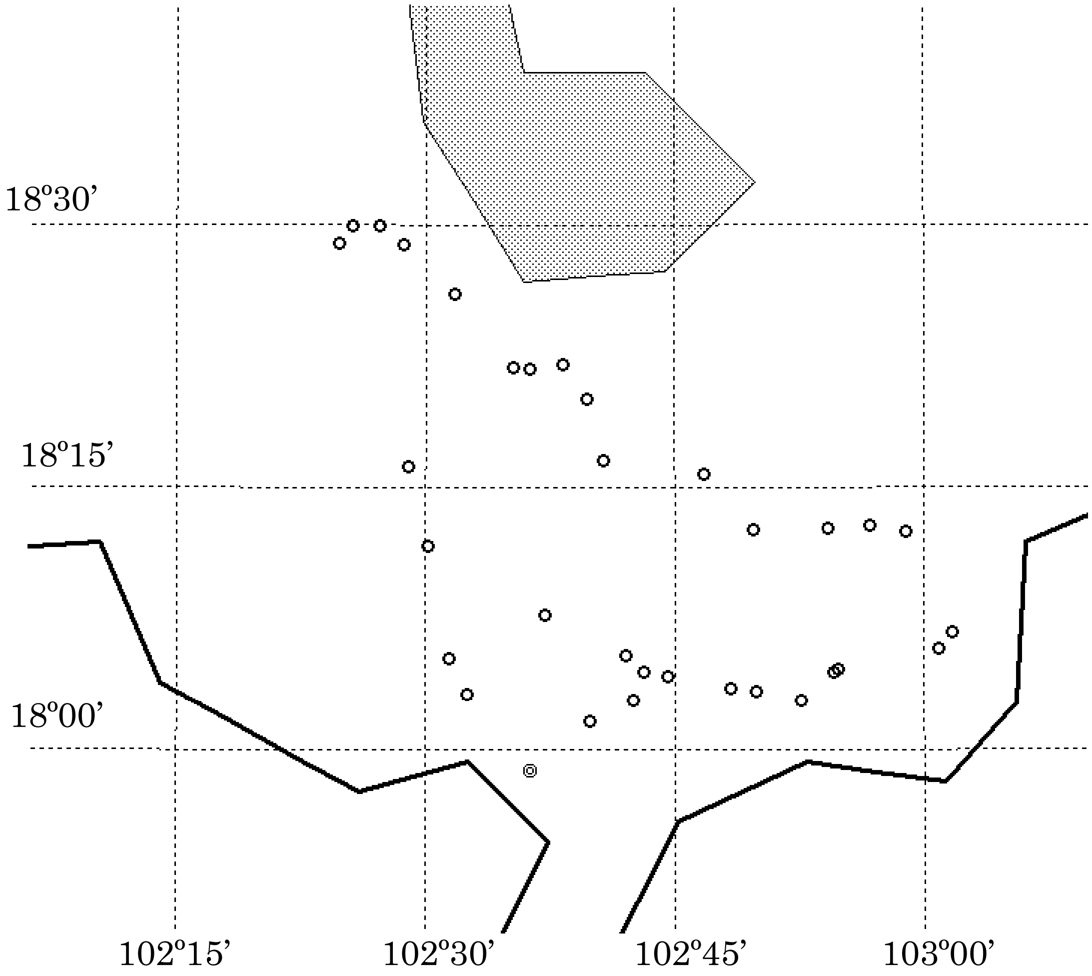


Figure 3-2.1. Thirty-three survey places in Vientiane Province, Lao PDR. Altitude of the thirty-three places is from 168 m – 178 m. The measurements were conducted in 2 paddy fields in each place.

3-2.2.2 Measurements

The leaf area index (LAI) was measured using a plant canopy analyzer (LAI-2200, LI-COR) with a single sensor mode in a sequence of two above and four below canopy at each field. In order to reduce the influence of the adjacent fields and the operator, a 90° view-cap was applied to the optical sensor. The measurement was conducted 4 times before the heading period (from 22 to 25 July, from 10 to 12 Aug, from 30 Aug to 1 Sep and from 16 to 18 Sep). The LAI for each measurement was referred to as LAI_{1st},

LAI_{2nd}, LAI_{3rd} and LAI_{4th}. Because the peak of the heading in these study sites was on 22 Sep, LAI_{4th} contained almost all of the maximum LAI values.

Nine rice plant samples were harvested, and the plant density was measured in 56 of the 66 farmers' fields to determine the grain yield (g m^{-2}) and total dry weight (TDW; g m^{-2}) at the maturing stage (from 22 to 25 Oct). The other 10 fields were excluded from the sampling because the rice plants during these periods were too premature to harvest or had already been harvested. The grain yield and TDW were determined after oven-drying at 70 ºC for more than 2 days.

The soil samples from 33 of the 66 fields were collected from the surface soil (0 to 20 cm deep) at the same date as LAI measurement. All of the soil samples were air-dried and ground to pass through a 2-mm sieve before analysis. The total nitrogen (N) and carbon (C) contents in the soil were analyzed using a trace mass spectrometer (Tracer MAT, Fisons Instruments).

3-2.2.3 The Model

The air temperature (maximum temperature, minimum temperature and average temperature) was measured by thermometer/hygrometer (DCA, Decagon). The data was recorded using a field monitoring system (Mizoguchi, 2012) in Vientiane.

The LAI data were analyzed by the following regression line:

$$LAI = a\,T + b \qquad (1)$$

where a and b are the regression coefficients, and T is the effective accumulated temperature (°C d; base temperature of 10°C) from 22 July. The coefficient a is defined as the LAI growth rate, and the transplanting date was estimated based on the x-intercept (– b/a) (Fig. 3-2.2). In order to validate the estimated transplanting date, we defined the observed transplanting date as that estimated from interview and the observation based on normal rice growth during the first and second investigation from 22 to 25 July and 10 to 12 August, respectively.

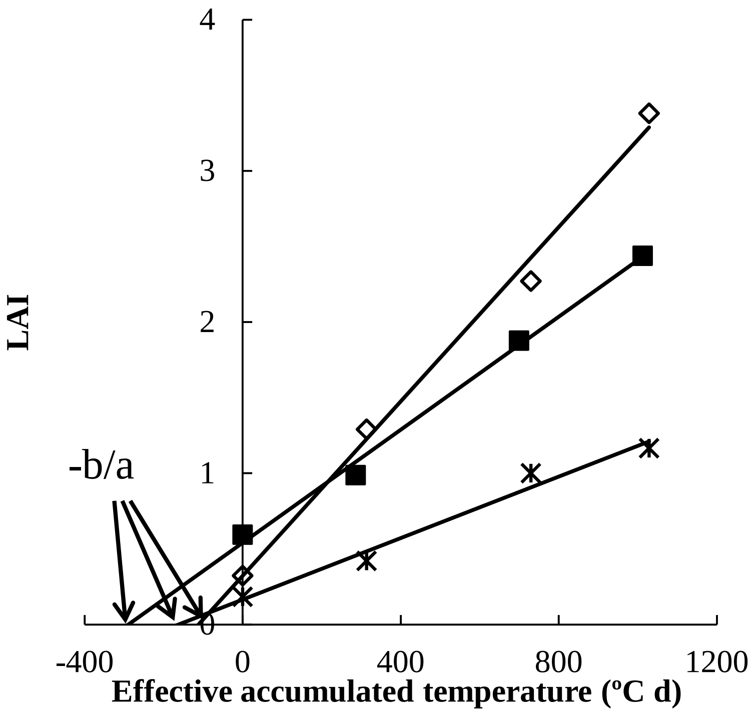


Figure 3-2.2. Changes with the effective accumulated temperature (°C d; base temperature of 10 °C) of the LAI. The effective accumulated temperature was calculated from 22 July.

3-2.3 Results

Fig. 3-2.3 shows the seasonal changes in the average, maximum and minimum air temperature in Vientiane during the rice growth periods. Almost all of the daily average temperatures during the growth period were 25-30 ºC. The average temperature of the middle growth period (22 August to 21 September) was about 1.5 ºC greater than that of the early (22 July to 21 August) and late growth periods (22 September to 21 October).

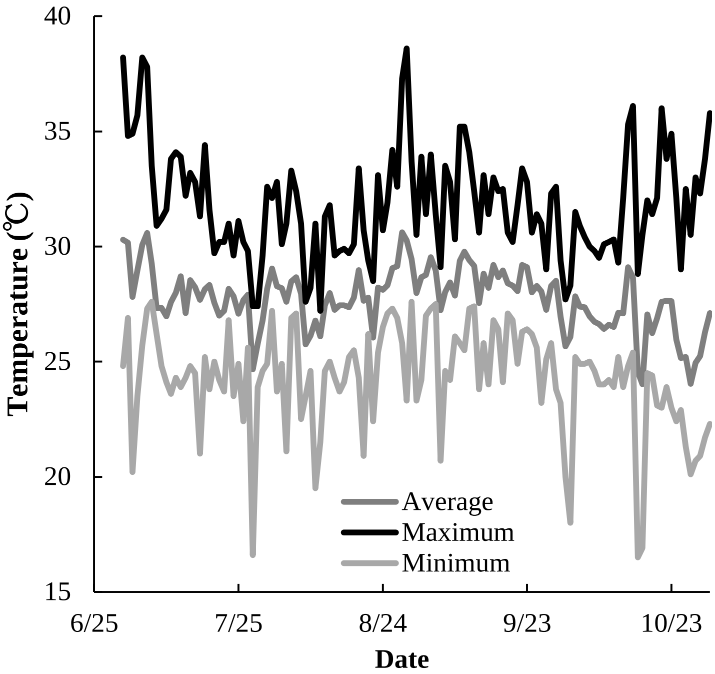


Figure 3-2.3. The seasonal changes in the average, maximum and minimum air temperature as acquired using a field monitoring system in Vientiane in 2013 during the rice growth periods.

The TDW ranged from 248.4 g m^{-2} to 1089.0 g m^{-2} (660.0 g m^{-2} on average), and the grain yield ranged from 63.8 g m^{-2} to 411.8 g m^{-2} (235.8 g m^{-2} on average). The TDW and the LAI were correlated with the grain yield (TDW: R^2 = 0.52, LAI: R^2 = 0.18) (Fig. 3-2.4). The average harvest index (grain yield/TDW) was 0.36. The TDW was correlated with the LAI during the fourth investigation from 16 to 18 Sep (LAI_{4th}) (R^2 = 0.48) (Fig. 3-2.5).

