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Effects of seedling age and root pruning on root characteristics and dry matter accumulation dynamics in machine-transplanted rice

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Abstract: To investigate the impact of different seedling transplanting times on rice growth, the present study evaluated seedling age and root pruning using treatments consisting of root pruning (RC20, RC30, and RC40) and no root pruning (CK20, CK30, and CK40). Quantitative analysis using curve fitting of the changes in dry matter accumulation (DMA) during the seedling and field stages was performed, and the changes in root parameters during the re-greening stage were observed. The results showed that the seedling stage could be divided into a gradual increase period, a rapid increase period, and a slow increase period. Transplanting at different time periods resulted in different transplanting shock effects. During the field stage, the DMA exhibited a slow-fast-slow "S" shaped curve as the developmental time progressed. However, significant differences were observed in growth parameters among the different treatments. Root injury promoted early maturity in young seedlings but also prolonged the whole growth period in older seedlings. The inhibitory effect of root pruning on rice root growth increased with young seedling age. The present results provide a theoretical basis for the design of seedling needle structure and the optimisation of rice seedling cultivation practices.

Keywords: agronomic productivity; plant physiology; rice yield optimisation; stress adaptation; transplantation techniques

Rice (*Oryza sativa* L.) is an important staple crop cultivated worldwide, with a cultivation area exceeding 167 million hectares (Latif et al. 2022). Rice production contributes approximately 20% of the global daily caloric intake (Pimentel et al. 1975), fulfils approximately 13% of the per capita protein intake and 19% of the per capita energy requirements worldwide. On a global scale, per capita rice consumption has shown an increasing trend (Peng et al. 2017). As rice becomes increasingly important worldwide, achieving food security faces significant challenges. To meet the population's growing demand, it has been estimated that rice production needs to increase by at least 1% annually (Schneider and Asch 2020). The future enhancement of rice production relies on achieving higher crop yields (Horie et al. 2005) and improving the replanting index (Yang et al. 2019). The southern region of China is one of the areas with the highest replanting index for rice (Yang et al. 2020). Figure 1 shows the timeline of double-cropping rice cultivation in this region. Suppose the planting time for the early rice remains unchanged

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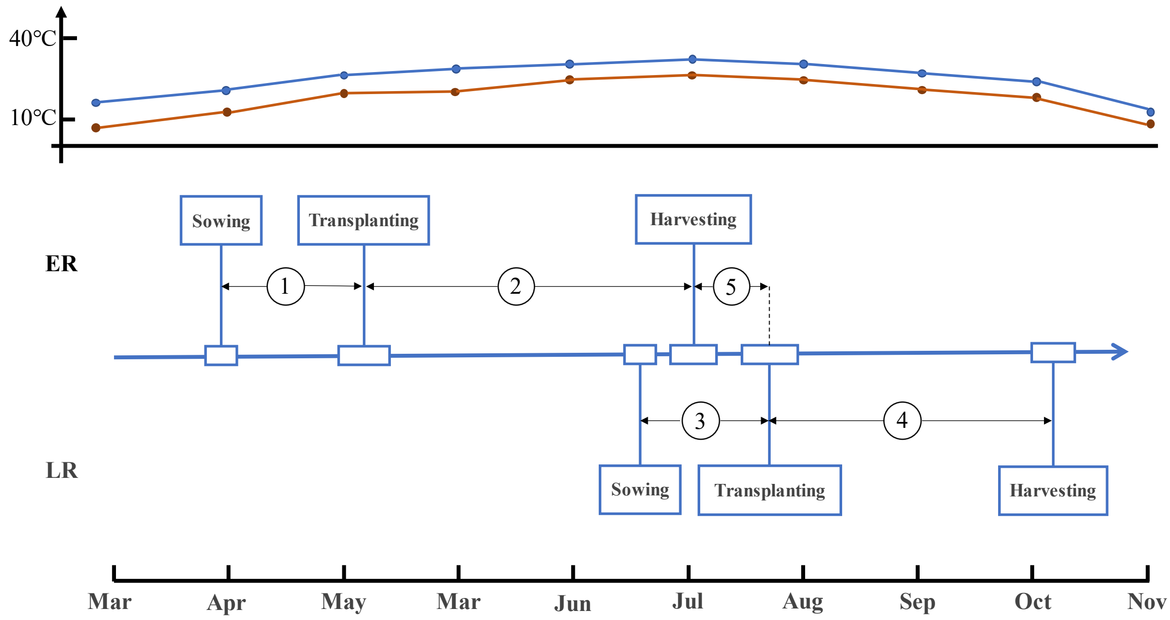

