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PREDICTING NURSERY GROWTH AND TRANSPLANTING SHOCK IN RICE

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SUMMARY

Seedling growth in the nursery and the magnitude of shock experienced by the seedlings after transplanting can affect subsequent growth and development of transplanted rice (*Oryza sativa*). These two processes have not been adequately represented by rice growth simulation models. In this study, seedling growth in the nursery was described with respect to endosperm mobilization, dry matter (DM) distribution and seed size. In addition, the transplanting shock process was represented describing the crop development and growth in relation to seedling age at transplanting. These relationships, as two sub-models, were incorporated into CERES-Rice, a rice growth model, and their performances compared with independent field data. The nursery growth sub-model was also evaluated with another model, RIBHAB. Results of the comparison showed that the nursery growth sub-model, either with CERES-Rice or RIBHAB, closely predicted observed seedling growth. On the other hand, CERES-Rice overestimated root and leaf DM and underestimated culm DM, while RIBHAB underestimated all the growth traits considered in the evaluation. Transplanting shock period predicted by the sub-model closely mimicked observation, whereas CERES-Rice highly overestimated it. It is concluded that the developed nursery growth and transplanting shock sub-models can be incorporated into CERES-Rice and other rice growth models for better simulation of those growth processes.

INTRODUCTION

Throughout diverse geo-climates, rice growing areas constitute 53% irrigated, 26% rainfed lowland, 13% rainfed upland and 8% deepwater ecosystems (Crosson, 1995). In those environments, both direct seeding and transplanting techniques of stand establishment are practiced (De Datta, 1981). Transplanted rice undergoes two more growth processes than does the directly seeded rice, nursery growth and transplanting shock.

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For the transplanting technique, rice seeds are sown in the nursery, seedlings emerge in time and are raised in a relatively dense population (1000–20 000 seedlings m^{-2} depending upon raising technique) before being transferred into the padi field. In the padi field, seedlings are transplanted to a lesser density, 100–400 seedlings m^{-2}, depending on hill density and seedling number per hill. Immediately after transplanting, seedling growth ceases; this is an expression of shock due to a change in environment from the nursery to the padi field. This phenomenon is known as 'transplanting shock' and the time span the seedlings remain in shock is called the 'transplanting shock period'. Seedlings resume normal growth after the recovery from shock. A conceptual pattern of growth and developmental processes of transplanted rice is shown in Fig. 1.

Application of simulation models for studying rice growth and development processes has now become widespread both in developed and developing countries. Salam *et al.* (1999) list at least 21 rice models that have been developed or adapted since the 1970s. During the early days of rice modelling, modellers either ignored or characterized poorly seedling growth in the nursery and transplanting shock in the padi field, primarily because of a lack of adequate quantitative data (Penning de Vries *et al.*, 1989). In developing the RIBHAB model, Salam (1992) first attempted mechanistic simulation of seedling growth in the nursery and transplanting shock in the padi field; however, those attempts were not validated due to a lack of experimental data (Salam *et al.*, 1994a). ORYZA1 and CERES-Rice, the most widely known rice models, can now

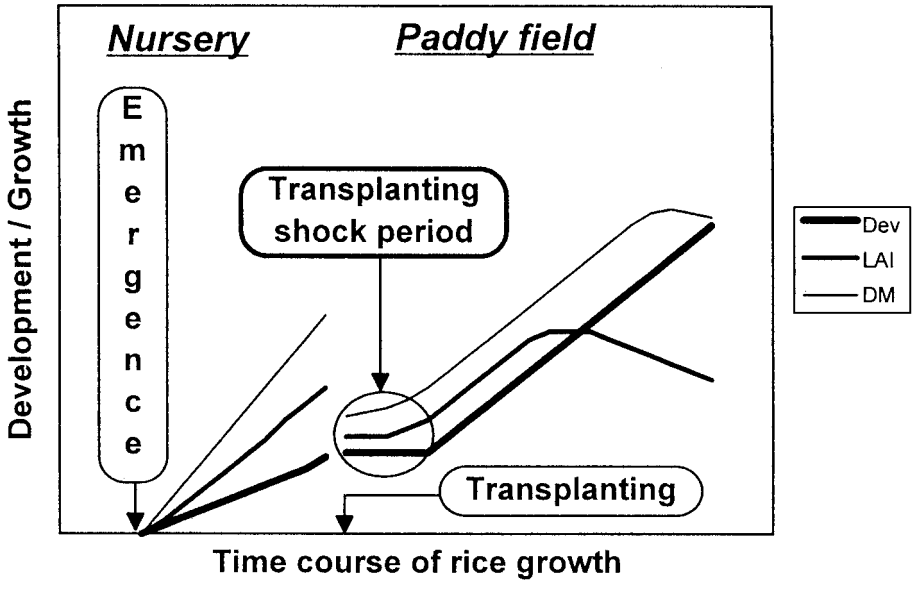


Figure 1. A conceptual pattern of growth and developmental processes of transplanted rice. 'Dev' denotes phenological development stage, LAI leaf area index and DM total seedling or crop dry matter. At transplanting, LAI and DM are reduced due to reduction in population density from the nursery to the padi field.

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simulate those two processes but, again, they have not been validated. Some recent studies (Ahmed, 1995; Kashem *et al*., 1995; Khatoon, 1995; Sattar, 1995; Salam *et al*., 1997) provide an opportunity to understand underlying factors related to rice seedling growth and transplanting shock, and are useful to evaluate performances of nursery growth and transplanting shock of rice.