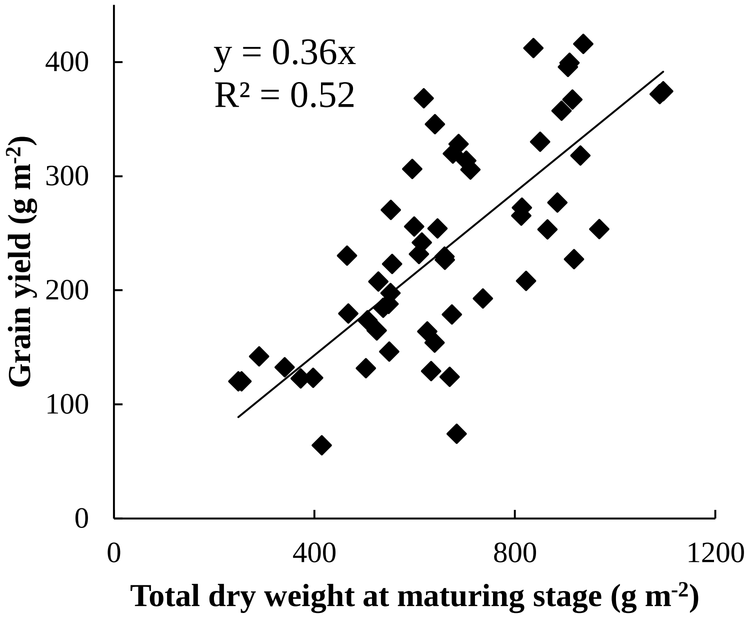


Figure 3-2.4. Relationship between the grain yield (g m^{-2}) and the total dry weight at the maturing stage (g m^{-2}). during the rice growth periods.

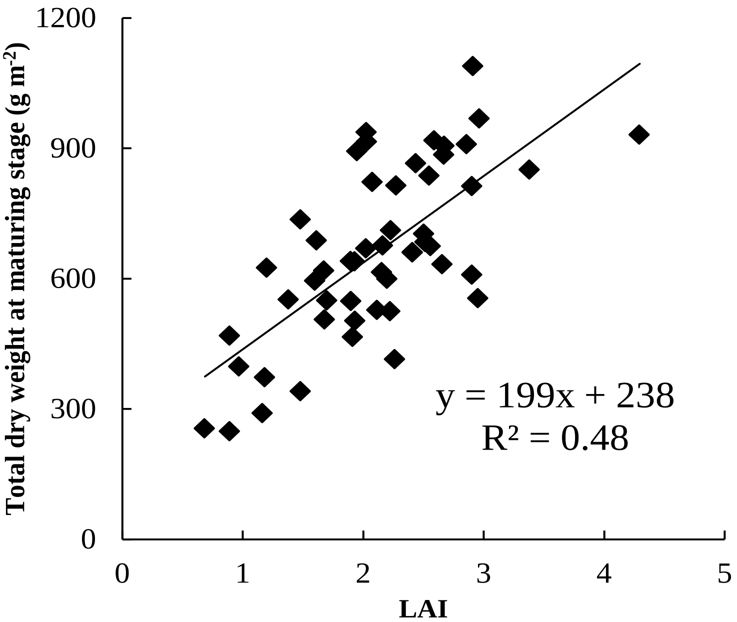


Figure 3-2.5. Relationship between the total dry weight at the maturing stage (g m^{-2}) and the LAI at the fourth investigation (LAI_{4th}).

Fig. 3-2.2 shows the changes with the effective accumulated temperature of the LAI as measured by LAI-2200 in typical three farmers' fields. The LAI in the farmers' fields increased almost linearly. The slope of the regression line is defined as the LAI growth rate. The LAI growth rate in the 66 fields varied widely from 0.56×10^{-3} to 3.63×10^{-3} $m^2\ m^{-2}\ {}^{\circ}C^{-1}$ (1.94×10^{-3} $m^2\ m^{-2}\ {}^{\circ}C^{-1}$ on average). The estimated transplanting date calculated by the x-intercept (-b/a) was consistent with the observed transplanting date. The estimated transplanting date was substantially underestimated in the 4 plots (Fig. 3-2.6).

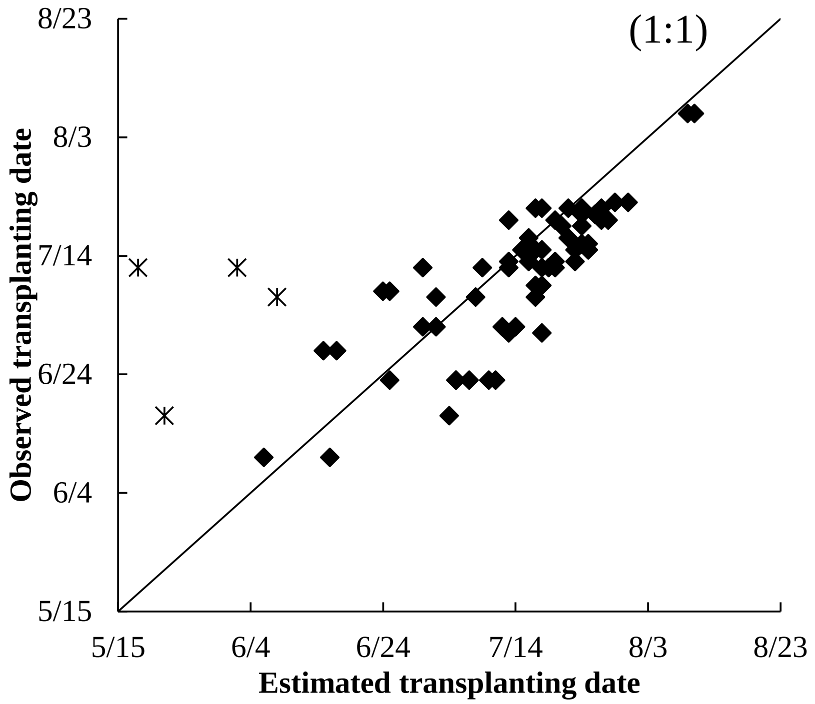


Figure 3-2.6. Relationship between the transplanting date as estimated from equation (1) and the transplanting date from observation during the first survey. 4 outlier plots were excluded from the next analysis.

The product of the LAI growth rate and the effective accumulated temperatures was strongly correlated with the LAI_{4th} (R^2 = 0.768) (Fig. 3-2.7 (a)). LAI_{4th} was correlated with the LAI growth rate (R^2 = 0.776) but rarely with the effective accumulated temperatures (R^2 = 0.004) (Fig. 3-2.7 (b), (c)). The N and C contents in the soil in the farmers' fields ranged from 0.41 to 1.98 g kg^{-1} (0.99 g kg^{-1} on average) and from 2.4 to 24.0 g kg^{-1} (10.1 g kg^{-1} on average), respectively. The N and C contents in soil had a positive correlation (R^2 = 0.926). The LAI growth rate was associated with the N and C contents of the soil in most of the fields (Fig. 3-2.8).

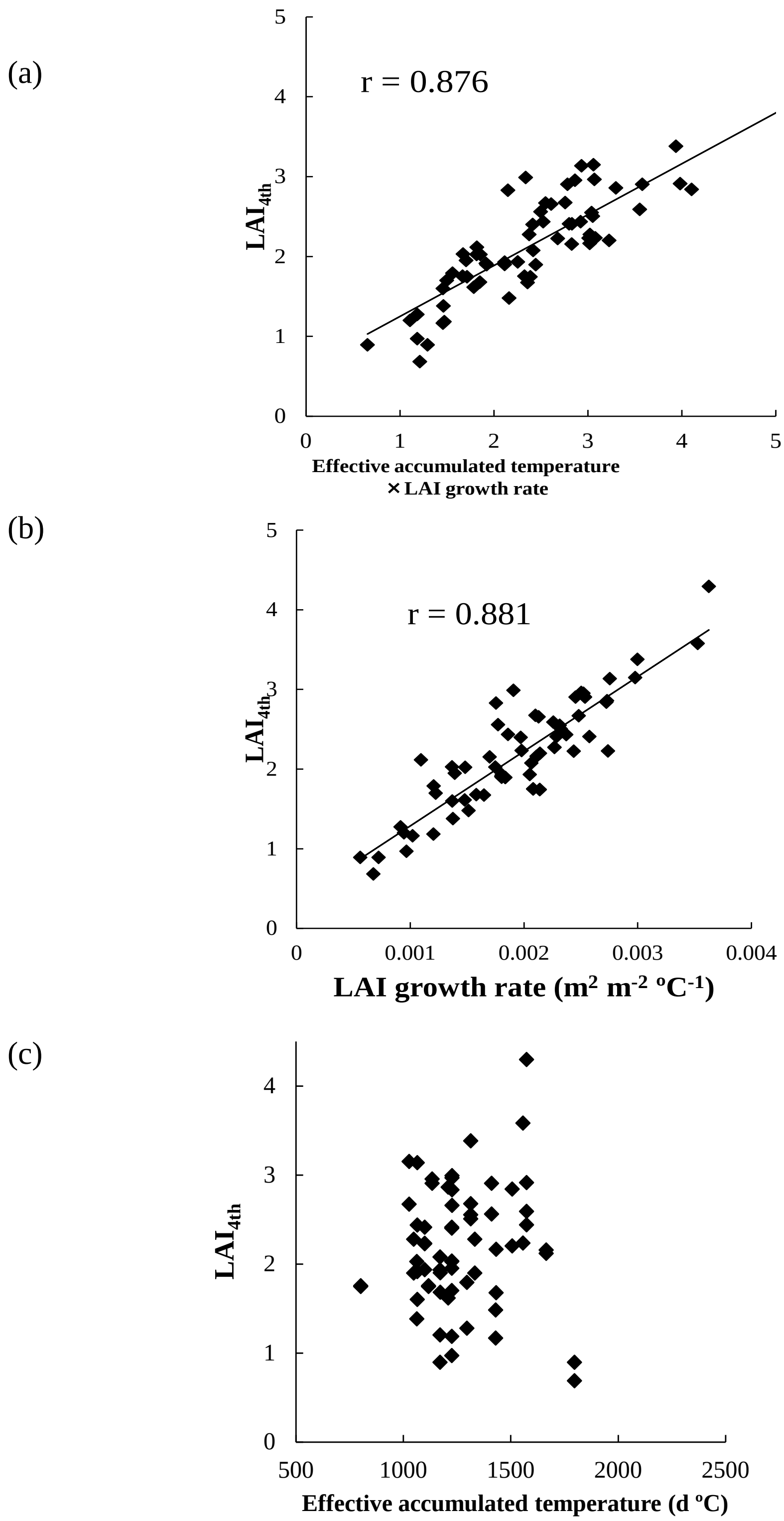


Figure 3-2.7. Relationship between the LAI during the fourth investigation and (a) the product of the LAI growth rate and the effective accumulated temperature, (b) the LAI growth rate (m^2 m^{-2} $^oC^{-1}$), and (c) the effective accumulated temperature from the estimated transplanting date (°C d).