Figure 1. Double-cropping full stages of rice. (1) Early rice (ER) nursery stage; (2) early rice field stage; (3) late rice (LR) nursery stage; (4) late rice field stage, and (5) ratoon stage

and lower temperatures are encountered during the early rice field stage (2) or rainfall is experienced during the early rice harvest. In that case, it can significantly extend the late rice nursery stage (3), leading to the occurrence of over-aged seedlings during machine transplanting. The machine transplanting technology for rice in China has been widely applied to transplant conventional rice seedlings. However, this technology has encountered several issues in transplanting hybrid rice with longer seedling ages, including the phenomenon of transplanting shock.

Transplanting shock is considered a suppression phenomenon caused by root injury during the transplanting process, mainly due to an imbalance between water absorption and transpiration (Close et al. 2005). Transplanting shock significantly affects the growth of rice (Li et al. 2016a), tillering pattern (Li et al. 2016b), and crop phenology (Du et al. 2008), thereby having adverse effects on grain yield.

The timing of seedling cultivation is directly related to transplanting shock. Proper seedling cultivation time can effectively reduce the impact of transplanting shock. It has been reported that mature seedling machine transplanting has lower tillering capacity, a shorter vegetative growth period, and lower dry matter accumulation (DMA) (Sarwar et al. 2011). Moin et al. (2001) reported that transplanting with different seedling ages can delay maturity by 3–11 days. Akihiko et al. (2004) constructed a transplanting shock model to explain the phenomenon of delayed heading due to different seedling ages in the Red River Delta region. Currently, research on transplanting shock mainly focuses on agronomic traits and biochemical indicators of plants after transplantation, while there are few reports on quantitative analysis of the effects of seedling age and root injury on transplanting shock.

Crop growth simulation models are important research tools for quantitatively analysing the characteristics of crop growth indicators (Mirschel et al. 2004). Many scholars have developed seedling growth simulation models and conducted quantitative analyses of seedling growth characteristics. Liu et al. (2016) used the logistic equation to fit the plant height, stem diameter, fresh weight, dry weight, and growth days of broccoli seedlings, thus establishing a seedling growth model for broccoli; based on this model, they conducted a quantitative analysis of phenological parameters and growth parameters of broccoli. Yu et al. (2017) applied the logistic and Gompertz models and their optimal combination model to fit the relationship between the growth dynamics and growth days of *Celastrus orbiculatus* seedlings. Through model derivation, characteristic parameters were obtained, and the growth stage of *Celastrus orbiculatus* seedlings was divided into four stages as follows: emergence period, early growth period, rapid growth period, and late growth pe-

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riod. Based on these stages, key seedling cultivation measures were proposed for each period. Wang et al. (2012) considered the influence of temperature on cucumber growth and developed a growth and development simulation model for cucumber plug seedlings based on growing days. The model was used to quantitatively analyse the growth parameters of cucumber plug seedlings at various stages of growth.

The present study selected hybrid rice in the middle and lower reaches of the Yangtze River as the research object, using growth and development time as a scale to describe the rice growth and development stage. Through characteristic curve simulation of DMA in rice of different ages and analysis of the changes and relationships between characteristic parameters of DMA and root system characteristics under different ages and root pruning, the present study aimed to provide a theoretical basis for the optimisation of rice mature-seedling machine transplanting technology and agronomy in the middle and lower reaches of the Yangtze River region.

MATERIAL AND METHODS

Root injury analysis

As shown in Figure 2A, the seedling claw separates the seedling blanket through two cutting surfaces, namely the seedling-taking surface (FA_2) and the block-cutting surface (FA_1). The seedling-taking process is illustrated in Figure 2B, in which the seedling claw provides cutting force in the direction D_1 and tearing force in the direction D_2 to the seedling blanket by its uniform rotation around the sun gear and non-uniform rotation around the planet gear. The root length during the seedling-taking process is denoted as "L" as follows:

$$L = \sqrt{(\frac{l_1}{2})^2 + (\frac{l_3}{2})^2 + l_2^2} \quad (1)$$

where: l_1 – transverse seedling length; l_2 – substrate thickness; l_3 – longitudinal seedling length.