In this paper, the processes of nursery growth and transplanting shock in rice are described. Two sub-models were developed (one for each of the processes) and their performances tested with independent field data by incorporating them into CERES-Rice and RIBHAB models.

MATERIALS AND METHODS

New nursery growth and transplanting shock sub-models for rice were incorporated into CERES-Rice as described by Ritchie *et al*. (1987) and Singh *et al*. (1993). The nursery growth sub-model was also incorporated into RIBHAB, described by Salam (1992) and Salam *et al*. (1994a).

Nursery growth sub-model

Seedling growth in the nursery is described in terms of three main aspects: endosperm mobilization, dry matter (DM) partitioning, and a relationship between seed size and seedling growth.

Endosperm mobilization. Cereal seedlings begin as heterotrophs, depending totally on food mobilized from the endosperm. They then pass through a transition stage during which photosynthesis commences while endosperm mobilization continues (Whalley *et al*., 1996). Finally, seedlings depend entirely on photosynthesis and become autotrophic. Rice models, including CERES-Rice, handle the pre-autotrophic phase in the same way as the autotrophic phase paying little attention to the mechanism of endosperm mobilization from seed and its accumulation into the seedling. The endosperm mobilization from seed to seedling in CERES-Rice (equation 1) and RIBHAB (equation 2) is treated as a single time operation during the initialization process as follows:

$$\text{SWACCU} = \text{SW} \tag{1}$$

$$\text{SWACCU} = \text{SW}*0.25 \tag{2}$$

where SWACCU is the mobilized seed DM (g) that is accumulated into the seedling, and SW is the seed weight (g). It is highly unlikely that all the seed weight could be transferred into the seedling because the husk which cannot be mobilized constitutes about 20% of the seed weight (Yoshida, 1981). RIBHAB's consideration (equation 2) that 25% of the seed weight is accumulated into the seedling is based on the assumption for cereal crops in general (Penning de Vries *et al*., 1989). A recent study indicates that a 0.42 ± 0.04 g g^{-1} seed weight of rice is accumulated into the seedling (Salam *et al*., 1997). Furthermore, this accumula-

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tion takes place not at a point in time, but over a period (up to 321 degree-days (°C.d) after emergence, assuming a base temperature, T_b, of 9 °C). During this period, accumulation is rapid in the heterotrophic phase and slows down during the transition phase. The mobilization process is also affected by temperature (Yoshida, 1973). Based on the available information, equation 2 was restructured as follows:

$$\text{SWACCU} = \text{SW}^* (a - b1^*\text{TSUM} + b2^*\text{TSUM}^2 - b3^*\text{TSUM}^3), \quad R^2 = 0.824, n = 72 \tag{3}$$

where TSUM is the daily accumulated temperature (°C.d) from emergence above a T_b of 9 °C, calculated after Cross and Zuber (1972); and a = 13.147, b1 = 0.1171, b2 = 0.0003, and b3 = 0.0000002. This relationship is valid for TSUM $\geqslant 19 \leqslant 200$ °C.d because information on the pattern of pre-emergence seed DM accumulation was not available, and after 200 °C.d the accumulation becomes small and non-continuous, and may thus be negligible.

Dry matter partitioning. DM partitioning during the early stage of rice seedling growth is not well understood. Penning de Vries *et al.* (1989) reported that about 14% of DM produced during the period between emergence and half-way to anthesis was allocated to roots, and the rest to shoots. Kropff *et al.* (1994), on the other hand, indicated that the DM distribution between root and shoot is equal at emergence, but that root DM declines to about 30% mid-way between emergence and anthesis. In their previous study the authors observed that allocation of root DM declined with time after emergence but reached an almost constant level of around 25% at the transition phase (Salam *et al.*, 1997). After analyzing a number of experimental results, Dingkuhn (1996) showed that DM allocation to root ranges between 20 and 30% during early growth of direct-seeded rice. RIBHAB follows the approach of Penning de Vries *et al.* (1989), while CERES-Rice considers a constant root : shoot ratio of 35 : 65. Here, the root : shoot ratio was formulated according to the phasic development of rice seedlings (Table 1).

Most studies regarding shoot DM partitioning during early growth indicated a constant culm : leaf ratio of about 50 : 50 (Penning de Vries *et al.*, 1989; Kropff *et al.*, 1994; Salam *et al.*, 1997). In contrast, CERES-Rice considers no DM allocation to culm (except for initialization) during nursery growth. For the sub-

Table 1. Dry matter partitioning ratios during the course of nursery growth of rice seedlings adopted in CERES-Rice model and newly-developed nursery growth sub-model.

	CERES-Rice		Nursery growth sub-model	
Growth phase	Root : Shoot	Culm : Leaf	Root : Shoot	Culm : Leaf
Heterotrophic phase (up to 74 °C.d)	35 : 65	0 : 100	35 : 65	52 : 48
Transition phase ($>74 \leqslant 321$ °C.d)	35 : 65	0 : 100	32 : 68	52 : 48
Autotrophic phase (>321 °C.d)	35 : 65	0 : 100	30 : 70	52 : 48

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model here, the shoot DM distribution was considered to be in the ratio of 52 : 48 for culm and leaf (Table 1).