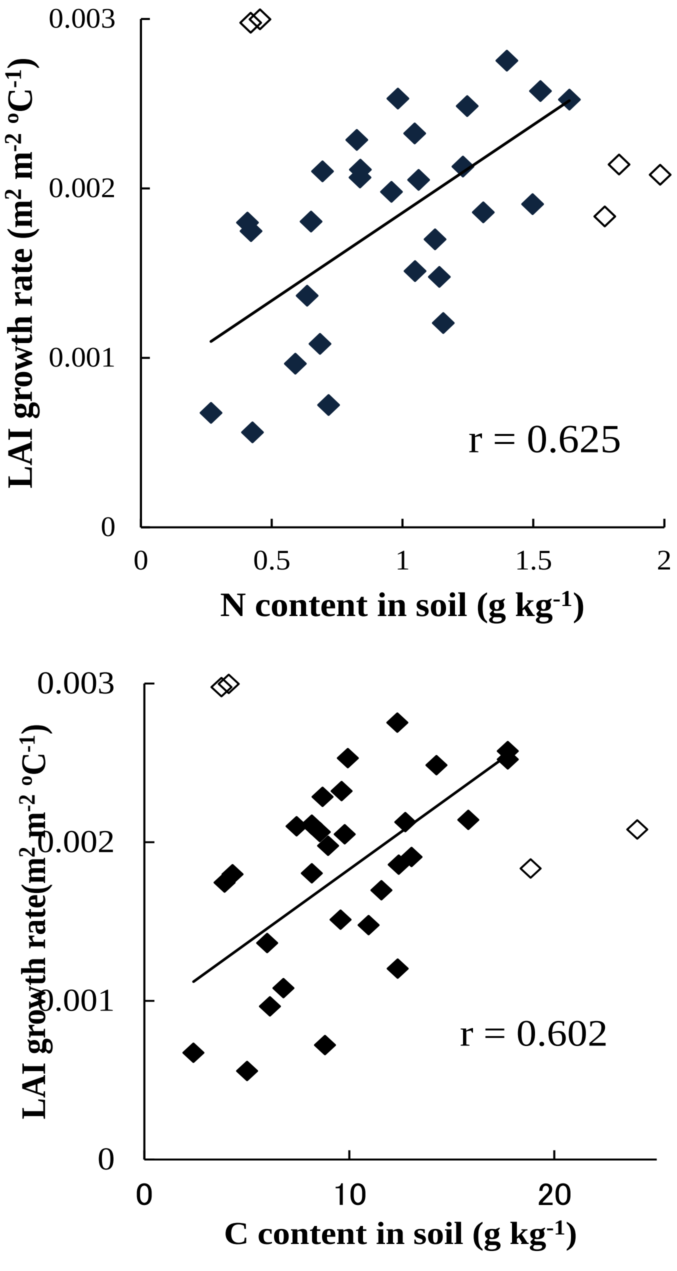


Figure 3-2.8. Relationship between the LAI growth rate (m^2 m^{-2} $^oC^{-1}$) and the (a) N and (b) C contents in the soil (g kg^{-1}).

3-2.4 Discussion

The average grain yield of 56 investigated fields was 235.8 g m^{-2}, and this yield level is low. The yield level was very similar to that of Inamura *et al*. (2003), who also evaluated the rice yield in the farmers' fields in the study area in Lao PDR in 1999 and 2000, suggesting that the improvement in the yield was not obvious for a decade.

The grain yield in this study correlated with the total dry matter during the maturing stage (TDW) (Fig. 3-2.4), which correlated with the LAI at the fourth investigation (LAI_{4th}) (Fig. 3-2.5). These results indicate that the limitation of the LAI development restricts the dry matter production and, thus, the yield in the study area. The average LAI growth rate in this study (1.94×10^{-3} m^2 m^{-2} $^{o}C^{-1}$) corresponds approximately to that which was obtained in the 56 years unfertilized fields in Japan (Chapter 2-1). This study used a plant canopy analyzer, LAI-2200, to measure the LAI. Although the analyzer has the accidental error against the destructive measurements, the error would be acceptable (Stropiana *et al.*, 2006; Sone *et al*., 2008). Moreover, the nondestructive measurement by this analyzer is suitable for research, such as this study, that targets a number of unspecified farmers' fields. The analyzer also reduces the laboriousness of the destructive measurements for LAI and makes frequent measurements easier. Accordingly, the most advantageous aspect of this analyzer may be the quantification of the LAI dynamics based on frequent measurements (Chapter 2-1).

Based on the aspect of the LAI changes in the different farmers' fields (Fig. 3-2.7), a linear regression was employed to quantify the LAI dynamics. The estimated transplanting date calculated by the x-intercepts (-b/a) was consistent with the observed transplanting date except for in 4 fields. These exceptions seem to be caused by the late measurement of the LAI: measurement when the LAI approaches saturation underestimates the developmental rate and overestimates the transplanting date. Therefore, it is suggested that the estimation of the transplanting date is possible by measuring the LAI when the LAI development is vigorous: the best timing is until approximately 2 months after transplanting. This simple method of estimating the transplanting date can be useful because the acquisition of accurate information from farmers is often difficult. The transplanting date is occasionally closely related to the dry matter production of rice (Homma *et al.*, 2007; Jalota *et al.*, 2009), although the relation was not significant in this study ($R^2 = 0.04$).

The LAI is determined by the LAI growth rate and the growth periods (Yoshida *et al.*, 2007). Although the LAI_{4th} was strongly correlated with the product of these two parameters in this study, Fig. 3-2.7 indicates that the LAI growth rate was the main determination factor of the LAI at the later growth stage of rice in farmers' fields in Lao PDR. The result might derive from larger coefficient of variance of the LAI growth rate (cv = 0.33) than that in effective accumulated temperature (cv = 0.16).

N and C contents of the soil in this study were similar to those in Cambodia and Thailand investigated by Kawaguchi and Kyuma (1977), suggesting that soil fertility in this area is thought to be low. LAI growth rate was associated with the N and C contents of the soil. A few fields did not follow this relationship, where drought or fertilizer application may affect the LAI growth. Except for these fields, these results suggest that the rice productivity of farmers' fields is mainly governed by the soil fertility through LAI growth. LAI development was depended on soil fertility and fertilizer (Yoshida *et* *al.*, 2010). Thus, in order to enhance the LAI growth and to increase the rice production, fertilizer application may be necessary. Otherwise, an improvement of the soil fertility may be important. The close relationship between the C content and the LAI growth rate suggests that rice straw management after harvest is a key factor for sustainable production in farmers' fields as was previously shown in Northeast Thailand (Homma *et al.*, 2003). The results of this study also suggest that LAI monitoring can estimate the soil fertility in the study area and support the fundamental theory of evaluating the soil fertility using a simulation model with LAI monitoring and remote sensing (Homma *et al.*, 2014; Maki *et al.*, 2014).

Chapter 3-3 Evaluation of Cultivation Management Based on LAI Measurement in Farmers' Paddy Fields in Pursat Province, Cambodia

3-3.1 Introduction

Rice is by far the most important crop in Cambodia, where 51 % of total employment is agricultural, with most farmers cultivating rice for a living (Matsukawa *et al.*, 2015). However, the rice grain yield (g m^{-2}) and the amount of export in Cambodia are much lower than those in neighboring countries such as Thailand and Vietnam (Rakotorisoa, 2011). Rice is grown in Cambodia mainly under rainfed conditions, and the extent of adoption of improved rice varieties is generally low (Wang *et al.*, 2014). A number of technological and environmental constraints have resulted in a low yield of rice.

Rice productivity is strongly affected by water, temperature, and solar radiation and their utilization by cultivation management (Inoue *et al.*, 2014). To increase the rice yield in farmers' fields, evaluating cultivation environment and management (water, fertilizer, soil fertility, seeding/transplanting, cultivar etc.) is recommended. Although several studies have investigated the water management and irrigation system in Cambodia (Wokker *et al.*, 2011; Tsujimoto *et al.*, 2013), information about the other aspects of cultivation environment and management and their effects on rice production in farmers' paddy fields is quite limited. Acquiring such information is very important to reveal the constraints in rice production.

The leaf area index (LAI) is an important trait that is related to canopy photosynthetic rate and dry matter production during growth periods (Vaesen *et al.*, 2001), and its growth is regulated by cultivation environment and management. Chapter 3-2 reported that the LAI growth rate in farmers' paddy fields in Lao PDR was closely associated with soil C and N contents, under similar cultivation management (transplanting, low fertilizer rate and no drought stress). On the contrary, cultivation management varies (transplanting/broadcasting, various fertilizer rate and so on) in Cambodia (Kodo *et al.*, 2014; Kamoshita *et al.*, 2009). Investigating the LAI growth rate in farmer's fields in Cambodia may enable us to quantify the effect of cultivation management together with the cultivation environment, such as soil fertility.

The objective of this study was to evaluate the effect of the cultivation environment and management on the LAI growth in relation to rice production in Cambodia. For this purpose, LAI measurement, interviews, yield measurement, and water and soil investigations were conducted in farmers' fields in the study area.

3-3.2 Materials and Methods

3-3.2.1 Study Sites

This study was conducted in 2014 in farmers' paddy fields in the Bakan district, Pursat province, Cambodia. Pursat province, located in the northwest of Cambodia, is one of the representative rice producing areas of the Great Lake flood plain. Seventy-seven farmers' paddy fields were selected for surveying throughout the growth period. The altitude of the 77 fields ranged from 14 m – 21 m a.s.l. The longitude and latitude of the study fields were recorded by a Global Positioning System (GPSMAP 62SJ, Garmin International, Inc., Kansas City). Thirty-seven of 77 fields had access to irrigation facilities (canal and ponds). We interviewed 62 farmers with regard to rice-cultivation management, including the cultivar, rice growth duration (seeding date, transplanting date and harvesting date), transplanting or broadcasting, the amount and timing of the fertilization, and management practices for weeds and pests.

3-3.2.2 Measurements

The leaf area index (LAI) was measured using a plant canopy analyzer (LAI-2200, LI-COR) with a single sensor mode in a sequence of two above and four below the canopy at each field. To reduce the influence of the adjacent fields and the operator, a 90° view-cap was applied to the optical sensor. The measurement was conducted 4 times before the heading period (from 26 to 28 July, from 9 to 11 Aug., from 3 to 5 Sep. and from 18 to 20 Sep.). The LAI for each measurement was referred to as LAI_{1st}, LAI_{2nd}, LAI_{3rd} and LAI_{4th}, respectively. Because the peak of the heading in these study fields was on 27 Sep, LAI_{4th} may represent the maximum LAI in the growing season.