According to the local technical specifications, the transverse length of the seedling taking (transverse seedling length) and the width of the seedling needle (seedling needle width) are both 14 mm. The substrate thickness is 20 mm, and the longitudinal length of the seedling taking (longitudinal seedling length) is 8 mm. Based on these specifications, the length of the root during the seedling-taking process can be calculated as 21.6 mm.

Experimental conditions and design

The experiment used the research object of the commonly cultivated cv. Chuangliangyou 4418 rice in the middle and lower reaches of the Yangtze River. The potted soil was collected from the surface soil of the rice field in the Agricultural Garden of Anhui Agricultural University. After sieving and mixing, it was used as the experimental soil. The basic physicochemical properties of the soil were as follows: pH value of 5.7, organic carbon content of 14.04 g/kg, total nitrogen content of 2.19 g/kg, available nitrogen content of 95.63 mg/kg, available phosphorus

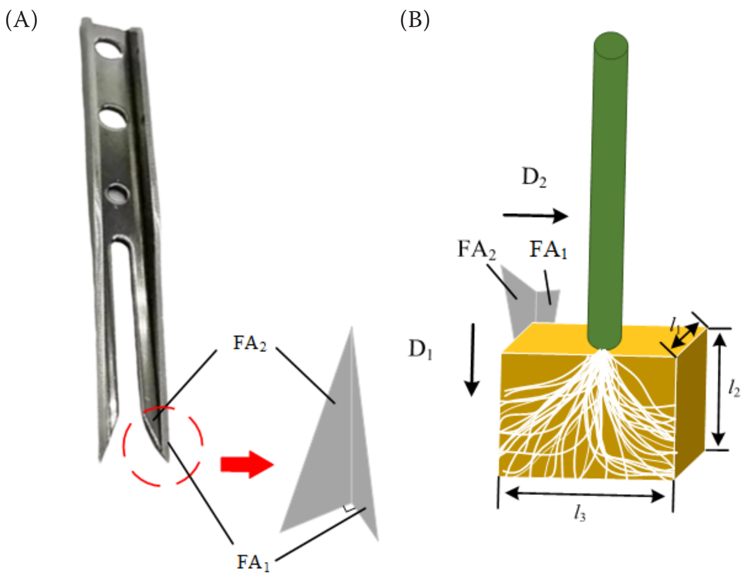

Figure 2. Analysis of root injury during seedling separation. (A) Seedling needle structure and (B) seedling needle for transplanting seedlings. FA_1 – block-cutting surface; FA_2 – seedling-taking surface; l_1 – transverse seedling length; l_2 – substrate thickness; l_3 – longitudinal seedling length; D_1 – cutting direction of the seedling needle relative to the seedling blanket; D_2 – tearing direction of the seedling needle relative to the seedling blanket

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content of 24.46 mg/kg, and available potassium content of 139.21 mg/kg. The potted experiment was conducted in the Agricultural Garden of Anhui Agricultural University greenhouse.

The seedling process used hard plastic nursery trays with dimensions of 58 cm × 28 cm × 3 cm, and each tray had a 20-mm thick substrate with a weight of 2 kg. A total of 10 nursery trays were used. Before sowing the rice seeds, they were treated with a 25% metsulfuron-methyl solution (5 kg substrate was added to 1 mL of solution). The rice seeds were soaked in the solution for 24 h until they turned white, and the excess water was then drained. For sowing, a standard grid layout of 18 rows × 36 columns was used for precise manual sowing. Each planting hole had two rice seedlings. The experiment included three different stages of sowing, which were carried out at 20, 30 and 40 days after the initial sowing on May 1st, with transplanting dates of May 21st, May 31st, and June 10th, respectively. The seedlings were transferred to plastic buckets during transplanting, with the water depth maintained at approximately 3 cm in each bucket. The height and inner diameter of the plastic buckets were 22 cm and 18 cm, respectively, and each bucket contained 5 kg of soil with an approximate height of 12 cm.

The pot experiment was conducted using a 3 × 2 factorial design, comprising a total of six treatments. The treatments involved three different seedling ages, each with two conditions as follows: root-pruned (RC) with a root length of 21.6 mm and a control group (CK) without root pruning. Each treatment had 20 pots. The specific treatments were CK20, RC20, CK30, RC30, CK40, and RC40. The rice seedlings were transplanted into plastic buckets, with one hole per bucket and two rice seedlings planted in each hole. All treatments had the same phosphorus, potassium, and nitrogen content, with an N:P:K ratio of 1:0.5:0.8. In terms of fertilisation, $CO(NH_2)_2$ was applied three times in a ratio of 3:3:4, including basal fertiliser, tillering fertiliser, and panicle fertiliser. $Ca(H_2PO_4)_2$ was used as the phosphorus fertiliser, and KCl was used as the potassium fertiliser.

