A Model for Phenological Development of Vietnamese Rice Influenced by Transplanting Shock

Akihiko Kotera, Eiji Nawata, Pham Van Chuong*, Nguyen Ngoc Giao* and Tetsuo Sakuratani

(Graduate School of Agriculture, Kyoto University, Kyoto, 606-8502, Japan; *Vietnam Agricultural Science Institute, Thanh Tri, Hanoi, Vietnam)

Abstract: Phasic development of rice is influenced by various climatic conditions and the nursery duration. As a step toward the analysis of yield potential and yield loss in the Red River Delta, Vietnam, we conducted field trials with different nursery durations and transplanting times to develop a model for estimating heading times of a non-photosensitive cultivar CR203 in the Red River Delta. Days from seedling emergence to heading varied from 73 to 106 d, the rainy season crops having a shorter duration than the winter-spring season crops. The heading time could generally be estimated by the function of air temperature, but the delay in heading due to transplanting (transplanting shock), defined as the difference in the days from emergence to heading between transplanted and direct-seeded rice, ranged from 1 to 9 d and caused a substantial error in the heading time estimation. This variation in the delay of heading was explained as a function of the seedling age at the transplanting time. The model considering the transplanting shock estimated the heading dates in the independent data sets obtained at fields of local farmers with root mean square deviation (RMSD) of 2.15, while the model not considering the transplanting shock estimated those with a RMSD of 3.34. We conclude that this simple transplanting shock model was applicable for estimating the rice phasic development in the Red River Delta.

Key words: Development, Growth delay, Model, Red River Delta, Rice, Transplanting, Transplanting shock.

Rice production in the Red River Delta, Vietnam has increased rapidly over the last decade. However, productive stability is still low due to a number of yield constraints including drought, flood, diseases and insects. The magnitude of damage depends greatly on the growth stage of rice plants when they encounter damaging conditions. For instance, the stage from reduction division to heading is most sensitive to drought and submerging (Matsushita, 1967; Yoshida, 1981). Therefore, the ability to predict the growth stage would play an important role in the analysis of the yield loss and productive stability.

Rice cultivation in the Red River Delta is mainly carried out as a double crop, i.e., winter-spring and rainy season crops, by transplanting. Cultivation conditions of the two crops differ largely depending on the climatic and water conditions (Fig.1). Where photoperiod-insensitive varieties are grown, growth period in the winter-spring crop is longer than in the rainy season crop because of low temperature. Rice growth is sometimes troubled by very low temperature and water deficit in the winter-spring crop and by submergence of the field in the rainy season crop. Especially, younger rice plant is damaged easily. Therefore, the transplanting schedule is often adjusted to avoid the trouble and the nursery period is also very variable.

The transplanting has a considerable impact on the rice growth. Transplanting procedure generally delays the phenological development of rice. Roots of the seedlings are injured by transplanting, and the seedlings lose the balance between water uptake and transpiration. As a result, seedling leaves wilt due to water stress, and, under severe stress, some leaves could partly die (Yamamoto et al., 1978; Yamamoto, 1989). Various metabolic processes in transplanted seedlings are also disturbed by the influence of the decline of water content and root pruning (Mimoto, 1983). Consequently, the growth and development of the seedlings become stagnant temporarily. This phenomenon is called transplanting shock. The magnitude of the transplanting shock may differ depending on the seedling characteristics and the weather conditions before and after transplanting (Yamamoto et al., 1995). However, there is virtually no information on the magnitude of growth delay due to transplanting in the Red River Delta. Therefore, we need to determine the influence of transplanting shock on rice development and identify the major factors that affect growth delay in the Red River Delta.
Although various simulation models have been developed to predict the phenological development of rice (e.g. Takezawa and Tamura, 1991; Nakagawa and Horie, 1995; Yin et al., 1995; Huang et al., 1998), most models do not cover the influence of the transplanting shock because they were not targeted to transplanting cultivation or because of a lack of adequate quantitative data for model development. Only a few models, CERES-Rice (Ritchie et al., 1987), ORYZA1 (Kropff et al., 1994), RIBHAB (Salam et al., 1994) and the transplanting shock sub-model for CERES-Rice and RIBHAB (Salam et al., 2001), considered the transplanting shock which was estimated from the seedling age expressed as degree days during the nursery period. However, most of these transplanting shock sub-models, except the sub-model developed by Salam et al. (2001), were developed based on unpublished data and have not been validated sufficiently.