The water conditions in each field were recorded as a water score (WS) (Kamoshita *et al.*, 2010). Unflooded conditions were scored as −1 (“dry”), −0.5 (“moist but not saturated”), or 0 (“saturated but no standing water”). The flooded condition was given by a score of x/10, where x = depth (cm) of the standing water. The WS was measured 3 times (from 26 to 28 July, from 20 to 22 Aug., and from 18 to 20 Sep.). Farmers’ fields were divided into three levels based on averaged water score (less (L) water level: WS ≦ 0; middle (M) water level: 0 < WS < 1; high (H) water level: WS ≧ 1)

We harvested rice plants and weeds within 1 m^2 circle at 57 of the 77 farmers’ fields.

Rice grain yield and the above-ground biomass of rice plants and weeds at the maturing stage (from 16 Oct. to 20 Nov.) were determined after oven drying at 70 °C for more than 2 days.

The soil samples were collected from the surface soil (0 to 20 cm deep) on the same date as the LAI measurement. All of the soil samples were air-dried and ground to pass through a 2-mm sieve before analysis. The total nitrogen (N) contents in the soil were measured by the Kjeldahl method (Vickery, 1946), and the total carbon (C) contents in the soil were measured by the Walkey method (Walkey, 1947).

3-3.2.3 Weather Data and Analysis Method

The daily average air temperature was measured by temperature probes (A-HMP45D, Vaisala) and precipitation was measured by rainfall meter (A-TK-2, Agematsu) at Pursat province weather station (12°32'N, 103°54'E).

The LAI growth rate was calculated using the following linear function in the plot where LAI increased linearly during the measurement (Eq. (1); Chapter 3-2).

$$LAI = a \times T + b \qquad (1)$$

where a and b are the regression coefficients, and T is the effective accumulated temperature (°C d; base temperature of 10 °C) from 22 July. The coefficient a is defined as the LAI growth rate.

Analysis of covariance (ANCOVA) was used to determine the effect of each factor on the LAI growth rate using the following mathematical model:

$$a = \mu + PM + W + b_1 C_{soil} + b_2 C/N_{soil} + b_3 N_{fert} + e \qquad (2)$$

where a is the LAI growth rate, μ is intercept, PM is the fixed effect of the planting method (two levels: transplanting or broadcasting), W is the fixed effect of the water level based on the water score (three levels: L, M and H), C_{soil} is the continuous variable of the C content in the soil, C/N_{soil} is the continuous variable for the C/N ratio in the soil, N_{fert} is the continuous variable for the amount of N fertilizer, b_1, b_2 and b_3 are the partial regression coefficient, *e* is the residual effects.

Because the effect of N_{fert} was not significant, the following equation was applied for ANOVA.

$$a = \mu + PM + W + b_1C_{soil} + b_2C/N_{soil} + e \qquad (3)$$

3-3.3 Results

Fig. 3-3.1 shows the seasonal changes in the average air temperature in Pursat province during the rice growth periods. Almost all of the daily average temperatures during the growth period were 25-30 °C. The C and N contents in the soil in the farmers' fields ranged from 5.3 to 23.3 g kg^{-1} (11.9 g kg^{-1} on average) and from 0.73 to 3.30 g kg^{-1} (1.52 g kg^{-1} on average), respectively. In this study, we divided the farmers' fields into three levels (L water, M water and H water) based on the average water score. The average water score ranged from -0.77 to 3.12 (0.47 on average); 21 fields were included in L water, 37 fields in M water and 19 fields in H water.

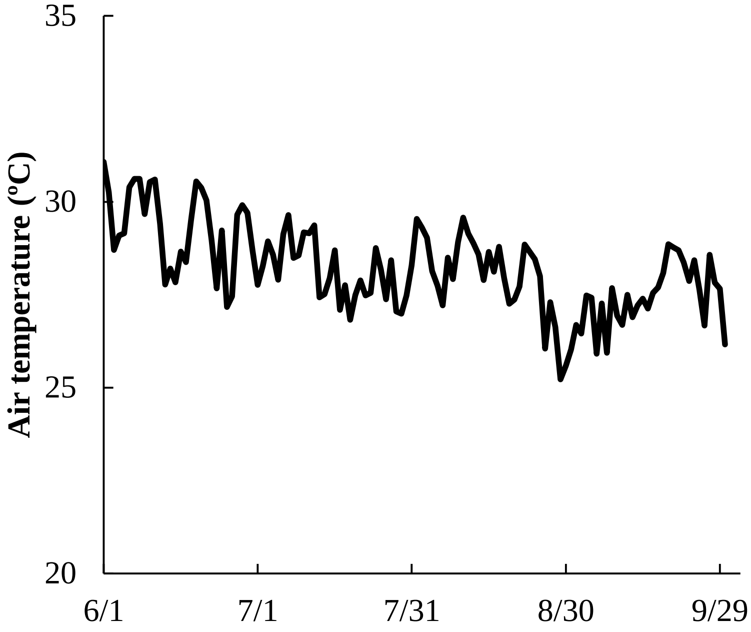


Figure 3-3.1. The seasonal changes in the average air temperature as acquired using temperature probes (A-HMP45D, Vaisala).

The grain yield ranged from 70.8 g m^{-2} to 499.0 g m^{-2} (290.5 g m^{-2} on average), and the TDW ranged from 523.8 g m^{-2} to 2083.1 g m^{-2} (1022.2 g m^{-2} on average). The grain yield and the TDW were significantly correlated with the LAI at the fourth investigation (LAI_{4th}) (grain yield: r = 0.631, TDW: r = 0.488) (Fig. 3-3.2). LAI_{4th} ranged from 1.24 to 4.53 (2.80 on average). The dry weed weight in the BC fields is about twice as much as that in the TP fields (BC: 19.1 g m^{-2}; TP: 11.7 g m^{-2}).

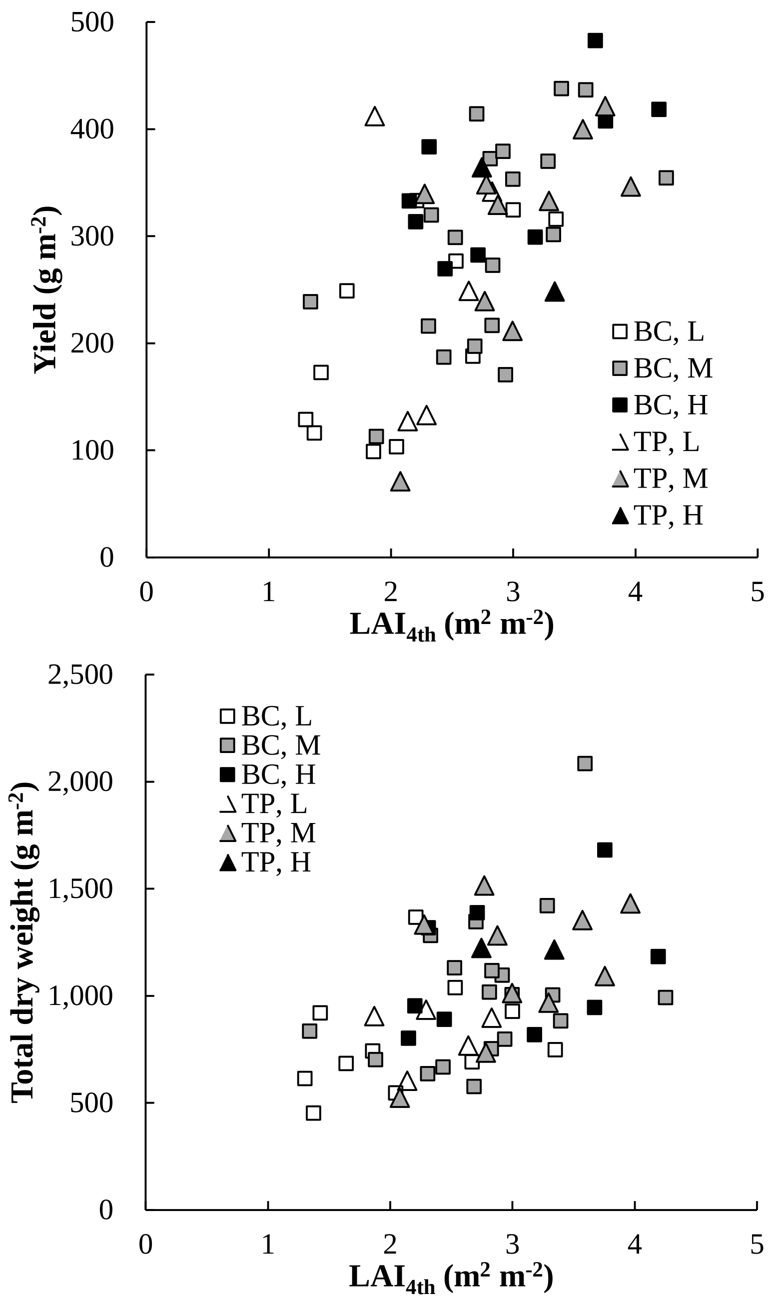
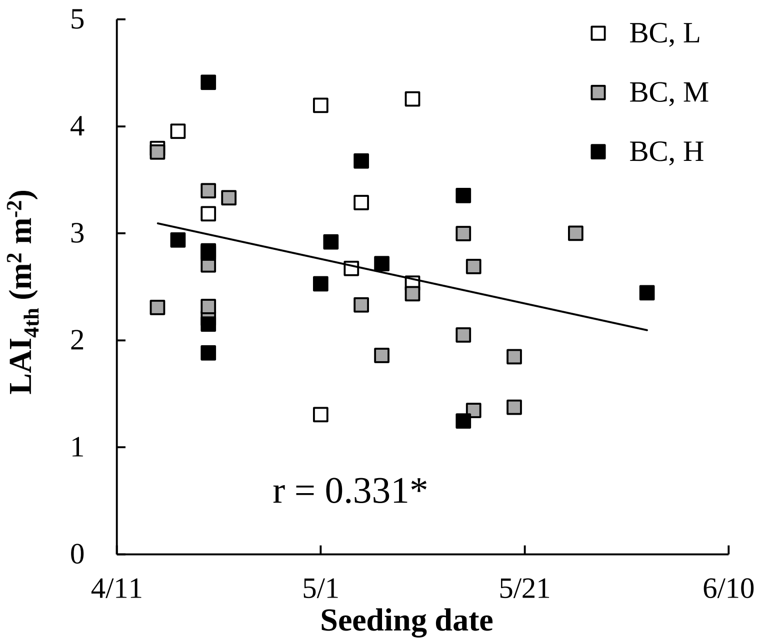


Figure 3-3.2. The relationship of leaf area index (LAI) at the 4th investigation from 16 to 18 Sep. (LAI_{4th}) (m^2 m^{-2}). 2014 with (a) yield (g m^{-2}) and (b) total dry weight at maturing stage (g m^{-2}). BC: broadcasting fields; TP: transplanting fields. L: low water level fields; M: middle water level fields; H: high water level fields.