Growth and seed size relationship. The importance of seed size for enhanced seedling growth has been recognized in maize (Cooper and MacDonald, 1970). For rice, researchers also recommended the use of seeds that contain larger reserves to ensure more vigorous seedlings (Arraudeau and Vergara, 1984). Whalley *et al.* (1966) expressed a similar view but emphasized that this might be true only within a seed lot and not between strains. Cardwell (1984) argued that the relationship between seed size and seedling vigor is prominent in most small-seeded crop species but not so consistent in cereals. Although the grain yield and seed size relationship in cereals is still contradictory (Gan and Stobbe, 1996), indications are that seedlings produced from large seeds grow more rapidly and accumulate more DM than do seedlings from small seeds (Lafond and Baker, 1986; Spilde, 1989; Gan and Stobbe, 1996). Also, it seems that more seed reserves in grasses and rice are mobilized from larger seeds than from smaller ones but the proportion diverted into seedlings remains the same (Whalley *et al.*, 1966; Salam *et al.*, 1997). Thus the total amount of seed DM utilization will always be higher in the seedlings emerging from larger seeds. While production of leaf number is genetically and environmentally controlled, seed size can influence the leaf area (size and thickness). Some models, such as ORYZA1, capture this phenomenon indirectly by considering two parameters for LAI at early growth, namely, the leaf area per plant and relative leaf area growth rate. The leaf area development in CERES-Rice during early growth is related to cumulative phyllochron intervals (CUMPH) or, in other words, leaf number, leaf size and/or thickness, are considered as constant (A), given by:

$$\text{MPLAG} = \text{A}/\text{CUMPH} \tag{4}$$

where MPLAG is the leaf area growth of the main plant (culm). In the model, the value of the parameter A has been fixed as 3800. On the basis of the experimental data (Salam *et al.*, 1997) and running the model with the data, a relationship between A and seed size was formulated as,

$$\text{A} = \text{a} + \text{b}^*\text{SW}, \; r^2 = 0.65 \tag{5}$$

where SW is the seed size (g), a = 1199, and b = 121236. The value of A from equation (5) then becomes an input of equation (4).

Transplanting shock sub-model

The processes involved in transplanting shock in rice are not properly understood (SARP, 1987). It is assumed that the shock arises due to root injury (Yamamoto *et al.*, 1978) and leaf loss (Yamamoto and Hisano, 1990) at the time of pulling seedlings from the nursery. The degree of shock depends on a number of factors including seedling age, pulling methods, handling during transplanting, air temperature and soil fertility and, possibly, on cultivar characteristics (SARP,

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1987). The general assumption is that no shock will occur if the seedlings are uprooted carefully, along with sufficient soil to ensure the root mass is minimally exposed, and transplanted delicately (F. W. T. Penning de Vries, personal communication). The authors, in attempting to simulate transplanting shock, considered two main physiological aspects, crop development and crop growth. Evidence indicates that the grain yield either is not directly affected by transplanting shock (SARP, 1987; Kashem *et al.*, 1995) or cannot be wholly explained (Torres *et al.*, 1994). So, no direct relationship between transplanting shock and grain yield was drawn at this stage.

Crop development during transplanting shock. It is well established that, due to the stagnation of developmental processes immediately after transplanting, transplanted rice usually takes longer to mature than does directly seeded rice (Dingkuhn *et al.*, 1990; Schnier *et al.*, 1990) (Fig. 1). To reflect this situation in modelling, Mekwattanakarn (1991) proposed to delay the crop development by a particular factor in a straightforward way. Dua *et al.* (1990) increased the pre-flowering duration by 0.1 times to mimic the transplanting shock period. RIBHAB attempted to describe the shock period more mechanistically as follows:

$$\text{SHOCK} = \text{AAD}/\text{GTW} \tag{6}$$

where, SHOCK is the period (d) of transplanting shock, AAD is the total amount of DM loss (kg ha^{-1}) from seedling parts, and GTW is the crop growth during the shock period (kg ha^{-1} d^{-1}). Salam (1992) described in detail how the GTW differed from growth during the normal period. The approach represented in equation 6 requires an additional input to run the model, i.e. how much DM is really lost during the pulling operation. The exact quantification of DM loss is hard to work out as it is affected by a number of factors such as the degree of nursery soil compaction, seedling age, the quantity and distribution of root mass in the soil, and the method of pulling seedlings. For the purpose of simplification, Sattar (1995) made a direct relationship between seedling age and transplanting shock period:

$$\text{SHOCK} = (\text{a} - \text{b}/\text{SA})*\text{SA} \tag{7}$$

where SA is the seedling age (d) at transplanting, and a and b are constants, parameterized as 0.786 and 15.473, respectively. Because he expressed both the shock period and seedling age in calendar days, the relationship failed to show any differences in shock period due to variations in transplanting time over a year constrained by temperature. It is now recognized that temperature affects the duration of the transplanting shock period (Kashem *et al.*, 1995). In ORYZA1 Kropff *et al.* (1994) resolved the problem by expressing both the shock period and the seedling age in terms of degree-days as:

$$\text{SHOCK} = \text{SA}*\text{SHCKD} \tag{8}$$

where SHOCK is the transplanting shock period and SA is the seedling age, both

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expressed as degree-days. SHCKD, the parameter indicating the relation between seedling age and delay in phenological development, was valued as 0.4. The same relationship is used in CERES-Rice. Equation (8), however, has some limitations. Firstly, a narrow range of seedling age (12–21 d), based on Torres *et al.* (1994), was considered in developing the relationship whereas, in many situations, seedlings as old as 80 d are transplanted (a list has been presented by Salam (1992)). Secondly, a linear relationship between seedling age and transplanting shock period may not be equally effective for seedlings older than 21 d; the slope of 0.4, especially, seems too large. In considering a very wide range of seedling age (10–80 d), the authors observed that the relationship fitted well in a third-degree exponential equation ($R^2 = 0.99$) as follows:

$$\text{SHOCK} = -\text{a} + \text{b1}*\text{SA} + \text{b2}*\text{SA}^2 - \text{b3}*\text{SA}^3 \quad (9)$$

where SHOCK is the transplanting shock period, SA is the seedling age at transplanting, both expressed as degree-days with a T_b of 9 °C, and a = 2.29469, b1 = 0.118934, b2 = 0.000249 and b3 = 0.0000001545.