The objectives of this study were to quantify the influence of the transplanting shock on rice phenological development in the Red River Delta, and to improve the model accuracy by incorporating the influence of transplanting shock.

**Materials and Methods**

1. Field experiments

Field experiments were conducted at the Vietnam Agricultural Science Institute (VASI) in Hanoi, Vietnam (20°58' N, 105°52' E), for six cropping seasons in 1999 and 2000, using a Vietnamese improved variety, CR-203, with a photoperiod-insensitive character (Truong, 1998). In each cropping season, both direct-seeding and transplanting culture were carried out to expose seedlings to different environments (Table 1). The difference in days from emergence to heading between transplanted and direct-seeded rice was defined as the growth delay by transplanting shock (\(N_{d}f\)) in this study.

The experiment was laid out in a randomized complete block design with three replications and the size of each plot was 9 m\(^2\) (3 × 3 m). In the direct-seeding culture, seed were sown on a leveled flooded soil at a seeding rate of about 10 g m\(^{-2}\). In the transplanting culture, seedlings were raised in a shallow flooded nursery seeded at a seeding rate of 100 g m\(^{-2}\), then transplanted at a planting density of 48 hills m\(^{-2}\) (three plants per hill) without leaf pruning. The nursery was adjacent to the main plots so that air and water temperatures in the nursery were similar to those in the main plots.

Fertilizer inputs as a basal dressing were at a rate of 400 kg P ha\(^{-1}\) as single superphosphate, 100 kg K ha\(^{-1}\) as potassium, and 100 kg N ha\(^{-1}\) as urea. Additional 50 kg K ha\(^{-1}\) and 100 kg N ha\(^{-1}\) were broadcasted at the tillering stage and 100 kg K ha\(^{-1}\) and 50 kg N ha\(^{-1}\) at the booting stage. Weeding was performed manually, and pest was controlled following the standard recommendation. Floodwater was kept at 5-15 cm deep until 2 weeks after flowering.

Heading day was defined as the day when the panicles emerged from 50% of all productive culms.

**Table 1. The experimental data used for model parameterization.**

| Cultivation Type | Emergence date | Transplant date | Days in nursery | Heading date | Days to heading | Days of growth delay (N_{d}) |
|------------------|----------------|-----------------|-----------------|--------------|----------------|-----------------------------|
| DS* 25 Jan. '99   | 0              | 0 30 Apr.       | 95 ±0.3**       |              |                |                             |
| TP** 25 Jan. '99  | 26             | 6 May           | 101±0.6         | 6            |                |                             |
| DS 15 Jun. '99    | 0              | 29 Aug.         | 75±0.6          |              |                |                             |
| TP 15 Jun. '99    | 4 Sep.         |                | 81±0.6          | 6            |                |                             |
| DS 25 Jun. '99    | 0              | 6 Sep.          | 73±0.6          |              |                |                             |
| TP 25 Jun. '99    | 13 Sep.        | 20              | 80±0.6          | 7            |                |                             |
| DS 8 Feb. '00     | 20 May         | 106±0.6         |                |              |                |                             |
| TP 8 Feb. '00     | 20 Nov.        | 21 May          | 103±0.6         |              |                |                             |
| TP 8 Feb. '00     | 18 Mar.        | 24 May          | 108±0.6         |              |                |                             |
| DS 20 Jun. '00    | 0              | 5 Sep.          | 77±0.6          |              |                |                             |
| TP 20 Jun. '00    | 9 Sep.         | 81±0.6          |              |              |                |                             |
| TP 20 Jun. '00    | 12 Sep.        | 84±0.6          |              |              |                |                             |
| DS 5 Jul. '99     | 16 Sep.        | 73±0.6          |              |              |                |                             |
| TP 5 Jul. '99     | 21 Sep.        | 78±0.6          |              |              |                |                             |
| TP 5 Jul. '99     | 31 Aug.        | 82±0.6          |              |              |                |                             |