Measurements

Seedling quality. From the emergence day, 10 randomly selected seedlings were measured at intervals of 5 days. First, the seedling height and stem base width were measured. The seedling height refers to the length from the plant base to the highest point. The measured plant samples were placed in an oven and dried at 80 °C until the sample weight stabilised, after which they were weighed.

Root system characteristics. Excess soil was shaken off after removing the intact plants from the pots. The roots were severed from the base and placed in a beaker with water. Ultrasonic vibration was applied for 10 min to separate the soil and roots completely. The roots were then removed, and the water on the root surface was gently absorbed using filter paper. Subsequently, the roots were scanned using a digital scanner (Epson Scanner, Suwa City, Japan), and root morphological analysis software (Win-RHIZO 2008a, Quebec, Canada) was used to analyse the root system. Measured parameters included total root length (Rl), root volume (Rv), number of root tips (Ts), and root surface area (Sa). Each parameter was measured three times for each time point after transplanting, which included 0, 3, 6 and 9 days.

Dry matter accumulation. From transplanting to maturity, the dry biomass of rice was measured every 20 days. Three plots were selected for each treatment, and whole rice plants were sampled from each plot for measurement. Firstly, the roots were washed and placed in nylon mesh bags. The aboveground and belowground parts of the rice plants were then separated, collected in sample bags, and placed in an electric air-drying oven. The samples were subjected to a 30-min quenching treatment at 105 °C, followed by drying at 80 °C until constant mass was achieved. Subsequently, the samples were removed, and the dry biomass of whole rice plants at different growth stages was measured using an electronic balance with a precision of 0.01 g.

Function model

The following logistic equation was used to fit a nonlinear regression for DMA in rice:

$$W = \frac{K}{1 + ae^{-bx}} \tag{2}$$

where: W – dry mass of rice plant, g/m^2; x – time after sowing, d; K – theoretical maximum DMA, g/hole^2.

The equation represents a continuous unimodal curve, where the peak of the curve is the maximum growth rate of dry matter. By taking the derivative (or the second derivative of the logistic equation) based on the equation for the rate of DMA and setting it to zero, the relative time (X_{max} = (ln$a$)/b) at which the maximum growth rate of dry matter occurs can

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be determined, with the maximum rate being V_{max} = (–bK)/4.

Taking the third derivative of the logistic equation and setting it to zero allows for determining two inflection points on the DMA rate curve. The relative accumulated temperature values corresponding to the two inflection points are $X_1 = (\ln a - 1.317)/b$ and $X_2 = (\ln a + 1.317)/b$. In the intervals [0, X_1] and [X_2, ∞], the DMA rate is in a period of slow change, whereas between [X_1, X_2], the DMA rate is in a period of rapid growth. Darroch and Baker (1990) pointed out that crop growth is considered to have ceased when the dry biomass reaches 95% of the maximum biomass (0.95 K). Based on this, the crop growth cycle is as follows: $X_{max} = (\ln (1/19) - a)/b$.

Sensitivity coefficient

The sensitivity coefficient (SC) of rice DMA characteristic parameters with respect to seedling age and root pruning treatment was defined as follows:

$$P_{sc} = \frac{\frac{\Delta S}{S}}{\frac{\Delta ET}{ET}} \quad (3)$$

where: P_{sc} – sensitivity coefficient; S – characteristic parameter of DMA in the CK treatment; ET – CK treatment root length, cm; ΔS – amount of change in the characteristic parameters of each treatment compared to the CK treatment; ΔET – amount of change in the root system compared to the CK treatment.

Data analysis. Statistical analysis and plotting were performed using Excel 2019 (Washington, USA), Prism (California, USA), and Visio (Washington, USA). The logistic growth equation was fitted using Origin (Northampton, USA), and the main characteristic parameters of rice DMA were computed using Mathematica 8 (Illinois, USA). For significance analysis, SPSS 22.0 (Illinois, USA) was used with the least significant difference (*LSD*) method, and the significance level was set at $P < 0.05$. The accuracy of the equation was evaluated using the R^2 coefficient of determination.