Crop growth during transplanting shock. It was assumed in earlier work that seedling growth processes stopped during the entire shock period (Salam, 1992). Sattar (1995) also supported this idea. However, Kropff *et al.* (1994) expressed the view that crop growth halted during only a part of the shock period, and, to mimic the situation, no LA growth was considered for a quarter of the transplanting shock period. CERES-Rice captures the phenomenon differently. It assumes that both LA and root growth are affected during transplanting shock period and this is handled in the model by gradually sliding the shock effect (from severe to normal) over a 14-day period after transplanting:

$$\text{TSHOCK} = 1.0 - (\text{SA} + 14)/14 \quad (10)$$

where TSHOCK is the fraction of growth reduced in a given day during transplanting shock, and SA is the seedling age (d). The authors think the approach adopted in CERES-Rice is better than that of ORYZA1 as it considers the effect on root growth (in addition to LA) as well as evidence from Yamamoto and Hisano (1990). However, it is illogical to keep the scale of shock sliding constantly for a fixed 14-d period. If the shock period is shorter or longer than 14 d, the prediction of growth may be over- or underestimated respectively. Thus it is proposed here to use the exact shock period, instead of a fixed 14-d period for sliding the shock effects. Equation (10) then becomes,

$$\text{TSHOCK} = 1.0 - (\text{SA} + \text{SHOCKD})/\text{SHOCKD} \quad (11)$$

where SHOCKD is the transplanting shock period (d) predicted by the model at the time of transplanting.

Validation data

Validation of nursery growth was based on data from a semi-controlled

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experiment conducted in a location (24.75°N and 90.50°E) in Bangladesh during 1994. The experiment evaluated the development and growth of seedlings from two seed-size categories, large and small, for two *indica* type rice cultivars, BR11 and BR14. The average weight of large and small seeds of BR11 was 0.028 and 0.020 g, respectively, and that of BR14 was 0.032 and 0.022 g, respectively. For the purpose of this evaluation, five seedlings from each of the five replicates of each treatment combination were sampled each day during the 30-d experimental period. The seedlings were separated into roots, culms (stem and leaf sheath) and leaves (leaf blade) and oven dried at 72 °C for 72 h. Details of this experiment are given by Salam *et al.* (1997).

The transplanting shock period was validated with the data from one field and two pot experiments (using large pots) conducted in the same location as the nursery experiment. The field experiment was carried out over the early-summer and late-summer growing seasons in 1991. Twenty-one *indica* rice cultivars were grown using two planting techniques, direct seeding and transplanting. Seedlings for the early-summer crops were transplanted after 37 d in the nursery, for the late season crops after 42 d in the nursery. The transplanting shock was measured by measuring the difference in growth duration between the planting techniques for each of the cultivars and in both seasons. Details of this experiment may be found in Kashem *et al.* (1995).

Both pot experiments were carried out for two growing seasons: late summer (1994) and winter (94/95). The performance of seedlings transplanted at ages ranging between 30 and 75 d, were evaluated. Each pot accommodated six hills (3 seedlings per hill). The difference between the two experiments was the cultivar grown. Two *indica* types, BR14 and BR3, were used. The transplanting shock was measured by assessing the change in seedling DM after transplanting, as described by Sattar (1995). Ahmed (1995) and Khatoon (1995) provide details of the experiments.

Crop development (flowering and total growth duration) and grain yield were evaluated using data from an experiment conducted in 1986 at Munoz, Philippines (15.70°N and 120.90°E), one of the field research stations of the International Rice Research Institute (IRRI). In that experiment, cultivar IR58 was evaluated under 10 levels of nitrogen fertilizer during the dry season (Singh *et al.*, 1993).

For running the model, daily weather data from the locations were used. The cultivar-specific parameters for Bangladeshi cultivars were derived from Hussain (1995) and that of IRRI from the International Fertilizer Development Center, Muscle Sholes, Alabama, USA (P. Wilkens, personal communication).

RESULTS

Validation of nursery growth sub-model

The observed and simulated seedling growth in a 30-d nursery period, with respect to total DM and its components, root DM, culm DM and leaf DM, were

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compared for four scenarios – combinations of two cultivars (BR11 and BR14) and two seed sizes (large and small). Figures 2 and 3 indicate that the nursery growth sub-model, when incorporated into CERES-Rice or RIBHAB, closely predicted total seedling DM together with its three components, root, culm and leaf, for all the four scenarios, while CERES-Rice and RIBHAB without the sub-model did not properly do so.