*DS: Direct Seeding, **TP: Transplanting, ***The standard error is in parentheses.
We observed the heading progress of 10 hills at the center of plot every day since the first heading. Air temperature was recorded at VASI with an automatic weather observation system (Datalogger CR10X and Temperature Probe CS500, Campbell Scientific, UT, USA).

The data used to validate the model were collected from 7 paddy fields of local farmers at Vinh Phu, Ha Nam and Hai Duong provinces located in the Red River Delta. The experiments were conducted in the winter-spring and rainy season crops in 1999 with totally 11 sowing times using the same rice variety, CR-203 (Table 2). All cultivation methods followed common practices performed by each farmer.

Daily weather data for the simulation at each local farmer’s site were obtained from the nearest weather stations; Vin Phu from Noi Bai station (21°01’ N, 105°51’ E, 20 km away from experimental area), Ha Nam from Nam Dinh station (20°26’ N, 106°09’ E, 25 km away) and Hai Duong from VASI (30 km away). The geographical conditions of each test site and the weather station were similar. In the Red River Delta region excluding a coastal area, the temperature condition is uniform (Cuong, 1968). Therefore the influence of the distance from each field to the station (20-30 km) would be small. During our experiment, from February to September in 1999, the difference of average temperatures between 3 weather stations was 0.3°C (Noi Bai 26.3°C, Nam Dinh 26.0°C, VASI 26.1°C).

2. Model

(1) Model structure

The developmental process of rice has been described using the developmental index (DVI) on a scale of 0 (emergence) to 1 (heading) (Horie and Nakagawa, 1990). The value of DVI is the integration of the developmental rate (DVR). In this study, we used the beta function to express the DVR response to temperature as proposed by Yin et al. (1995),

\[
DVR = \exp(\mu)(T - T_b)\alpha(T_c - T)^\beta, \quad (T_b < T < T_c)
\]

where \( T \) is daily mean air temperature, \( T_b \) and \( T_c \) are the base and the ceiling temperatures respectively, and \( \mu \), \( \alpha \), and \( \beta \) are cultivar-specific coefficients defining the curvature of the relationship respectively. The photoperiodic response was not included in our model because the variety we used was non-photosensitive.

After the transplanting, DVR was assumed to remain at zero, and DVI to be on a plateau for \( N_h \) days until the day of full recovery from the transplanting.
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Table 3. Values of parameters in Eq. (1) in the model TS and DS estimated from the data in table 1.

| model type | $\mu$ | $\alpha$ | $\beta$ | $T_{B(C)}$ | $T_{c(C)}$ | Winter-Spring(6)* | Rainy Season(10) | Whole Season(15) |
|------------|-------|----------|--------|------------|------------|------------------|------------------|------------------|
| model TS   | -13.89| 9.624    | 1.329  | 8          | 42         | 0.964            | 1.67             | 0.713            |
|           |       |          |        |            |            |                  |                  | 1.97             | 0.975            | 1.88             |
| model DS   | -13.95| 9.993    | 1.374  | 8          | 42         | 0.591            | 2.65             | 0.128            |
|           |       |          |        |            |            |                  |                  | 3.52             | 0.924            | 3.26             |

* The number of data sets fitted is in parentheses.
** $r^2$ is the linear regression between predicted and observed days.
*** RMSD is the Root Mean Square Deviation.

Fig. 4. Comparison of days to heading estimated by the two models: model TS with observed growth delay (○) and model DS (+). The line indicates a 1:1 relationship.