Most farmers interviewed in this study planted the same cultivars; the most popular is Somali, which has a high market value. Only seven farmers grow the other cultivars, Phka Rumduol, Phka Malis, Dumnerk and Dumnerb. The interview results also show that the amount of N fertilizer varied from 0 to 12.2 g N m^{-2} (5.09 g N m^{-2} on average) The farmers have two choices for rice planting, broadcasting (BC) or transplanting (TP) (BC: 51 fields, TP: 26 fields). In the BC fields, the seeding date varied from 15 April to 26 May. In the TP fields, the seeding date varied from 12 April to 10 June, and the transplanting date varied from 25 May to 25 July. In the BC fields, the seeding date was negatively correlated with the LAI_{4th} (r = -0.331) (Fig. 3-3.3), while in the TP fields, the seeding date and transplanting date were not significantly correlated with LAI_{4th}.



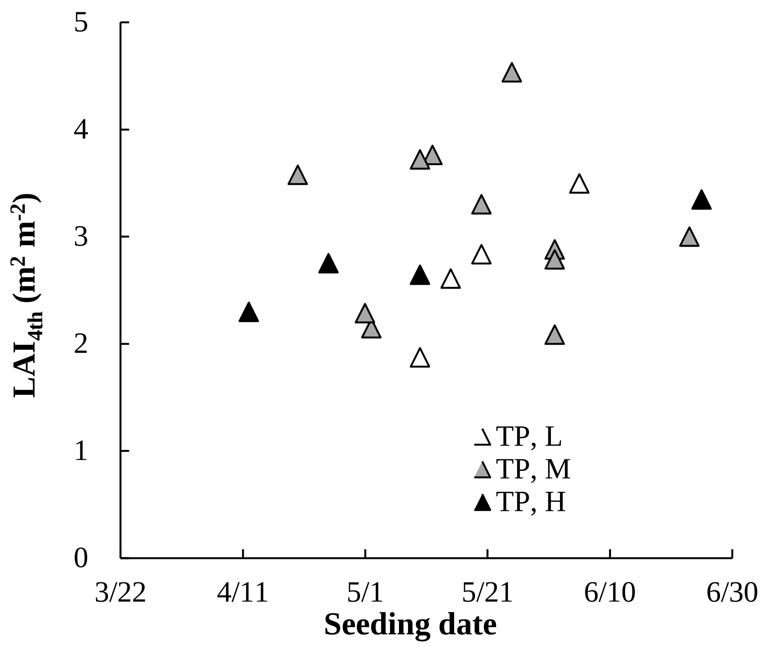


Figure 3-3.3. The relationship between leaf area index (LAI) at the 4th investigation (m^2 m^{-2}) and seeding date in (a) BC fields and (b) TP fields. Symbols are the same as in Fig. 3.3.2.

The LAI in the farmers' fields increased almost linearly except for 5 fields. The slope of the regression line is defined as the LAI growth rate. The LAI growth rate in the fields varied widely from 0.57 × 10^{-3} to 3.76 × 10^{-3} m^2 m^{-2} $^oC^{-1}$ (2.26 × 10^{-3} m^2 m^{-2} $^oC^{-1}$ on average). The LAI_{4th} was strongly correlated with the LAI growth rate (r = 0.828) (Fig. 3-3.4).

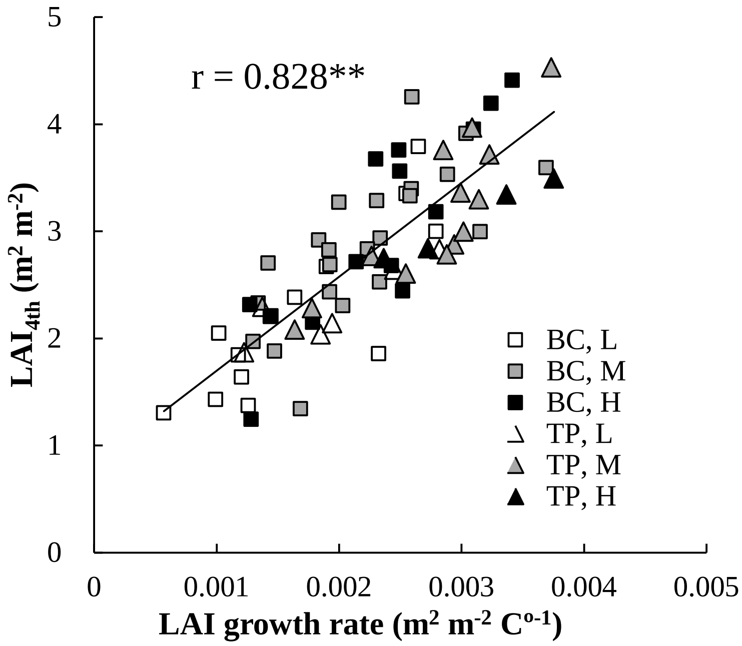


Figure 3-3.4. The relationship between LAI at the 4th investigation (m^2 m^{-2}) and LAI growth rate (m^2 m^{-2} $^oC^{-1}$). Symbols are the same as in Fig. 3.3.2.

The result of the ANOVA shows the effect of each factor (planting method, water status, C contents in soil, C/N ratio in soil and the amount of N fertilizer; Eq. (2)) on the LAI growth rate (Table 3-3.1). The effects of the planting method and the water status were significant at the 0.1 % level, and the effects of the C contents and the C/N ratio in soil were significant at the 10 % level. On the other hand, the effect of the N fertilizer was not significant (p = 0.71). Fig. 3-3.5 also shows that the effect of the N fertilizer was not obvious. Excluding the factor of the N fertilizer (Eq. (3)), the ANOVA results are shown in Table 3-3.1 and the following model was obtained:

The LAI growth rate ($m^2\ m^{-2}\ 10^{-4}$) = 8.14 + (0 BC, 5.26 TP) + (-5.99 L water, 0 M water, 0.42 H water) + 7.22 C_{soil} + 0.45 C/N_{soil} (4)

The coefficient of determination of Eq. (4) was 0.331. Transplanting had a positive effect and the L water level had a negative effect on the LAI growth rate. The LAI growth rate was also related to the C contents and C/N ratio in the soil (Fig. 3-3.6).

Table 3-3.1. The result of analysis of covariance (ANCOVA) of each factor (Transplanting / Broadcasting, Water level, C content in soil, C/N ratio in soil and the amount of N fertilizer) influencing LAI growth rate. (a): the result of Eq. (3). (b): the result of Eq. (4).

(a)

Source of Variation	df	F value	P value	
PM	1	8.01	<0.01	**
W	2	5.26	<0.01	**
C_{soil}	1	3.28	0.08	+
C/N_{soil}	1	3.52	0.07	+
N_{fert}	1	0.14	0.71	ns

(b)

Source of Variation	df	F value	P value	
PM	1	8.00	<0.01	**
W	2	5.29	<0.01	**
C_{soil}	1	3.27	0.08	+
C/N_{soil}	1	3.80	0.06	+

** Significant at the 0.01 probability level.
+ Significant at the 0.1 probability level.

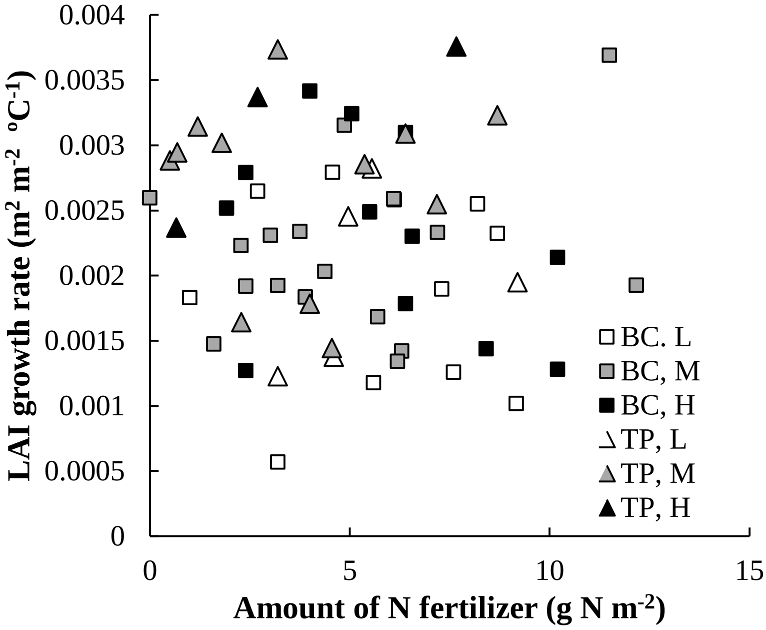


Figure 3-3.5. The relationship between LAI growth rate (m^2 m^{-2} $^oC^{-1}$) and N content in fertilizer (g kg^{-1}). Symbols are the same as in Fig. 3.3.2.