RESULTS

Seedling quality at nursery stage

Seedling quality at different time points. Table 1 shows the seedling traits at different nursery times. The plant height increased by 17.2 mm in the first 20 days and slowed to a 6.2 mm increase in the next 20 days, reaching a maximum of 30.6 mm at 40 days. The stem base width increased by 0.97 mm between 15 and 25 days, peaking at 3.43 mm at 40 days. The dry matter showed no significant difference within the first 15 days but varied significantly with increasing nursery time, reaching a maximum of 0.224 g per plant. Both aboveground and belowground dry matter increased with nursery time, but the increase in aboveground dry matter was more pronounced, leading to a decrease in root-shoot ratio from an initial 3.4 to 1.0.

Characterisation of DMA at the seedling stage. The regression analysis of seedling age and DMA is presented in Figure 3. The logistic regression model between seedling age and DMA was as follows:

$$W_1 = \frac{0.18}{1 + 25.23e^{-0.11x}} \quad (4)$$

where: W_1 – mass of aboveground dry matter (g) of seedlings per hole at the seedling stage; x – seedling rearing time.

Table 1. Seedling quality at different time points

Seedling age	Height (cm)	Stem base width (mm)	Whole plant dry matter (mg)	Dry matter accumulation (mg)	Underground dry matter (mg)	Root top ratio
5	7.2^{e}	1.45^{g}	21.5^{e}	5.0^{f}	16.5^{cd}	3.4^{a}
10	13.5^{d}	1.59^{g}	23.0^{e}	9.0^{ef}	14.0^{d}	1.6^{b}
15	17.9^{c}	1.81^{f}	30.0^{e}	15.0^{e}	15.0^{cd}	1.0^{c}
20	24.4^{b}	2.23^{e}	48.0^{d}	28.0^{d}	20.0^{c}	0.7^{c}
25	24.4^{b}	2.78^{d}	72.0^{c}	41.5^{c}	30.5^{b}	0.7^{dc}
30	23.7^{b}	2.94^{c}	75.0^{c}	44.5^{c}	30.0^{b}	0.7^{d}
35	29.0^{a}	3.12^{b}	100.5^{b}	64.5^{b}	35.5^{ab}	0.6^{d}
40	30.6^{a}	3.43^{a}	112.0^{a}	73.0^{a}	39.0^{a}	0.5^{d}

Different letters in each column indicate significant differences between different fertiliser applications ($P < 0.05$; *LSD* test)

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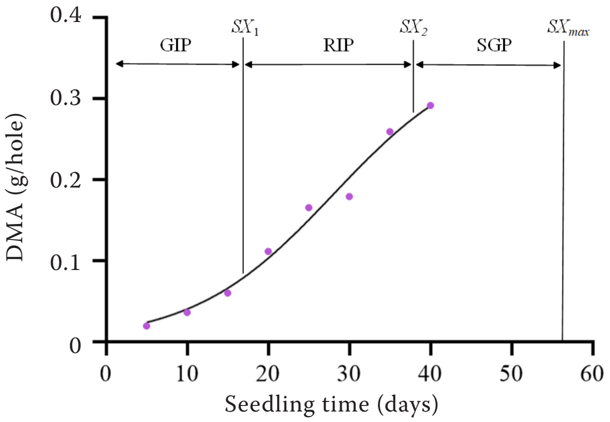

Figure 3. Dynamic growth of dry matter accumulation (DMA) in rice seedlings during the seedling stage. GIP – gradual increase period; RIP – rapid increase period; SGP – slow increase period; SX_1 – start time of rapid dry matter accumulation; SX_2 – end time of rapid dry matter accumulation; SX_{max} – end time of dry matter accumulation

In the logistic regression equation of aboveground dry matter of seedlings and nursery time, the coefficient of determination (R^2) was 0.9865, and the residual standard error of the model (RSEM) was 0.01404. By Eq. (2), the key parameters of the seedling period were determined as follows: the rapid accumulation period of dry matter (SX_1) started at 16.7 days; the peak period (SX_0) occurred at 28.1 days, and the late peak period (SX_2) appeared at 39.6 days. The maximum aboveground DMA during the seedling period was 0.00524 g/hole, and the maximum growth period for seedlings was 53.7 days. The gradual increase period (GIP), rapid increase period (RIP), and slow increase period (SGP) were from 0 to 16.7 days, from 16.7 to 39.6 days, and from 39.4 to 53.7 days, respectively.