The sub-model simulating TSRR is developed based on the findings reported previously on transplanting shock and the experimental results in the present study. Detailed modeling processes of transplanting shock (TSRI sub-model) will be presented in "Result" section based on experimental data analyses.

In order to evaluate the influence of the transplanting shock on rice phenological model, we compared two types of model: "model TS" incorporating the influence of the transplanting shock and "model DS" without incorporating the transplanting shock. Fig. 3 shows the difference between developmental processes in models TS and DS. Although the equations for the phenological development are common to the two models, the parameters in this equation differ between the two models.

(2) Parameterization

The model parameters were estimated so that the sum of squares of the errors between observed and simulated days becomes minimum (Horie and Nakagawa, 1990). The simplex method (Nelder and Mead, 1965) with a program by Press et al. (1993) was utilized as a least square regression method for non-linear function. The estimates of $T_b$ and $T_c$ in Eq. (1) with the above method may not be reliable because
our data did not include an extreme temperature range. Yin et al. (1995) analyzed the sensitivity of \( T_b \) and \( T_c \) by varying \( T_b \) from 5 to 15 \(^\circ\)C and \( T_c \) from 35 to 45\(^\circ\)C, and showed that goodness of fit of Eq. (1) was hardly changed within a wide range of values for \( T_b \) and \( T_c \). Therefore, according to Yin et al. (1995), the standard values, 8 and 42 \(^\circ\)C, were given to \( T_b \) and \( T_c \), respectively, in our model.

Results

1. Growth and environmental conditions

Daily mean air temperature at VASI varied between 9.4 and 32.3\(^\circ\)C during the field experiments, covering most of the range observed for the past ten years at Hanoi (9.4 and 34.0\(^\circ\)C). Time from emergence to heading (\( N_e \)) varied from 73 to 106 d (standard deviation, S.D. = 11.83) (Table 1). \( N_e \) was largely different between the winter-spring season crop grown under low-temperature conditions (95 -106 d; S.D. = 4.04) and the rainy season crop grown under hot conditions (73-84 d; S.D. = 3.84). Growth delay caused by transplanting, \( N_{dt} \), ranged from 1 to 9 d. \( N_{dt} \) showed no significant correlation with \( N_e \).

Table 2 shows the results of cultivation experiments at the fields of the local farmers which were need to validate the model. Daily mean air temperature varied between 12.2 and 32.4\(^\circ\)C. \( N_e \) varied from 71 to 100 d (S.D. = 11.70), the shortest being observed in the field transplanted with 64-old seedlings at Hai Duong in the rainy season crop. The nursery period in each farmer's field varied widely from 6 to 27 d. Farmers in Vin Phu and Hai Duong tended to use younger seedlings preferably, since they are ensured early harvest. On the other hand, Ha Nam in the rainy season used older seedlings because of the poor drainage of the fields.

2. Effect of transplanting shock in model estimations

Two types of models were fitted to the experimental data to identify the influences of the transplanting shock on the heading dates: the first without transplanting shock (model DS) and the second with transplanting shock (model TS). In fitting the parameters of DVR in model TS, \( N_{ds} \) was given from the observed \( N_{dt} \). The parameters of the Eq. (1) for the model TS and DS are given in Table 3.

In order to verify descriptive ability of the two models, we compared the estimated value and the observed data used for parameterization (Fig. 4). The model DS reproduced well the heading day variation between cropping seasons with the whole data (root mean square deviation, RMSD = 3.26, coefficient of determination, \( r^2 = 0.924 \)), but poorly explained the within-season variation, notably in the rainy season datasets (RMSD = 3.52, \( r^2 = 0.128 \)). The model TS described the observed \( N_e \) better than model DS (RMSD = 1.88, \( r^2 = 0.975 \) for whole data, RMSD = 1.97, \( r^2 = 0.713 \) for rainy season data sets).

3. Relationship of transplanting shock with seedling age and temperature - TSRI sub-model -

Fig. 5 shows the correlation of observed \( N_{dt} \) with seedling age the average temperature during days of observed growth stagnation after transplanting. TSRR-S and TSRR-W are explained in the text.

