Development of a rice simulation model for remote-sensing (SIMRIW-RS)

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Abstract

To evaluate rice production and management on a regional scale, a simulation model combined with remote-sensing is recommended. This study aimed to develop a simulation model for use with remote-sensing (SIMRIW-RS) to evaluate the field-to-field variation in rice production on a regional scale. This model was developed based on a simulation model for rice weather relations called SIMRIW and its derived models. The model consists of 6 components (water budget, nitrogen uptake, phenological development, leaf area index (LAI) growth, dry matter production and yield formation) and has 2 representative field parameters and 5 representative cultivar parameters. The parameters that were determined with the data from previous field studies seemed to be reflected with field and cultivar characteristics, and differences in the rice growth and production among the fields and cultivars were well explained by the model. The application of the model on a regional scale using remote sensing is discussed.

Key words: Farmer's management, Leaf area index (LAI), Nitrogen uptake, Regional scale, Soil fertility.

1. Introduction

From the viewpoint of environmental management in Asia, the regional evaluation of rice production is a key factor because paddy fields occupy a large part of land, and rice supports a large number of people in Asia. Although rice simulation models are usually considered effective tools for the evaluation of rice production, previous models have been developed based on weather rice production relationships or field-scale observations (Horie *et al.*, 1995; Bouman, 2001; Timsina and Humphreys, 2006; Yoshida and Horie, 2010). Accordingly, a combination with remote-sensing has been explored to apply rice simulation models on a regional scale (Inoue *et al.*, 1998; Oki *et al.*, 2013; Wang *et al.*, 2014).

A simulation model for rice weather relations called SIMRIW (Horie *et al.*, 1995) can explain the climatic variability in rice production (Tanaka *et al.*, 2010; Kotsuki and Tanaka, 2013) and has been used to estimate rice production in future climates (Matthews *et al.*, 1997; Murdiyarso, 2000). Ohnishi *et al.* (1997) modified SIMRIW to a nitrogen (N)-driven type that incorporated the rice plant response to N uptake to evaluate fertilizer application in irrigated fields. Homma and Horie (2009) expanded the N-driven type to simulate rice growth under rain-fed condition (SIMRIW-Rainfed) by incorporating water stress and N supply modules. However, because these models were developed independently of remote sensing, the development of a calibrating procedure by remote sensing is necessary.

In order to calibrate a simulation model for rice growth by remote sensing, the leaf area index (LAI) output from the simula-

tion model is often calibrated by that from remote sensing (Inoue *et al.*, 1998; Xue *et al.*, 2005). However, because LAI growth is determined by certain causes, the calibration should be performed for parameters that represent the causes. The field-to-field variation in LAI is mostly determined by soil fertility, water availability and farmers' management if the growth characteristics of cultivars are similar in the region (Homma *et al.*, 2007b; Hirooka *et al.*, 2017). This situation also implies that the calibration of the LAI growth of rice demonstrates field-to-field variation in soil fertility, water availability or farmers' management.

This study aimed to develop a simulation model for use with remote sensing (SIMRIW-RS) to evaluate the field-to-field variation in rice production on a regional scale. This model was based on SIMRIW, N-driven type SIMRIW and SIMRIW-Rainfed and incorporated the field parameters of soil fertility and water availability to be determined by remote-sensing. To validate the performance of this model and to obtain the parameters, several datasets were used, namely datasets that were obtained in experiments in Kyoto and from field observations in Indonesia and Thailand (Homma *et al.*, 2007b; Hirooka *et al.*, 2013; Homma *et al.*, 2013). The possibility of application with remote sensing was discussed based on the validation. A trial application was described in the accompanying paper in this issue (Maki *et al.*, 2017).

2. Materials and Methods

2.1 Components of the model

This model calculates daily values and consists of the following 6 components: (1) water budget, (2) nitrogen balance, (3) phenological development, (4) LAI growth (5) dry matter production and (6) yield formation. Because each component has been previously discussed (Horie *et al.*, 1995; Ohnishi *et al.*, 1997; Homma and Horie, 2009), here, they are only described briefly.