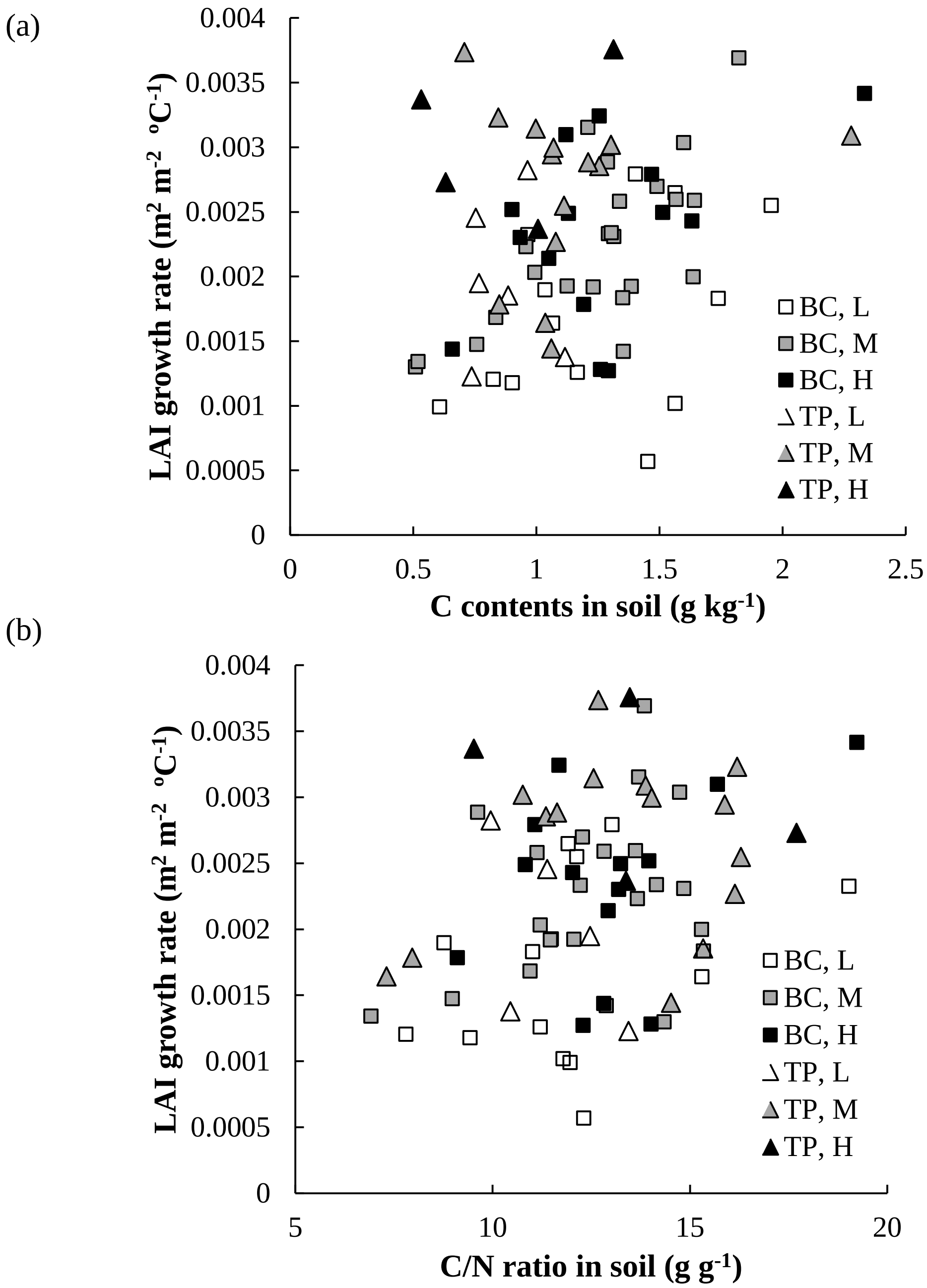


Figure. 3-3.6. The relationship between LAI growth rate (m^2 m^{-2} $^oC^{-1}$) and (a) C content in the soil (g kg^{-1}), (b) C/N ratio in the soil (g g^{-1}). Symbols are the same as in Fig. 3.3.2.

3-3.4 Discussion

The average grain yield of the 57 investigated fields was as low as 290.5 g m^{-2}. While the yield level of this study was similar to the yields reported by Yu and Diao (2011) and Kodo *et al.* (2014) in the farmers' fields in Cambodia, it was lower than those of Thi and Kajisa (2006) in Vietnam and Laborte *et al.* (2012) in Thailand. The comparison suggests that improvement in rice production is possible in Cambodia. The grain yield and total dry weight (TDW) in this study correlated with the LAI at the fourth investigation (LAI_{4th}) (Fig. 3-3.2), which was conducted around the heading, i.e., LAI_{4th} was almost equal to the maximum LAI. The correlation coefficient between grain yield and LAI_{4th} in this study is comparable with that in Chapter 3-2 obtained in farmers' fields in Lao PDR. These correlations indicate that the limitation of the LAI growth restricts yield in the study area.

The growth period is occasionally closely related to the dry matter production of rice (Homma *et al.*, 2007; Jalota *et al.*, 2009). However, the phenomenon was observed only in the BC fields in this study, where earlier planting led to larger LAI and then to larger dry matter production (because the major cultivar, Somali, is a photosensitive cultivar, earlier planting causes longer growth duration). On the contrary, earlier planting did not cause significantly larger LAI nor TDW in the TP fields. The results suggest that the growth period is not the productivity constraint in the TP fields.

Chapter 3-2 reported that the LAI growth rate was the main determining factor of the maximum LAI of rice in farmers' fields in Lao PDR. This study also shows the high correlation coefficient between LAI_{4th} and the LAI growth rate. However, the LAI in five farmers' fields in this study did not increase linearly. These exceptions were caused by the severe water stress (LAI stopped growing temporarily) or saturation growth of LAI (data not shown). Chapter 2-2 showed that the LAI growth from transplanting to heading is well explained by a logistic function that includes the saturation growth of the LAI, although frequent measurement (i.e., once a week) was necessary. Accordingly, if more frequent measurements were available, the effect of water stress on LAI growth could be quantified.

Rice productivity is strongly affected by drought in Cambodia (Seng *et al.*, 1999). The LAI growth rate was smaller in the L water level field where the average water score was less than 0. Some farmers conducted several rounds of irrigation, which increased the water score from 0.36 to 0.60, on average, in this study. These facts imply that irrigation is an effective means to increase rice productivity. Although the development of the irrigation facilities is primarily important, the irrigation is ordinarily conducted by pump, which is costly for rice production. The timing and intensity of the water deficit has been recognized as one of the main causes affecting rice productivity (Ouk *et al.*, 2007). Development of an effective water-saving irrigation method is strongly recommended.

The average LAI growth rate obtained in this study (2.26×10^{-3} m^2 m^{-2} $°C^{-1}$) corresponds approximately to that obtained in an study of non-fertilized fields in Japan (Chapter 2-2). The correspondence suggests that nutrients were inadequate in the study area. Carbon (C) and nitrogen (N) contents in the soil in this study were similar to those found in Thailand and Laos in studies by Kawaguchi and Kyuma (1977) and Chapter 3-2, suggesting that soil fertility in this area is low. The C content has a positive effect on the LAI growth. The close relationship between the C content and the LAI growth rate suggests that rice straw management after harvest is important for the sustainable production in farmers' fields, as was previously shown in Northeast Thailand (Homma et al., 2003). While a high C/N ratio often leads to low rice productivity (Asai et al., 2009), the C/N ratio in this study had a positive effect on the LAI growth. This result suggests that rude organic matter with a high C/N ratio is more important for rice production in the study area or that the C/N ratio might be associated with nutrient-holding capacity.

An enhancement in the LAI growth rate might be caused by fertilizer application. However, the effect of fertilizer was not statistically obvious in this study. Since the amount of fertilizer obtained by the interview in this study was not inadequate (5.09 g N m^{-2} on average), the timing or method of fertilizer application might be improper. The results also suggest that fertilizer management is the key to improve rice production and requires further study.

Transplanting also had a positive effect on LAI growth in this study, but the proportion of the transplanting area has been decreased in Cambodia (Ikeda *et al.*, 2008). Kamoshita *et al.* (2009) concluded that transplanting is a more suitable method of planting for high rice productivity under the low soil fertility condition in Southeast Asia. A similar tendency was also observed in this study: 4 transplanted fields where the C contents in soil were quite low showed relatively higher LAI growth rate (Fig. 3-3.6). The selection of the planting method (broadcasting or transplanting) dependent on the soil fertility might be important.

3-3.5 Conclusion

This study used a plant canopy analyzer, LAI-2200, to measure the LAI non-destructively. The analyzer also reduces the laboriousness of the destructive measurements for the LAI of rice and makes frequent measurements easier (Stroppiana *et al.*, 2006; Sone *et al.*, 2008). Accordingly, the nondestructive measurement by this analyzer is suitable for research, such as in this study, which targets a number of unspecified farmers' fields (Hirooka *et al.*, 2015).

The results in this study suggest that rice productivity is restricted by LAI growth in farmers' fields in Cambodia, and LAI growth was mainly determined by water status, planting method (transplanting/broadcasting) and soil condition (C content and C/N ratio). The results also suggest that the key factors to improve rice productivity are earlier broadcasting, water-saving-irrigation methods, use of effective fertilizer application methods and selection of a planting method that is dependent on soil fertility.

Chapter 4

Applicability of SAR to Evaluate LAI Growth Rate of Rice in Farmers' Fields in Lao PDR

4.1 Introduction

Rice is undoubtedly the most important crop in the Lao People's Democratic Republic (Lao PDR), and approximately 70 % of the total calories in the Lao diet come from rice (Maclean *et al.*, 2002). While improving its productivity is strongly recommended, the information about rice growth characteristics in farmers' fields is limited (Bell and Seng, 2003; Fukai *et al.*, 1999; Inamura *et al.*, 2003). In Chapter 3-2, I measured leaf area index (LAI) and its growth rate using a plant canopy analyzer and reported that rice production was closely associated with LAI growth rate. However, because application of a plant canopy analyzer is not suitable on a regional scale, the evaluation by satellite based remote sensing is recommended.

Most rice production in Lao PDR is conducted in the rainy season (Schiller, 2006), during which cloudy conditions often interrupt satellite observation in visible and near-infrared range. Accordingly, remote sensing based on synthetic aperture radar (SAR) is proposed as a more suitable method to evaluate rice growth in this area because the observation is independent from cloud and solar illumination (Chakraborty *et al.*, 1997). The radar transmits a pulse and then measures the time delay and strength of the reflected echo, where the ratio of scattered and incident microwave energy is termed the back scattering coefficient (BSC) (Moran *et al.*, 2002). SAR uses polarized radiation and, therefore, can exploit polarization signatures of the imaged scatters for obtaining more information about the scatter's structure (Bamler, 2000). Although previous studies investigated the applicability of SAR to estimate LAI (Inoue *et al.*, 2014; Maki *et al.*, 2015), the estimation accuracy has not attained practical level. The present study analyzed the relationship between SAR images and LAI of rice measured by Chapter 3-2 and discusses the applicability of SAR to estimate LAI and its growth rate in farmers' fields in Lao PDR. The results showed although the accuracy was still the problems to estimate LAI, analyzing a sequence of BSC may provide a strategy to applicate SAR to evaluate rice production in developing countries.

4.2 Materials and Methods

4.2.1 Overview and Test Sites

This study used LAI data from farmers' fields in Vientiane province in 2013, Lao PDR (18°01' - 18°30'N, 102°24' - 103°02'E, 168 - 178 m asl.), observed by Chapter 3-2. We analyzed SAR data in relation to LAI, together with the normalized difference vegetation index (NDVI) measured in the same fields.

30 farmers' paddy fields in this area were selected for surveying throughout the growth period (Chapter 3-2). We selected the fields that had open space in the direction of satellite orbit (west and approximately 45º in the incident angle) and that were surrounded by relatively flat paddy fields (at least 1 ha in the area). The mean air temperature for the measuring period (from 22 July to 16 September) was 28.0 ºC. The

longitude and latitude of the selected fields were recorded by Global Positioning System (GPSMAP 62SJ, Garmin International, Inc., Kansas City). The cultivation methods (direct seeding/transplanting, fertilizer, planting density and cultivar) of rice plants and field conditions (standing water and weeds) in the farmers' fields under investigation were checked by the authors' observation and interviews to farmers. The fields where the maximum depth of standing water exceeded more than 30 cm were classified as deep water fields, and the fields where weeds covered a maximum of 20 % or more were classified as weedy fields in this study.