Differential response of root morphology during the re-greening stage of rice with different seedling ages to root pruning.

Detailed data on the root system is provided in Table 1, and Figure 4 shows the root scan images of rice seedlings of different ages undergoing root pruning treatments. The 20-day-old seedlings began growing lateral roots within 3 days post-pruning, while the 30-day-old seedlings started within 6 days. In addition, the 40-day-old seedlings showed lateral root growth only after 9 days. Nine days after pruning, the roots of the 20-day-old seedlings appeared slenderer and more extensive. In contrast, the 40-day-old seedlings in the control group exhibited signs of ageing compared to the 20-day and 30-day-old seedlings, with slower root growth and fewer lateral roots.

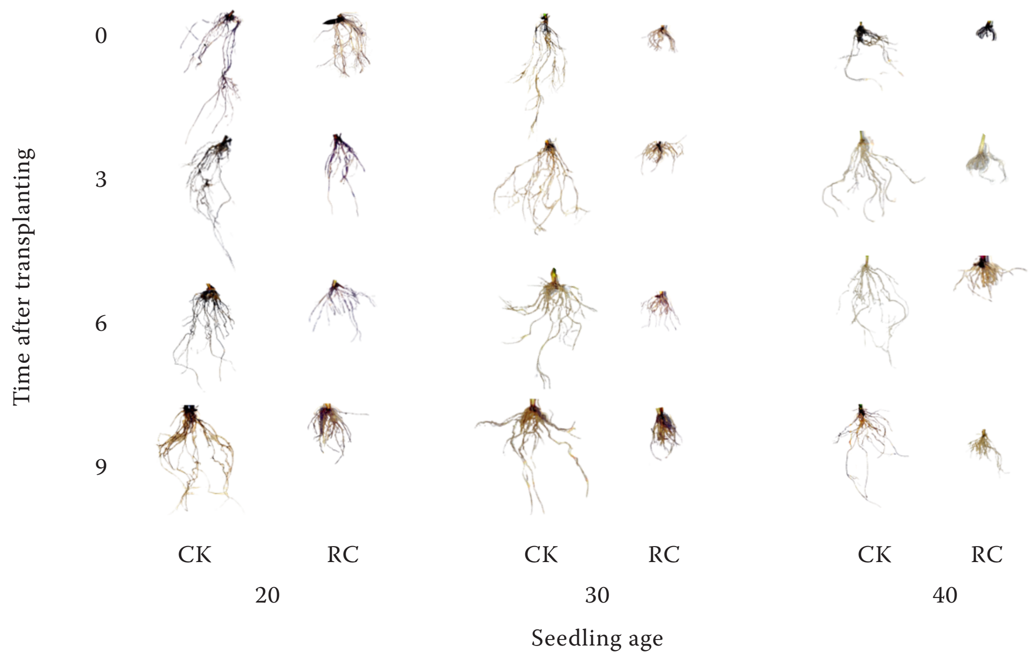

Figure 4. Scans of the root system with different treatments. CK refers to the control group, while RC indicates the root-pruned treatment. The numbers 20, 30, and 40 correspond to different transplanting ages of the seedlings (days). The numbers 0, 3, 6, and 9 represent different post-transplantation periods (days)

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DMA and sensitivity coefficient in rice at the field stage under different seedling ages and root pruning treatment conditions

Root pruning at different seedling ages had a minimal effect on the overall trend of rice DMA. All treatments demonstrated a monotonic increase in DMA throughout the growth period, following a "slow-fast-slow" sigmoidal curve pattern, as depicted in Figures 5B to 5D. The logistic growth curve was used to simulate DMA variations over time for each treatment. The correlation coefficients between the simulated and measured values were all above 0.98, indicating a highly linear relationship and confirming the reliability of the experimental results.