The first 2 components followed SIMRIW-Rainfed (Homma and Horie, 2009). The water budget component was mostly de-

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rived from Ritchie (1972) but has a variable for standing water (sdw , m).

$$(sdw, smc) = f_1(Weather, Soiltexture, LAI, \alpha_1) \quad (\text{Eq. 1})$$

$$ws = f_2(smc, \beta_1) \quad (\text{Eq. 2})$$

where smc is the soil moisture content ($\text{m}^3 \text{m}^{-3}$), and ws is the numerically indexed water stress ($\text{m}^3 \text{m}^{-3}$). The field characteristics were represented by a parameter for the available water capacity (α_1 , m). α_1 corresponds to the amount of water in the soil that the plant can uptake. The cultivar difference in the water stress sensitivity was represented by parameter β_1 ($\text{m}^3 \text{m}^{-3}$). The relationships between ws and the other components are described in Homma and Horie (2009).

The nitrogen balance component includes the N supply from the soil and fertilizer and the N uptake by the plant (nup , $\text{g m}^{-2} \text{d}^{-1}$). These procedures are simplified based on the experimental results (Homma *et al.*, 2003) and are represented by parameters for the N mineralization capacity (α_2 , g m^{-2}) and N uptake ability (β_2 , d^{-1}). α_2 is associated with the amount of N that is mineralized from the root layer soil, and β_2 is associated with the conductance of N from soil to plant.

$$\Delta N_{pool} = f_3(Weather, smc, \alpha_2, Fertilizer, nup) \quad (\text{Eq. 3})$$

$$\Delta nup = f_4(N_{pool}, ws, \beta_2) \quad (\text{Eq. 4})$$

where N_{pool} (g m^{-2}) is the available N in the soil, and Δ represents the daily increment.

The phenological development component followed SIMRIW (Horie *et al.*, 1995). The developmental status of the plant is numerically indexed (dvi) as 0 for seeding, 1 for heading and 2 for maturity. The daily development is termed the developmental rate (dvr).

$$dvr = f_5(Weather, ws, \beta_{cultivar}) \quad (\text{Eq. 5})$$

$$dvi = \sum dvr \quad (\text{Eq. 6})$$

The component of phenological development consists of several parameters, but the parameter sets were already prepared for several cultivars ($\beta_{cultivar}$).

The final 3 components for LAI (lai , $\text{m}^2 \text{m}^{-2}$), aboveground dry matter (dm , g m^{-2}) and grain yield ($yield$, g m^{-2}) followed the N-driven type SIMRIW (Ohnishi *et al.*, 1997). The components were relatively complicated but were represented mostly by parameters for the maximum relative expansion rate of LAI (β_3 , $\text{m}^2 \text{m}^{-2} \text{g}^{-1}$), the radiation conversion efficiency (β_4 , g MJ^{-1}) and the harvest index (β_5 , g g^{-1}).

$$lai = f_6(\Delta nup, ws, \beta_3) \quad (\text{Eq. 7})$$

$$dm = f_7(nup, lai, ws, \beta_4) \quad (\text{Eq. 8})$$

$$yield = f_8(dm, nup, ws, \beta_5) \quad (\text{Eq. 9})$$

Although these equations have many parameters in addition to the above-described representative parameters, we omitted these parameters in this study because their differences do not seem large among the fields or among the cultivars. Consequently, this model has 2 representative field parameters for the available water capacity (α_1) and N mineralization capacity (α_2) and has 5 representative cultivar parameters for the sensitivity of water stress (β_1), N uptake ability (β_2), maximum relative expansion rate of LAI (β_3), radiation conversion efficiency (β_4) and harvest index (β_5) in addition to parameters for phenological development ($\beta_{cultivar}$).

2.2 Parameterization

To obtain the parameters and to validate the performance of the model, we used a previously obtained dataset (Homma *et al.*, 2007b; Hirooka *et al.*, 2013; Homma *et al.*, 2013). This dataset included the soil chemical properties, plant growth (N uptake, LAI and dry matter production) and yield. The experiments in Kyoto consisted of 3 type of fields (custom-managed and 7-year- and 59-year-unfertilized before the experiments), and we set 3 types of fertilizer treatments (non-fertilizer, basal only and standard) in the custom-managed field (Hirooka *et al.*, 2013). The standard fertilizer treatment applied $\text{N-P}_2\text{O}_5\text{-K}_2\text{O} = 5\text{-}5\text{-}5 \text{ g m}^2$ as basal and twice $\text{N-P}_2\text{O}_5\text{-K}_2\text{O} = 2.5\text{-}2.5\text{-}2.5 \text{ g m}^2$ as a top dressing. The experiments were conducted in 2010 and 2011 using 6 cultivars: Nipponbare (Japonica, standard, Japan), Beniasahi (Japonica, traditional, Japan), Takanari (Indica, high-yielding lowland, Japan), Kasalath (Indica, traditional, India), Bei Khe (Indica traditional, Cambodia) and B6144F-MR-6-0-0 (B6144F) (Indica, high-yielding upland, Indonesia). The farmers' field observations were conducted in Northeast Thailand (Homma *et al.*, 2007b) and in West Java, Indonesia (Homma *et al.*, 2013). The observations in Northeast Thailand were conducted for 19 fields in 1997 and 1998. The major cultivars were KDML105 and its glutinous mutant RD6. The observations in West Java were conducted for 60 fields in 2011 and 2012. The major cultivar was Ciherang.