Table 4. Cultivation conditions and observed and estimated growth delays: \( T_{ave} \) is the average temperature during days of observed growth stagnation after transplanting.

| Plot letter | Emergence date | Days in nursery | DVI\(_{TP}\) | Average temp. \( T_{ave}(^\circ)C\) | Growth delay (days) | Estimated with TSRR-S | Estimated with TSRR-W |
|-------------|----------------|-----------------|-------------|-------------------------------|--------------------|-----------------------|-----------------------|
| a           | 25 Jan. 1999   | 26              | 0.242       | 13.7                          | 7                  | 6                     | 5                     |
| b           | 15 Jan. 1999   | 20              | 0.276       | 31.2                          | 6                  | 6                     | 6                     |
| c           | 25 Jan. 1999   | 20              | 0.274       | 30.6                          | 7                  | 6                     | 6                     |
| d           | 8 Feb. 2000    | 20              | 0.116       | 12.8                          | 1                  | 2                     | 3                     |
| e           | 8 Feb. 2000    | 39              | 0.256       | 20.2                          | 4                  | 5                     | 4                     |
| f           | 20 Jun. 2000   | 15              | 0.211       | 31.4                          | 5                  | 4                     | 5                     |
| g           | 20 Jun. 2000   | 30              | 0.409       | 27.0                          | 8                  | 9                     | 9                     |
| h           | 5 Jul. 2000    | 15              | 0.210       | 22.3                          | 5                  | 4                     | 4                     |
| i           | 5 Jul. 2000    | 31              | 0.420       | 28.2                          | 9                  | 9                     | 9                     |

\[ r^2 = 0.795, 0.761 \]

RMSD 1.05 1.11

Table 5. Root mean square deviation (RMSD) and the \( r^2 \) value for the linear regression between observed and predicted days to flowering by the three types of model on farmer’s fields in the Red River Delta.

| model type         | Winter弹簧(4)* | Spring(4)* | Rainy Season(7)* | Whole Season(11)* |
|--------------------|----------------|------------|------------------|-------------------|
|                    | \( r^2 \) | RMSD       | \( r^2 \)  | RMSD             | \( r^2 \) | RMSD |
| model TS with TSRR-S | 0.617       | 1.50       | 0.932            | 2.45              | 0.979       | 2.15 |
| model TS with TSRR-W | 0.667       | 1.22       | 0.988            | 2.42              | 0.983       | 2.07 |
| model DS           | 0.667       | 1.22       | 0.661            | 4.08              | 0.923       | 3.34 |

* The number of environments fitted is shown in parentheses.
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\[ f(T) = \exp(\kappa)(T - T_p)^\gamma(T_q - T)^\delta, \quad (T_p < T < T_q) \]

where \( T_p \) and \( T_q \) are the base and the ceiling temperatures for TSRR respectively, and \( \kappa, \gamma \) and \( \delta \) are cultivar-specific coefficients defining the curvature of the relationship.

In fitting the parameters of TSRR-S and TSRR-W, we calculated DVI_{TP} by using the parameters in Table 3. For \( T_p \) and \( T_q \) in Eq (6), the standard values 8 and 42°C were given, respectively, for the same reason as in the case of the parameters \( T_b \) and \( T_c \) in Eq. (1). The best estimates of the parameters in Eq. (4) and (6) were \( \eta = 22.22, \kappa = -12.49, \gamma = 1.501, \delta = 1.886 \).

Table 4 shows the \( N_{ts} \) (growth delay) estimated by each model. The TSRI sub-model with Eq. TSRR-S estimated \( N_{ts} \) with slightly higher accuracy than that with TSRR-W. Although the seedlings transplanted on 28 February 2000 (plot letter “d” in Table 4 and Fig. 5) were exposed to a very low temperature, growth delay \( N_{dif} \) was short in both observed and estimated values. This reflects the fact that very young seedlings were transplanted at that time.