All through the growing period, except for the initial week, RIBHAB consistently underestimated root, culm and leaf DM. CERES-Rice, on the other hand, highly overestimated root and leaf DM from about 12 days onwards. The same model severely underestimated the culm DM throughout the growth period; actually it showed no culm growth at all after seedling emergence. CERES-Rice did not respond to seed size variation in the cultivars, while RIBHAB did. Across the 30-d nursery growth, CERES-Rice simulated total seedling DM in a relatively smaller deviation from observation (calculated as 'root mean squared deviation from observation relative to mean' or RRMSD) for the large seeded BR14 (15%). For the remaining cultivar × seed size combinations, the model showed RRMSD as high as 52% (large seeded BR11, RRMSD = 33%; small seeded BR11, RRMSD = 52%, and small seeded BR14, RRMSD = 51%). RIBHAB, simulating total seedling DM, consistently showed a high RRMSD (46–50%) for the four cultivar × seed size combinations. The nursery growth sub-model, incorporated either into CERES-Rice (RRMSD = 9–15%) or RIBHAB (RRMSD = 9–18%), showed smaller RRMSDs for the four cultivar × seed size combinations.

Validation of the transplanting shock sub-model

The transplanting shock sub-model was validated using CERES-Rice. RIBHAB was not considered because the inputs (quantification of seedling DM loss during pulling as affected by soil compaction, seedling age, quantity and distribution of root mass, and method of pulling) needed to operate the shock process in the model, were not available. Firstly, the authors attempted to test the predicted transplanting shock periods against observed values from two cultivars in Bangladesh, BR14 and BR3 grown in two seasons, late summer and winter (Fig. 4). The seedlings were raised in the nursery at the same time but transplanted to the padi field at four different ages; 30, 45, 60 and 75 d. The experimental results indicated that the transplanting shock period increased with increasing seedling age and, also, that the shock was greater during winter than in the late summer season. Predictions from the transplanting shock sub-model closely followed the observed data for all seedling ages in both growing seasons. On the other hand, CERES-Rice predicted shock periods almost double those observed. For example, when 30-d old seedlings were transplanted, CERES-Rice simulated a shock period of 9.4 d for late summer crops (observation 3–4 d depending on cultivar) and 16.5 d for winter crops (observation 6–7 d depending on cultivar). Similarly, for 75-d-old seedlings, the model predicted a shock period of 30.8 d for late summer crops (observation 15–16 d

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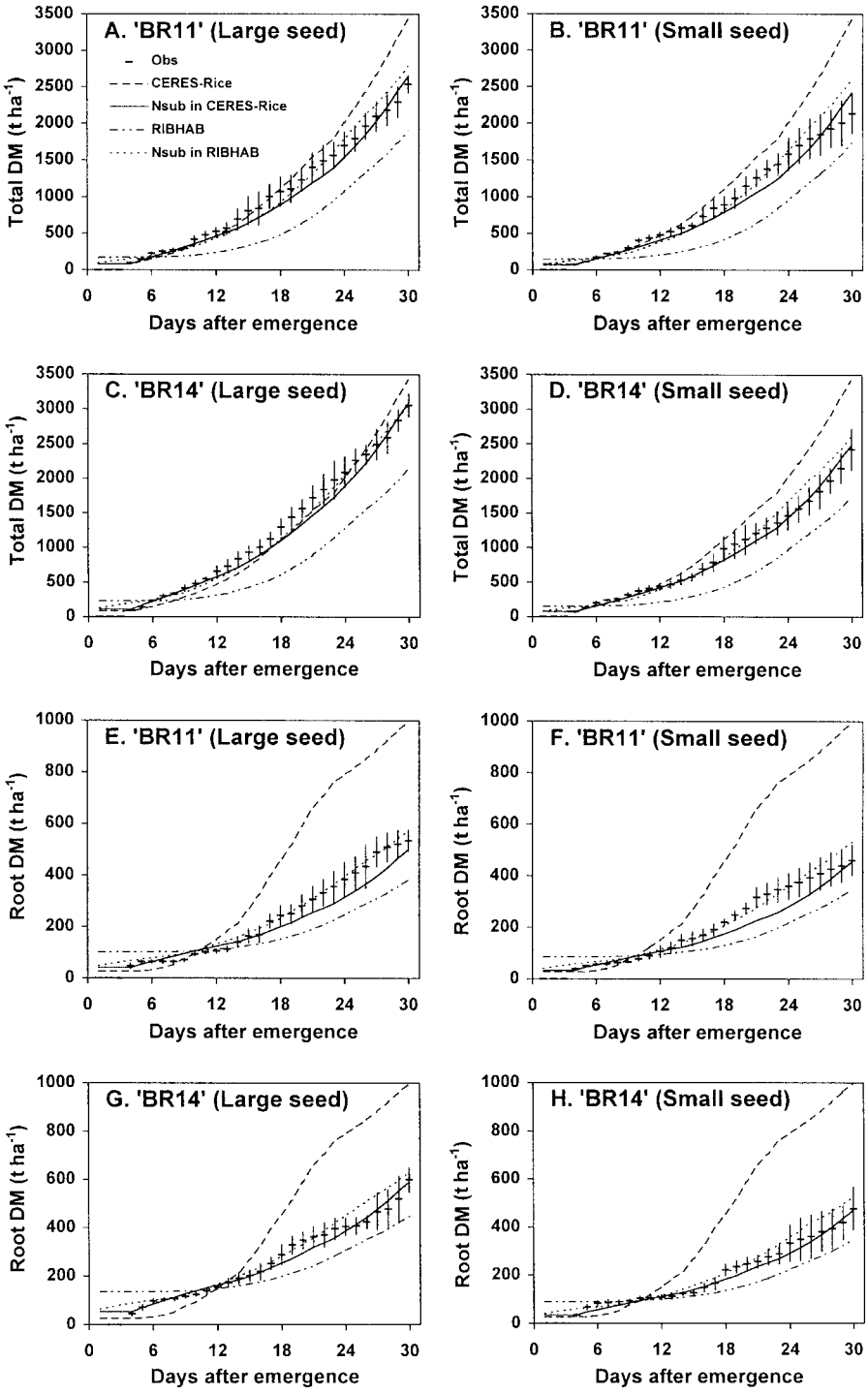


Figure 2. Observed (obs, – with vertical bars showing standard deviations) and predicted (lines) total and root DM of the seedlings during a 30-d nursery period. Scenarios of two cultivars sown with two seed sizes are presented. 'Nsub' denotes newly-developed nursery growth sub-model.