The parameter for the available water capacity was estimated based on the standing water and soil moisture in the farmer's fields in Northeast Thailand (Homma *et al.*, 2004). Because the fields in Kyoto and West Java had standing water during rice growth, and a constant value was applied for this parameter (no effect on the results). The parameters for the N mineralization capacity and N uptake ability were estimated based on the N uptake of the plant. The parameters for the maximum relative expansion rate of LAI, radiation conversion efficiency and harvest index were estimated based on the LAI, dry matter production and yield in the dataset, respectively. These estimations were conducted for each component by the simplex method to minimize the residual sum of squares between the observed and estimated values. The parameters for phenological development were derived from previous studies on Nipponbare (Horie and Nakagawa, 1990) and KDML105 (Homma *et al.*, 2001). The parameters for the other cultivars were estimated from experimental results (data not shown). The parameters except for these representative parameters were set as constants based on previous studies (Homma *et al.*, 2007b; Hirooka *et al.*, 2013; Homma *et al.*, 2013).

3. Results

3.1 Field parameters

The parameters for the available water capacity (α_1) as estimated for the farmer's fields in Northeast Thailand showed correlations with the elevation and clay contents in the soil. The N mineralization capacity (α_2) was consistent with the organic carbon content in the soil in Kyoto and Northeast Thailand but not in West Java. A higher N content in the soil may be associated with the parameter value in West Java (Homma *et al.*, 2013). The parameters in Kyoto showed relatively consistent values throughout the 2-year experiment (Table 1).

3.2 Cultivar parameters

The cultivar parameters that were estimated by the dataset are

shown in Table 2. Ciherang showed a high parameter value for the N uptake ability. Takanari also showed a higher value, suggesting that high-yielding lowland-type cultivars had a higher N uptake ability. Two japonica cultivars, Nipponbare and Beniasahi, showed lower parameter values than did the other indica cultivars.

Because the leaf expansion rate is mostly governed by the N uptake and parameter for the maximum relative expansion rate of LAI, the parameter itself suggests the ability of leaf expansion per unit N uptake, which consists of the allocation rate of N uptake to the leaf and the leaf area per unit N content. Kasalath showed a higher parameter value than did the other cultivars. Two high-yielding lowland-type cultivars, Takanari and Ciherang, showed lower parameter values, reflecting a higher N content per unit leaf

area and dry matter. Although the LAI of the 2 japonica cultivars was smaller than that of the indica cultivars (data not shown), the parameters for the maximum relative expansion rate were relatively higher in the japonica cultivars.

The parameter for dry matter production indicates the radiation conversion efficiency per unit leaf nitrogen. Kasalath shows a higher value that might be associated with a relatively higher stomatal conductance (Kanemura *et al.*, 2007). The parameter for the other cultivars was relatively similar.

The parameter for the harvest index was reflected by the yield against dry matter but does not represent actual values because the model uses a non-linear function of dry matter against yield. As commonly indicated, the high-yielding lowland-type cultivars,

Table 1. Field parameters for the N mineralization capacity (α_2 in Eq. 3).

	Kyoto			Thailand	Indonesia
	59 yr	7 yr	Custom		
2010	0.400	0.792	0.854		
2011	0.381	0.859	0.881		
Average	0.391	0.826	0.868	0.178	1.153

59 yr: 59-year unfertilized field before the experiments.

7 yr: 7-year unfertilized field before the experiments.

Custom: custom-managed field.

Average for 19 fields in Thailand and 60 fields in Indonesia.

Table 2. Cultivar parameters for the N uptake ability (NUA; β_2 in Eq. 4), maximum relative expansion rate of LAI (MRERL; β_3 in Eq. 7), radiation conversion efficiency (RCE; β_4 in Eq. 8) and harvest index (HI; β_5 in Eq. 9).