4. Comparison of model accuracy using independent data.

The comparisons between observed and predicted days to heading by the three models are shown in Table 5 and Fig. 6. Incorporating the influence of transplanting shock improved the accuracy of heading time estimation by about more than 1 d compared with the DS model. The superiority of the model TS was particularly obvious in the data sets in the rainy season crop. The model TS with TSRR-W estimated the heading time with slightly better accuracy than that with TSRR-S in whole season data, but the difference between two sub-models was small under the condition of the Red River Delta.

Discussion

Previous studies on transplanting shock have generally been focused on rooting period, which was often estimated by the leaf emergence rate (Mimoto, 1983), tillering activity (Yamamoto and Hisano, 1990) or dry matter accumulation rate (Ishizuka and Tanaka, 1969). Since all these factors relate to growth delay, \( N_{dif} \) was short in both observed and estimated values. This reflects the fact that very young seedlings were transplanted at that time.

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The field experiments in this study showed that growth delay (\( N_{dif} \)) by transplanting as compared with direct-seeding of rice varied from 1 to 9 d, and caused
a substantial error in the heading time estimation. Such a large variation in growth delay can take place in the actual rice cultivation in the Red River Delta because nursery duration and conditions are largely different between cropping seasons and paddy fields.

It is known that the difference in growth duration between transplanted and direct-seeded rice tends to increase proportionally as the growth period prolonged from hot to cool seasons, when seedlings of similar ages were used for transplanting (Dingkuhn et al., 1995). This suggests that growth delay (Nad) and growth period (Ni) have a close relationship. Therefore, the difference in Ni due to growth stagnation period was often lumped in a DVR function of temperature, so that many previous models could estimate Ni without a large error by estimating a lower DVR value. In fact, previous rice models without considering the transplanting shock generally have high accuracy; for instance, Nakagawa and Horie (1995) reported 1.5 to 3.6 d as the standard deviation of residuals. However, Nad and Ni under our experimental condition were not significantly correlated, since seedling age at transplanting was not uniform. Therefore, it is necessary to evaluate Nad independent of Ni in the model for applying to the Red River Delta. The result shown in Fig. 4 indicated that the descriptive ability of the original DVI model (model DS) was improved by considering Nad independently.

The previous studies showed that the temperature after transplanting influences the growth stagnation (Mimoto, 1983), but the model without the temperature effect (TSRR-S) could estimate the growth stagnation well. This is probably because the temperatures during growth stagnation were mostly distributed within the range where the effect of temperature was modest. We transplanted seedlings of various ages under different temperature conditions, but because this was not a controlled experiment, not all combinations of seedling ages and temperature during the rooting period were possible: Young seedlings (DVI < 2) were planted only under low temperature conditions and old seedlings (DVI > 4) only under high temperatures. Under these conditions, the seedling age effect probably overloads the effect of temperature. Especially, it is reported that the young seedling has superiority in the growth ability under the low temperature (Yamamoto et al., 1995). If old seedlings had been planted under cool conditions, the temperature effect on growth stagnation might have been pronounced.

Under the actual cultivation conditions in the Red River Delta, temperatures just after transplanting rarely become lower than 18°C (Fig. 1). The winter-spring crop might be exposed to a low temperature but the farmer can postpone the transplanting until the temperature rises. Therefore under the usual cultivation conditions in the Red River Delta, the growth delay due to transplanting would be expressed only by the function of seedling age.

When the seedlings are exposed to the abnormally high or low temperature after transplanting, they could die or be damaged by after-effects in later growth stages, but our model did not cover these processes. The range of the temperature during in the nursery was from 10.7 to 32.0°C. In this range, death of seedlings by after effects was not observed. The phenomenon beyond this temperature range was not tested in this study. On this meaning, this model should be used at least within this range of temperature.

We conclude that the prediction accuracy of this simple model (model TS with TSRR-S; RMSD = 2.15) would be practically satisfactory for analyzing the yield potential and yield loss in the Red River Delta.

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