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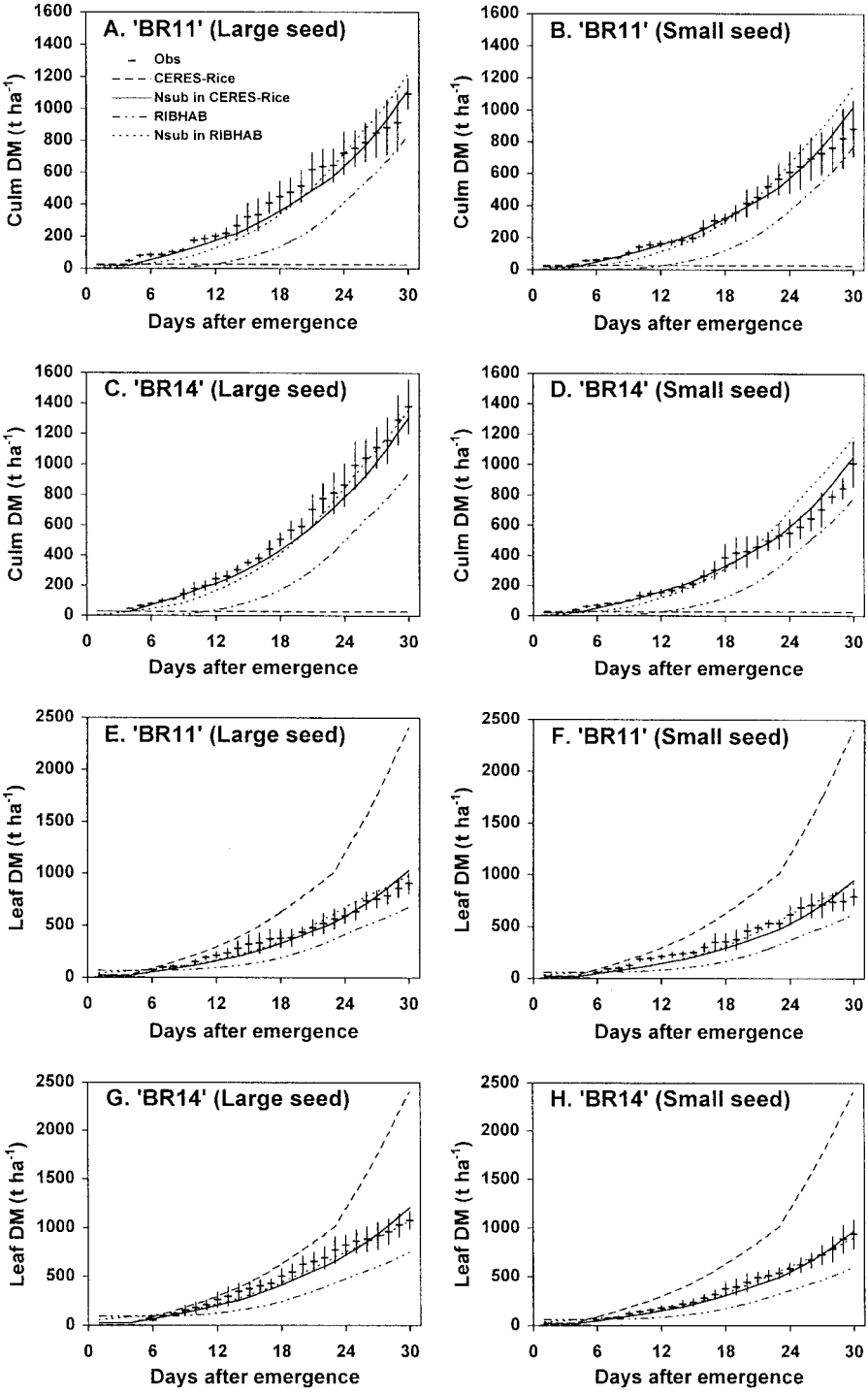


Figure 3. Observed (obs, – with vertical bars showing standard deviations) and predicted (lines) culm and leaf dry matter of the seedlings during a 30-d nursery period. Scenarios of two cultivars sown with two seed sizes are presented. 'Nsub' denotes newly-developed nursery growth sub-model.