	β_2 NUA	β_3 MRERL	β_4 RCE	β_5 HI
Nipponbare	0.0650	23.3	0.84	0.422
Beniasahi	0.0563	17.4	0.78	0.385
Takanari	0.0942	8.7	0.79	0.483
Kasalath	0.0898	66.4	1.13	0.406
Bei Khe	0.0719	12.4	0.86	0.308
B6144F ¹⁾	0.0852	16.2	0.87	0.421
Ciherang	0.1399	7.1	0.59	0.488
KDML105	0.0714	12.6	0.57	0.433

¹⁾ B6144F: B6144F-MR-6-0-0

Fig. 1. Simulated and observed LAI of the cultivar Nipponbare that was grown under 5 treatments in Kyoto, 2010.

Fig. 2. Simulated and observed (a) dry matter (g m^{-2}) and (b) grain yield (g m^{-2}) at the maturity of rice that was grown under 5 treatments in Kyoto, 2010 and 2011.

such as Takanari and Ciherang, had higher values, while the traditional cultivars, such as Beniasahi and Bei Khe, had lower values.

3.3 Simulation of plant growth

The model explained well the changes in the LAI and the differences among the fields and treatments (Fig. 1; also see Maki *et al.*, 2017). The simulated dry matter and yield at maturity were also consistent with those observed (Fig. 2).

4. Discussions

4.1 Concept of the model

The model that was developed in this study requires input data of weather and farming management (planting, fertilizer and cultivar). The field parameters (α_1 and α_2) and cultivar parameters (β_1 – β_5 and β_{cultivar}) also need to be set. Remote sensing is used to calibrate the model simulation. We considered that the calibration of the model simulation by remote sensing was applied not only to estimate the rice production accurately but also to obtain useful information. Namely, the calibration will adjust parameters or farming management depending on the information availability: the field parameters will be estimated if the cultivar parameters and farming management are available; and farming management will be estimated if the field and cultivar parameters are available. For this purpose, the model has explicit parameters for field and cultivar and has rather simplified components.

The factors that affect the yield are mainly weather, farming management (transplanting, fertilizer and cultivar) and soil fer-

tility. Although pest and natural disasters sometimes reduce the yield, we did not consider these for this model because their prediction is quite difficult. While weather data are available (Homma *et al.*, 2007a; Laurenson *et al.*, 2002), obtaining information for soil fertility is more difficult than for farming management. Accordingly, we primarily focused on the evaluation of soil fertility in this discussion.

4.2 Evaluation of field-to field variation in soil fertility based on the calibration of the simulation model by remote sensing

Some studies have demonstrated the soil organic matter as the index of soil fertility (Homma *et al.*, 2003; Ladha *et al.*, 2004), while others have demonstrated available nitrogen (Cassman *et al.*, 1996). Some studies have determined soil fertility with biological production (Homma *et al.*, 2003). This study suggests that soil fertility can be evaluated by plant growth, although the model represents the soil fertility by the N balance in the soil.

Ordinarily, information that is obtained by remote sensing is mostly affected by the field coverage, namely leaf area index (LAI), in the crop field (Hashimoto *et al.*, 2009). Accordingly, remote sensing may evaluate the LAI growth rate in addition to LAI itself. The LAI growth rate is mainly reflected by the cultivar characteristics and N uptake (Ohnishi *et al.*, 1999; Yoshida *et al.*, 2007). The N uptake is governed by the N supply from the soil and fertilizer and by the plant N uptake ability (Homma and Horie, 2009; Yoshida and Horie, 2010). These facts suggest that if in-

formation regarding the cultivar characteristics and fertilizer are acquired, monitoring the LAI growth rate will evaluate the N supply. Although soil chemical analysis, for example mineralizable N, is ordinarily selected to provide information regarding the N supply, these analyzed values are sometimes inconsistent with leaf growth because many chemical and physical properties, such as pH and the root layer depth, are also associated with the N supply and leaf growth. However, the parameter that was directly evaluated by LAI growth in this study is the so-called phytometric N supply ability, which represents soil fertility. Hirooka *et al.* (2017) also suggest that the monitoring of LAI growth can estimate the soil fertility. The applicability of this model will be tested in a following paper in this issue (Maki *et al.*, 2017).

The strategy of fertilizer application (amount, type and time) is ordinary recommended by agricultural institutes for research or extension (URRC, 2014; IAARD, 2014) but often varies among farmers because the farmers do not follow the recommendations (Homma *et al.*, 2007b; Homma *et al.*, 2013). This variation makes it difficult to obtain information regarding the fertilizer when applied on a regional scale. In such cases, the parameter for N supply as estimated by remote sensing would include the effect of the variation of fertilizer application. Farming strategies for fertilizer application seem to not largely change year-by-year (author's observation). Consequently, the parameter for N supply consists of the effect of soil fertility plus the farming strategy and may be consistent with rice productivity under the current situation.