4.2.2 LAI Measurements and Analysis

LAI was measured using a plant canopy analyser (LAI-2200, LI-COR, Inc., Nebraska) with a single sensor mode in a sequence of two above and four below canopy with 5 replications at each field. To reduce the influence of the adjacent fields and the operator, a 90^{o} view-cap was applied to the optical sensor. Measurements were conducted 4 times before the heading period (22 - 24 July, 10 - 12 August, 30 August - 1 September and 16 - 18 September). Since LAI linearly increased during the measurement, LAI growth rate was calculated using the following linear function (Eq. (1); Chapter 3-2).

$$LAI = a * DAT + b \quad (1)$$

DAT denotes days after transplanting, a represents LAI growth rate, and b represents approximate LAI at the transplanting date.

4.2.3 NDVI Measurement

For measuring spectral reflectance of rice canopies, we used a spectroradiometer (MS-720, EKO Instruments Co., Ltd., Tokyo). MS-720 measures radiation from 350 nm to 1050 nm by 3.3 nm intervals. We measured the sky radiation with a FOV 180° attachment and the plant reflection with a FOV 45° attachment from 1 m above the rice canopies, with 3 replications at each field when we measured LAI. We calculated canopy reflectance by dividing plant radiation by sky radiation. We calculated the normalized difference vegetation index (NDVI) using canopy reflectance in RED (620-670 nm) and NIR (841–875 nm) (Eq. (2)).

NDVI = (reflectance in NIR – reflectance in RED) / (reflectance in NIR+ reflectance in RED) (2)

4.2.4 SAR Images

X-band SAR images from the Constellation of Small Satellites for the Mediterranean Basin Observation COSMO-SkyMed system (ScanSAR Wide Region mode, HH polarization) were used in this study to acquire high temporal and spatial-resolution SAR data. COSMO-SkyMed can supply high temporal and spatial-resolution data by operating 4 satellites on the same orbit. All COSMO-SkyMed images used in this study were acquired during ascending orbit. The incidence angle for data acquisition was approximately 45°. Spatial resolution was adjusted to 30 m by multi-look processing and spatial filtering to reduce speckle noise. The 3 × 3 pixel Lee filter (Lee, 1980) was applied to the images used in this study. Back scattering coefficients (BSC) of SAR images is increased as rice plants grow in the paddy fields (Fig.4.1).

Eight SAR images were obtained from the period between transplanting and heading: on 22 and 30 July, 7, 15, 23 and 31 August and 8 and 16 September. 4 SAR images on 22 July, 7 August, 31 August and 16 September were selected to analyze the relation with LAI and NDVI measured on 22 - 24 July, 10 - 12 Aug, 30 Aug - 1 Sep and 16 - 18 Sep, respectively.

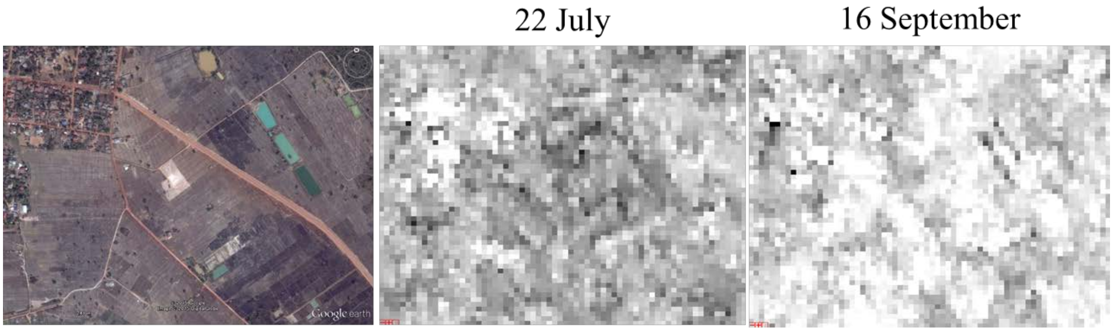


Figure 4.1. The map of Google earth (left) and synthetic aperture radar (SAR) images (center and right) for a part of the research area. Back scattering coefficient (BSC) is gray-scaled in the SAR images. The increase of BSC (gray in 22 July to white in 16 September) corresponded to the rice growth in paddy fields.

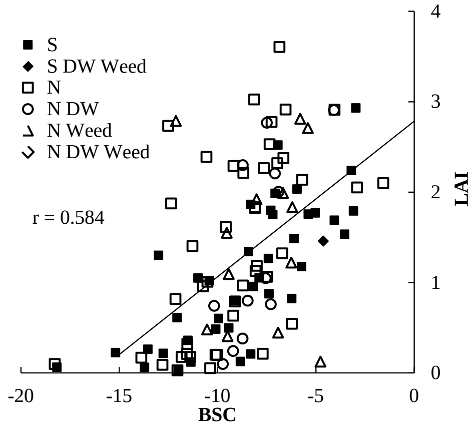
4.3 Results and Discussion

Back scattering coefficient (BSC) at the investigated fields in SAR images ranged from -18.3 to -1.57. LAI and NDVI ranged from 0.03 to 3.60 and from -0.24 to 0.81, respectively. BSC at 28 of 30 fields had a positive correlation with days after transplanting (DAT), corresponding with rice growth (Fig. 4.1). However, only 10 of these results were significant. Observations at the investigated fields indicated that non-significance was partly caused by deep water or weeds (see Fig. 4.2).

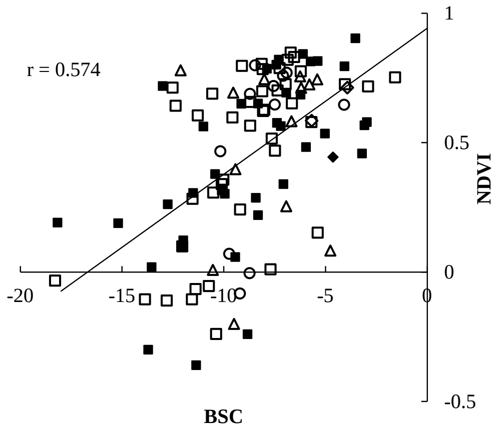
Fig. 4.2a shows that BSC was significantly correlated with LAI (LAI; $r = 0.584$, $p < 0.001$). Although the value was slightly lower than that previously reported (0.75 by Inoue *et al.*, 2014), the difference might be derived from that between X-band and C-band. Previous studies also reported that BSC at rice fields showed saturation greater than 3 in LAI similar to the levels NDVI often suggested (see Fig4.2c; Capodici *et al.*, 2013; Inoue *et al.*, 2014). However, BSC in this study did not show such saturation due to moderate correlation with LAI. Deep water and weeds are generally the factors that disturbed the relationship between LAI and BSC because BSC is decreased by water (Martinez and Toan, 2007) and increased by weeds (Liew *et al*., 1998). In this study, however, the relationship did not improve even if weedy and DW fields were excluded from the analysis (Table 4.1). Fig. 4.2a and Table 4.1 shows that BSC and LAI had a closer correlation at the fields where BSC and DAT had a significant correlation. These results suggest that the possibility of estimating LAI is dependent on location and that the observed increase in BSC with DAT is a required condition. Interference from adjacent area (Miyaoka *et al*., 2013) or orientation of ridge in paddy fields (Yamaguchi *et al.*, 2005) may cause such locational error. Although further study is necessary, selection of observation point on the basis of the relation between BSC and DAT probably improves the estimation accuracy for LAI with BSC.

Fig. 4.2b demonstrates that BSC was also correlated with NDVI ($r = 0.574$, $p < 0.001$). Although LAI and NDVI displayed a nonlinear relationship (Fig. 4.2c), no distinct difference was observed in the relationship between BSC and LAI and that between BSC and NDVI (Fig. 4.2a and Fig. 4.2b). Further studies are necessary to determine what structural factors in rice canopy affect BSC.

(a)



(b)



(c)

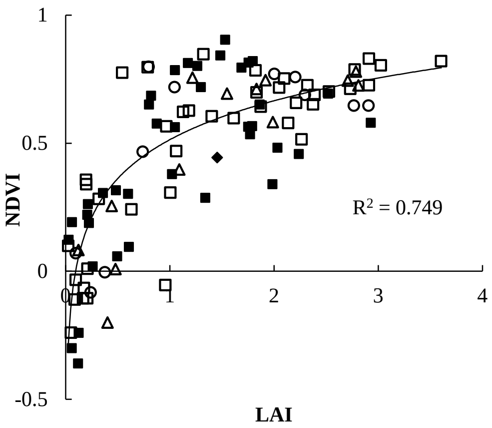


Figure 4.2. Relationship between (a) back scattering coefficient (BSC) and leaf area index (LAI), (b) BSC and normalized difference vegetation index (NDVI), (c) LAI and NDVI. S: the field where BSC and DAT had a significant correlation. N: the field where BSC and DAT had a non-significant correlation. DW: the field that had more than 30 cm depth of standing water. Weed: the field covered by more than 20 % weeds at the maximum.

Table 4.1. Correlation coefficients of back scattering coefficient (BSC) with leaf area index (LAI) and normalized difference vegetation index (NDVI). Except DW: DW fields were excluded from the correlation; Except Weed: Weed fields were excluded from the correlation; Except N: the fields where BSC and DAT had a non-significant correlation were excluded from the correlation; see Fig. 3.

	LAI	NDVI
All	0.584	0.574
Except DW	0.551	0.509
Except Weeds	0.603	0.585
Except N	0.766	0.593

The increased rates of BSC against DAT obtained in the fields where BSC and DAT had a significant correlation were also significantly correlated with LAI growth rate (the regression line in Fig. 4.3). However, those fields in which BSC and DAT showed a non-significant correlation tended to yield lower values of BSC increase rate that expected from the regression line. This finding suggests that if a significant increase of BSC against DAT was obtained, the increased rate may represent LAI growth rate. In Chapter 3-2, I reported that LAI growth rate was closely associated with soil C and N levels, which is a major indicator of soil fertility and consequent rice production in the study area. These facts suggest that soil fertility and rice productivity could be estimated from BSC even though LAI cannot be directly estimated from BSC.