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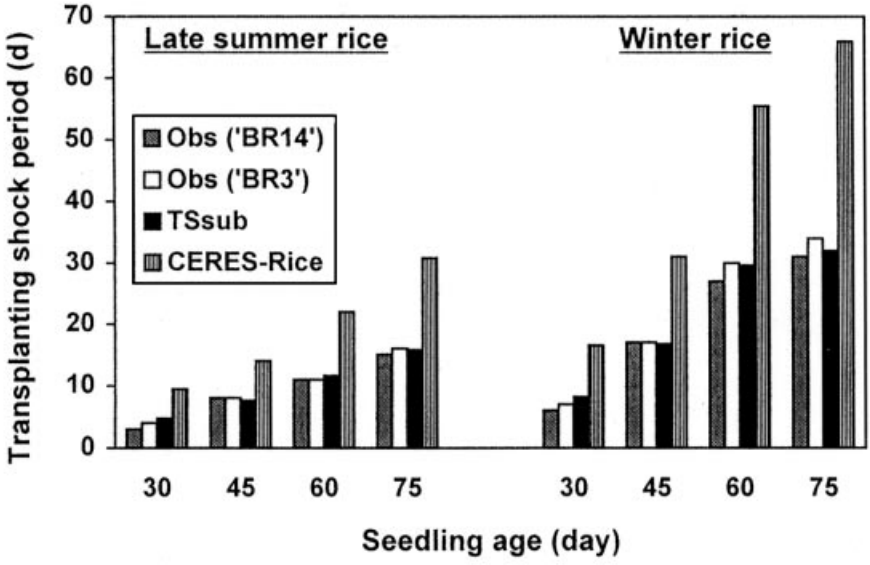


Figure 4. Observed (Obs, for two cultivars) and predicted shock period of rice transplanted at four different seedling ages grown in two seasons. 'Tsub' denotes newly-developed transplanting shock sub-model incorporated into CERES-Rice.

depending on cultivar) and 66 d for winter crops (observation 31–34 d depending on cultivar). Neither the transplanting shock sub-model nor CERES-Rice, however, could describe the variation in the transplanting shock period between the cultivars.

A second dataset, consisting of 21 cultivars grown in two seasons, was also used to validate the transplanting shock period. The early-summer crop was transplanted with 37-d-old seedlings and the late-summer crop with 42-d-old seedlings. Figure 5 shows that the transplanting shock sub-model, in both the seasons, closely simulated the shock period (6.5 d for early-summer and 7 d for late-summer crops), with observed mean values for the cultivars (6.9 d for early-summer and 8 d for late-summer crops), whereas CERES-Rice estimated a very large shock period (12.5 d for early-summer and 13 d for late-summer crops). Again, both the transplanting shock sub-model and CERES-Rice could not describe the variation in transplanting shock period between the cultivars. Across the 21 cultivars, the transplanting shock sub-model showed a RRMSD of 21% for the early-season and 18% for the late-season crops. CERES-Rice, however, showed much larger RRMSD (84% and 65%) for the respective seasons.

Validation of growth duration and grain yield

A complete dataset comprising nursery growth, transplanting shock, growth duration and yield from the same experiment was not available to compare the performances of developed sub-models with CERES-Rice and RIBHAB. So,

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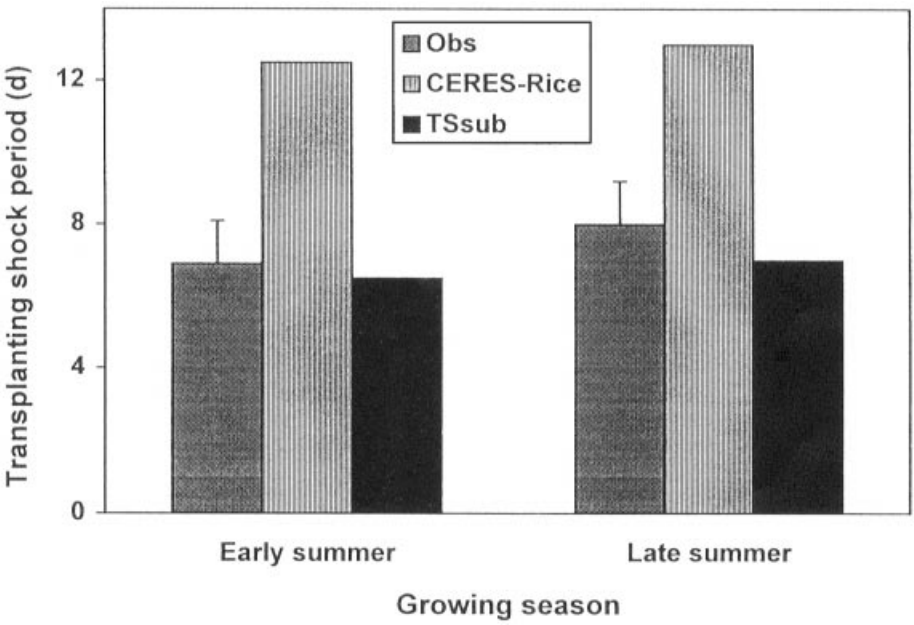


Figure 5. Observed (Obs) mean and standard deviations of 21 cultivars, and predicted transplanting shock period of rice grown in two seasons. 'Tsub' denotes newly-developed transplanting shock sub-model incorporated into CERES-Rice.

separate experimental data were used to validate different processes. The growth duration and grain yield were compared with the experimental data from IRRI (Philippines) for the cultivar IR58 treated with 10 levels of nitrogen fertilizer application. When the sub-models were incorporated into CERES-Rice, the predictions of total crop growth duration and flowering duration were very close to observation (both the periods were underestimated by 1 d), whereas CERES-Rice overestimated total growth duration by 5 d and flowering duration by 3 d (results not shown). In grain yield evaluation, results indicated a more-or-less close association between observed and predicted yields from both CERES-Rice and the developed sub-models incorporated into CERES-Rice (Fig. 6). However, the predicted yields from the sub-models incorporated into CERES-Rice were closer to the observed values (1 : 1 line) than was the yield simulated by CERES-Rice. Across the 10 nitrogen fertilizer levels CERES-Rice showed a RRMSD of 8%, while the sub-models incorporated into CERES-Rice showed a RRMSD of 6%.