4.3 Evaluation of the field-to-field variation in water stress by remote sensing

Another factor that affects rice growth is water stress. Water stress is estimated by the soil moisture dynamics, which are calculated by Eq. 1 using a parameter for the available water capacity. This parameter is also difficult to obtain because it is affected by many properties, such as porosity, root layer depth and ground water level. Accordingly, remote sensing is considered an effective tool to obtain field-to-field variation in the available water capacity. Homma (2011) reported that available water capacity in soybean field can be estimated by the canopy surface temperature as remotely sensed from aircraft. The satellite-based monitoring of the soil moisture or surface temperature might provide information regarding the water stress and the available water capacity, although these evaluation methods are still under study (Fujii *et al.*, 2009; Anderson *et al.*, 2012).

The monitoring of the LAI may also provide information regarding the available water capacity because the water stress reduces its growth, but distinguishing the effect of water stress from that of soil fertility is quite difficult. The effect of soil fertility is rather stable throughout the years, while that of water stress fluctuates with different amounts of precipitation throughout the years. This situation allows the model to estimate the parameter for the available water capacity if several years of monitoring are conducted. The strategy of the estimation of field parameters will be verified in further studies.

4.4 Cultivar parameters

The abovementioned strategy requires the preparation of a set of cultivar parameters. The results in this study suggest that if the cultivar parameters are prepared, the model can estimate rice

growth and yield by evaluating the field parameters (Fig. 1). The cultivar parameters that are shown in Table 2 suggest that the classification of traditional/improved and indica/japonica provides some information about the parameter settings. However, more information is necessary to estimate the parameters for a certain cultivar. We conducted several experiments in Kyoto using the rice diversity of a research set of germplasm abbreviated as RDRS (Kanemura *et al.*, 2007; Takahashi *et al.*, 2007) that was released from the National Institute of Agrobiological Science, Japan (Kojima *et al.*, 2005). RDRS includes 69 genotypes that cover a large part of genotypic diversity in rice. The data that were obtained in the experiments may enable us to estimate the cultivar parameters. Takahashi *et al.* (2007) also suggest that the indica genotypes are superior for their N uptake and LAI growth.

Ordinarily, several cultivars are used within a region. However, some regions use cultivars with similar characteristics (Homma *et al.*, 2007b). Other regions use different cultivars depending mainly on their physiological characteristics (Homma *et al.*, 2013), and other regions use improved and traditional cultivars (authors' observation). Several studies have reported that the heading and maturity seasons can be distinguished by remote-sensing (Hashimoto *et al.*, 2009). Kambayashi *et al.* (2012) also suggest that improved and traditional cultivars can be distinguished by remote-sensing. Although the cultivar and its parameter cannot be accurately estimated, additional information may provide the assumed cultivar parameters.

4.5 Strategy of model application

To apply the model on a regional scale, information regarding farming management (fertilizer, cultivar and planting date) is necessary. However, even minimal information regarding the fertilizer and cultivar may be enough to provide the distribution of soil fertility (soil fertility map) on a regional scale as described above. Information regarding the planting date is also necessary, but several studies have indicated that the method to estimate the transplanting date using remote sensing has almost been developed (Miyaoka *et al.*, 2013; Maki *et al.*, 2017).

To calibrate the LAI growth of rice and to obtain a soil fertility map, at least 2 calibrations during rice growth might be necessary (Oki *et al.*, 2013; Maki *et al.*, 2017). Although the LAI estimation using visible and near infrared satellite images seems to be easier (Hashimoto *et al.*, 2009), the opportunity to obtain this type of perfect image is rare. Accordingly, the development of LAI estimation using satellite images of synthetic aperture radar (SAR) is expected, of which observation is possible under all weather conditions (Inoue and Sakaiya, 2013; Hirooka *et al.*, 2015).

The continuous estimation of a soil fertility map may improve its accuracy. Once this map is established, the model can simulate rice growth and production under assumed conditions, such as proposed farming management, future climate and irrigation strategy. Although the actual application using remote-sensing is being validated (Maki *et al.*, 2017), its combination with a hydrological model is shown in another paper in this issue (Noda *et al.*, 2017). Combining remote-sensing and its application will be reported in the near future.

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