Although LAI ordinarily shows curvilinear growth such as sigmoid, this study estimated the growth rate by a linear function (Eq. (1)) according to Chapter 3-2. The linear growth indicates that the observation was conducted after exponential growth and before saturated growth. Low LAI (see Fig. 4.2a) may help rice to keep linear growth of LAI before heading. To follow rice growth more precisely, more frequent measurements are necessary especially just after transplanting and around heading. Such frequent observation of LAI and BSC might improve the estimation of rice growth.

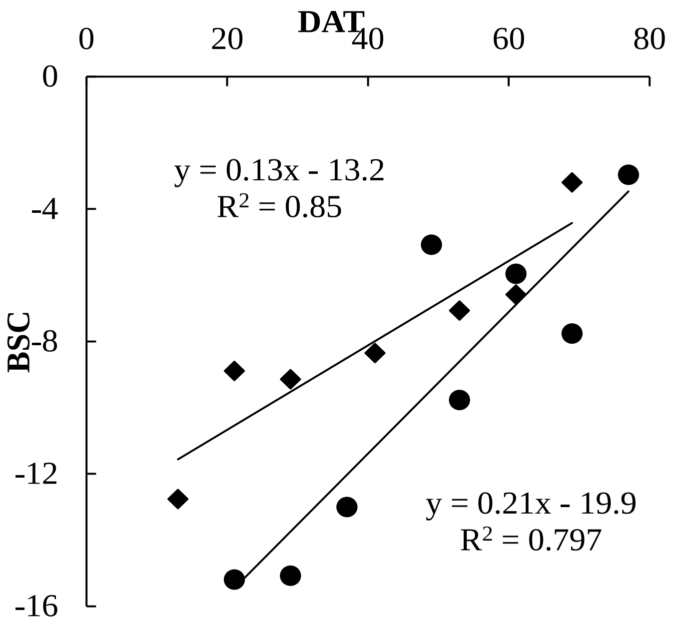


Figure 4.3. Changes in the back scattering coefficient (BSC) with days after transplanting (DAT) at the two fields where BSC and DAT had a significant correlation. The slope of the regression line was defined as rate of BSC increase.

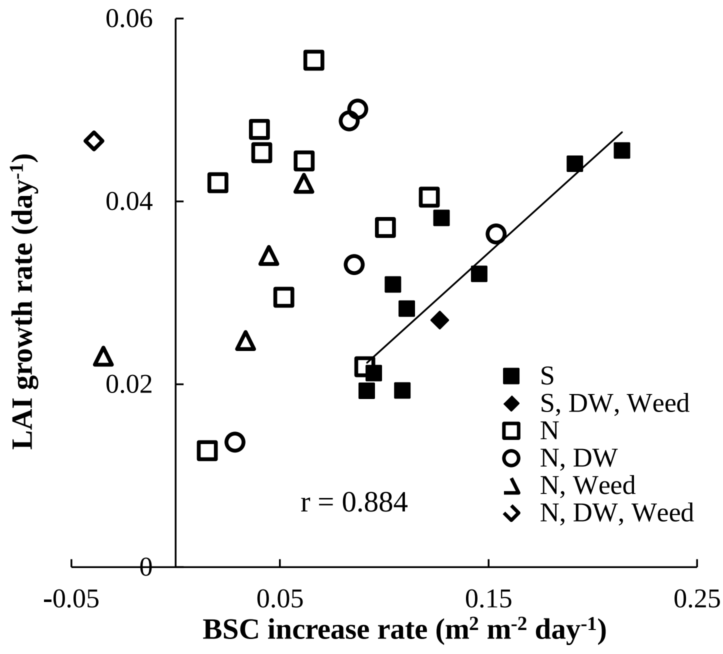


Figure 4.4. Relationship between leaf area index (LAI) growth rate ($m^2\ m^{-2}\ day^{-1}$) and back scattering coefficient (BSC) increase rate (day^{-1}). The line was regressed by the field where BSC and DAT had a significant correlation (S). The symbols are the same in Fig. 4.3; The fields which were classified into DW or Weed at least one time in Fig. 4.3 were defined as DW or Weed fields, respectively.

Rice production in Lao PDR is currently conducted on small and untidy paddy fields where many trees are left uncut (Kosaka *et al*., 2006; Miyagawa *et al.*, 2013). Uncontrollable water levels (drought and deep water) and weeds often constrain rice production in this area (Inamura *et al.*, 2003; Inthavong *et al.*, 2011). These factors are unfavorable for evaluating rice growth by SAR images. The dependence on incidence angle and azimuth angle of the SAR sensor in the relationship between BSC and LAI should also be analyzed further in order to accurately estimate LAI (Gautier *et al.*, 1998). Despite the remaining limitations, this study has demonstrated the capacity of SAR to evaluate rice production in developing countries. Combining an area map of planted rice as well as planting dates both of which are obtained from SAR images (Miyaoka *et al.*, 2013; Maki *et a*l., 2015) may help a more accurate evaluation of rice productivity.

Chapter 5

General Discussion

5.1 The Advantage of Non-destructive Measurement Method

The non-destructive measurement was used in agricultural research as the replacement of destructive measurement in the previous studies (e.g. Lohila et al., 2003; Haboudane *et al.*, 2006), but this study focused on the advantage of non-destructive measurement method. Non-destructive method enables us to measure the same canopy many times during growth period and this enables us to evaluate the characteristics of LAI dynamics much easier than conventional method. In this method, the parameters by several mathematical equations numerically showed the LAI dynamics and spatial characteristics, for which the data obtained by frequent and stratified measurements with a plant canopy analyzer were used. The difference in LAI dynamics and spatial characteristics among cultivars or environments is easily quantified by this method, which will be utilized at many occasions. Therefore, this method is believed to be applicable to many cultivars and is expected to contribute to evaluation of growth environments because this method facilitates measuring in many plots.

Although LAI values were used for simulation of the processes of dry matter production and yield forecasting in previous studies (e.g. Horie *et al*., 2003; Yoshida *et al*., 2007), this study investigated rice growth environments and managements based on the LAI measurement. The non-destructive measurements were used as input data in this study. Thus, this study evaluated rice growth characteristics based on the measurement, and used mathematical model to quantify the growth characteristics. This method is considered to be a distinguishing characteristic of this study, and might help us to evaluate the plan growth characteristic in the field environments.

5.2 Application of the New Evaluation Method to Field Research

In the field research, rice growth has been evaluated by the measurement of tillering number, plant height and chlorophyll (SPAD) (Dinkugn *et al.*, 1998; Esfahani *et al.*, 2008), and these measurements required large amount of time and labor. Previous studies measured and analysed the rice growth processes in reference to seed yield (e.g. Wada, 1981), but the measureable environments were limited. Therefore, evaluation method of rice characteristics of growth dynamics has not been generalized and established. Recently, non-destructive measurements such as remote sensing have been proposed for the agricultural research. In addition to non-destructive measurement, mathematical functions were employed for the quantification of rice growth characteristics in this study. This evaluation method is expected to be developed to general model and is also thought to be effective under various environments such as Southeast Asia and Africa.

Destructive method is not suitable for evaluation of LAI of rice when a large number of cultivars and farmers' fields are to be studied, because rice samples cannot be collected easily. Particularly in farmers' fields, rice samples cannot be collected destructively. This is the reason why crop response under fluctuating environments has not been fully understood. In this study, new evaluation method was applied to many cultivars and cultivation environments, and elucidates the genotypic variations and the variation factors of cultivation environments. The production constraints in the lowland paddy fields in South-east Asia are poor soil fertility, drought, flooding and diseases, contributing to the low rice yield (Schiller *et al.*, 2001), but the information about the cultivation environment and management and their effects on rice productivity in farmers' paddy fields is quite limited. By using parameters of LAI dynamics, growth characteristics of paddy fields in Southeast Asia were investigated. The result quantitatively shows the limiting factor of productivity in those areas.

5.3 The Non-destructive Evaluation Method of Rice Canopy Structure

The vertical distribution of LAI is the principle factor that determines light distribution and leaf physiological characteristics in rice canopies (Guo *et al.*, 2015). Since Monsi and Saeki (1953) first applied the Beer-Lambert law predict light transmission in the plant canopy assuming random distribution of leaves, several studies have investigated the vertical distribution of light for rice (*Oryza* spp.). These studies demonstrated "relatively small" vertical attenuation of light from top of the canopy in the new cultivars compared to old cultivars (Saitoh *et al.*, 1990), and characteristics of nitrogen distribution patterns in the leaf canopy (Hasegawa *et al.*, 1999; Shiratsuchi *et al.*, 2006). On the other hand, there are very few studies which analysed quantitatively to state how and to what extent the canopy architecture of the current cultivars are to be improved for better light use. This is because continuous monitoring of LAI vertical distribution under various plots made a big effort. This study enables us to monitor the LAI vertical distribution and analyse the effect of canopy structure.

5.4 Further Study of Evaluation Method in a Large Scale Area

This study evaluated rice growth characteristics and cultivation environment and management based on LAI data measured by plant canopy analyser. This study also analysed remote sensing data and shows the applicability of synthetic aperture radar (SAR) to evaluate rice productivity. Practically, there are many problems for accurate estimation of rice growth in farmers' fields by remote sensing data. Further studies for evaluation of rice growth characteristics on a regional scale in detail is needed, because LAI growth only can be roughly estimated by remote sensing data in this study.

Supports for farmers' decision on crop management has been needed because optimization of crop cultivation is strongly recommended (Mariano *et al.*, 2012). Rice growth characteristics were evaluated in this study, but in Japan, the information about growth characteristics of another crops such as soybean and/or wheat is needed more because there are many problems about the cultivation of those crops such as fertilization and insect management. In rice paddy fields, this evaluation method might be important in farmer's fields in less-productive area such as South-east Asia and Africa. Gathering information about rice growth characteristics from remote sensing data is one of the key method to optimize the cultivation in farmers' fields (Inoue *et al.*, 2014).

Many previous studies have investigated the practical application of remote sensing data to agricultural research (e.g. Inoue, 2003; Seelan et al., 2003), but only one remote sensing technology was used in these studies. The remote sensing data based on the red visible and near-infrared light images is not useful in east and monsoon Asia because there are frequent cloudy days during the rice growth periods. On the other hand, the remote sensing data based on microwave SAR images is affected by the slope of topography while this is not affected by cloud and sunlight. Therefore, further studies of using comprehensive remote sensing technologies may be needed. For example, agricultural research has focused on unmanned aerial vehicle (UAV) and thermal images (Uto *et al.*, 2013). These might help us to develop a method to evaluate rice growth characteristics because remote sensing data complement each other. The improved method might be very effective for the improvement of rice productivity in less-productive area.

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Hirooka, Y., Homma, K., Shiraiwa, T., Kuwada, M. Parametarization of Leaf Growth for Rice (*Oryza sativa*. L) by Utilizing Plant Canopy Analyzer. *Field Crops Research*. (in press)

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