DISCUSSION

Nursery management is one of the important rice cropping activities in tropical and sub-tropical Asia. Farmers widely manipulate nursery duration for a number of reasons. For example, draft power may not be available to prepare the padi

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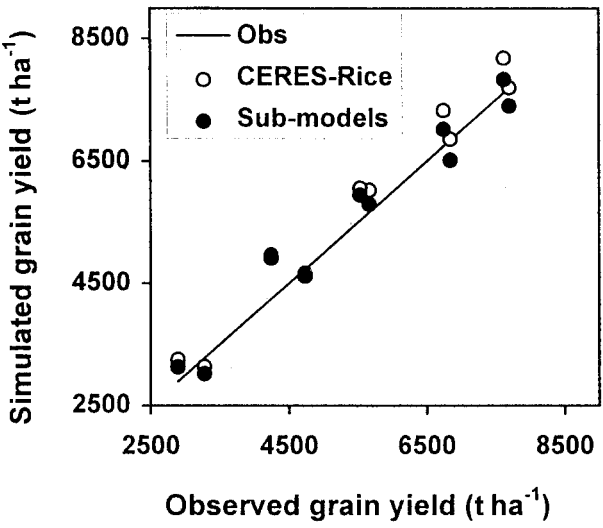


Figure 6. Observed (Obs, line) and predicted (circles) grain yield of rice, cv 'IR58'. 'Sub-models' denotes newly-developed nursery growth and transplanting shock sub-models incorporated into CERES-Rice.

field in time, or manpower may be inadequate to carry out timely transplanting; farmers are also reported to use aged seedlings purposely to reduce the duration of the crop in the field. This last may be to fit the crop into a multiple cropping system (Salam *et al*., 1994b), or reduce the requirements for costly irrigation water (Salam, 1992), a practice which has been found to be economically feasible (Salam *et al*., 1995). Manipulation of nursery duration may affect grain yield (Singh *et al*., 1991). It also affects the duration of the transplanting shock period. Model formulation and testing can serve to pinpoint where more work is needed to improve present knowledge, or to increase the domain of applicability of the model (Villalobos *et al*., 1996).

The newly developed nursery growth sub-model, in addition to showing close predictions to observed data, behaved very similarly in both CERES-Rice and RIBHAB models in simulating root, culm and leaf DM and, consequently, the total seedling DM. RIBHAB consistently underestimated growth especially after the initial week of stand establishment. This underestimation probably occurred due to the restriction made in the photosynthesis process in the model during the initial growth of seedlings (first two weeks after emergence). This was done to reduce photosynthetic contribution to seedling growth during heterotrophic and transition phases (for details, see Salam (1992) and Salam *et al*. (1997)); probably such a relationship was not well represented in the model. With respect to prediction of seedling growth by CERES-Rice, the reason for the highly over-estimated root and leaf DM, and severely underestimated culm DM, related mostly to DM partitioning functions and ratios adopted in the model. This is especially true for partitioning shoot DM between culm and leaf. The model, for a reason unknown, does not recognize any culm or stem growth in the seedlings

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under nursery condition; this produces high leaf growth at the expense of culm growth. Nevertheless, the model overestimated total seedling DM around, on and after day 12 of seedling emergence. Moreover, CERES-Rice failed to simulate the differences in seed size of the cultivars. This is because the model does not account for leaf area development in relation to seed DM (i.e. endosperm) mobilization into seedling (which, in turn, is affected by the seed size). The developed nursery growth sub-model considers many of the relationships that were not well captured by the CERES-Rice and RIBHAB models. At the present level of validation, it appears that the sub-model can adequately and confidently mimic seedling growth in the nursery. However, to capture a wider plasticity, validation should also be performed under different environments such as variable soil fertility (particularly nitrogen availability), temperatures, and moisture regimes.

From testing under different climatic conditions over a wide range of seedling ages, it appears that CERES-Rice overestimates the transplanting shock periods. This is because the model considers a linear relationship between seedling age at transplanting and the shock period (0.04 times seedling age expressed as degree-days). Because this relationship was based on seedling ages in the range of 12–21 d (Torres *et al*., 1994), it may not be valid for seedlings older than 21 d. The developed transplanting shock sub-model predicted the shock period reasonably well over the tested climatic conditions and wide range of seedling ages. Still, it seems that the performance of the sub-model is somewhat lacking, especially in that it cannot capture the differences in transplanting shock due to cultivar that were evident from the experimental results (Fig. 5). So, in future studies, attempts should be made to describe cultivar response to transplanting shock. Efforts should also be made to develop mechanisms in the models to find out ways of reducing the transplanting shock period especially in situations where aged seedlings are transplanted.

Nursery duration can affect rice grain yield. In previous studies, the authors tested this effect through simulations using the model RIBHAB (Salam *et al*., 1994a; Salam *et al*., 1995). Improvement of the nursery growth process through the newly developed nursery growth sub-model will be helpful for better yield prediction. Transplanting shock period, as such, has no effect on grain yield (Kashem *et al*., 1995) but it can affect the total crop growth duration. This was also observed in the present simulation study. However, if the shock period is due to using very old seedlings and the weather during crop growth is highly variable then yields may be affected. This phenomenon may be tested in future by the simulation exercises.

Based on the results of the present study, it is concluded that the nursery growth and transplanting shock sub-models developed here can perform better than the algorithms already in use in the major rice growth models for simulating nursery growth and transplanting shock processes of rice. Therefore, these sub-models may be incorporated into CERES-Rice and other rice growth models to improve the models' prediction of the two growth processes.

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