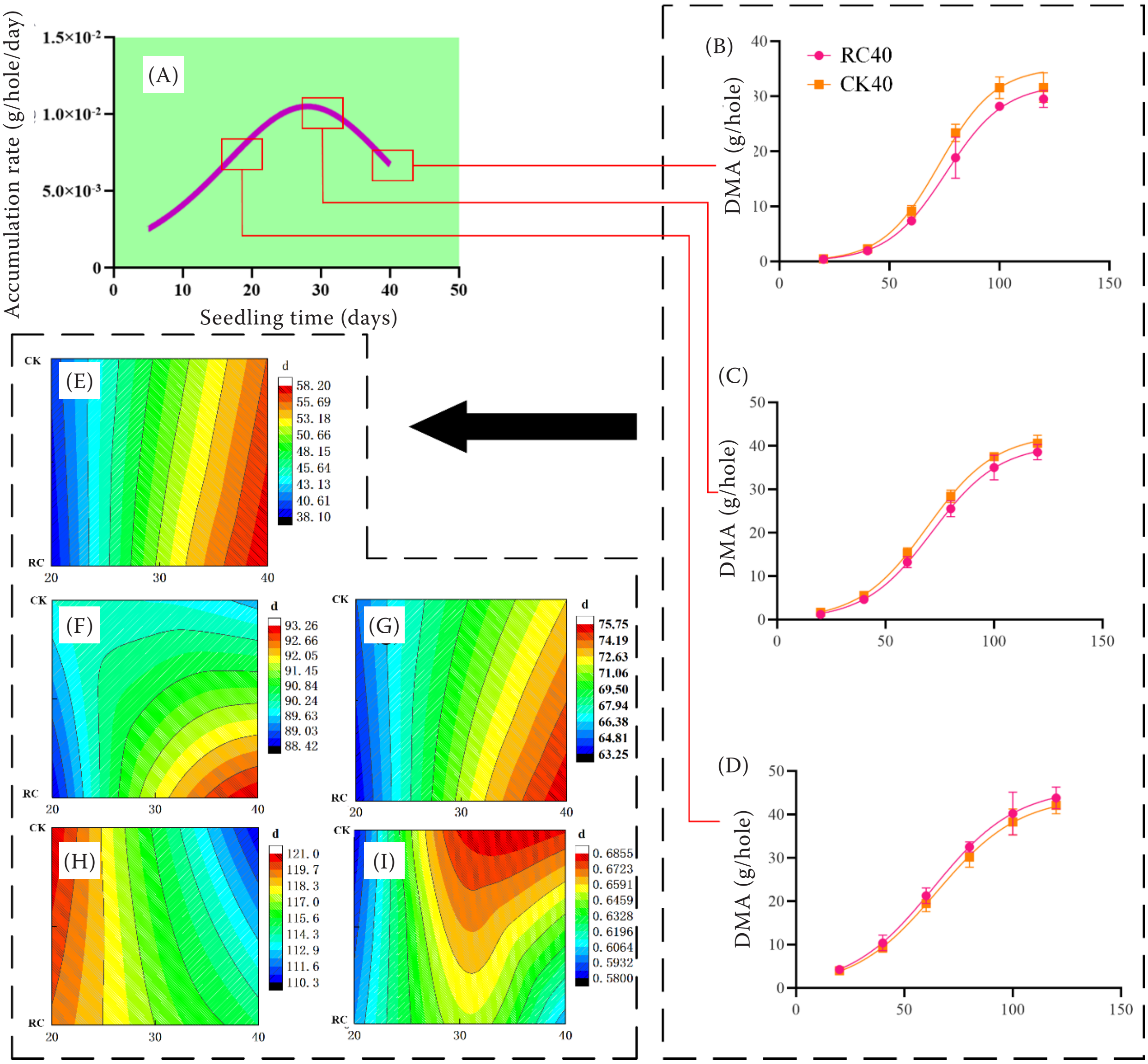

Figure 5. Effects of seedling age and root-pruning treatments on dry matter accumulation (DMA). (A) DMA rate at seedling stage; (B) DMA dynamics after transplanting at 40 days seedling age; (C) DMA dynamics after transplanting at 30 days seedling age; (D) DMA dynamics after transplanting at 20 days seedling age; (E) effects of seedling age and root-pruning treatment on X1; (F) effects of seedling age and root-pruning treatment on X_2; (G) effects of seedling age and root-pruning treatments on X_0; (H) effects of seedling age and root-pruning treatments on X_{max}; (I) effects of seedling age and root-pruning treatments on V_{max}. RC20 and CK20 denote root pruning and no pruning treatments for 20-day-old transplanted seedlings, respectively. RC30 and CK30 denote root pruning and no pruning treatments for 30-day-old transplanted seedlings, respectively. RC40 and CK40 denote root pruning and no pruning treatments for 40-day-old transplanted seedlings, respectively

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Table 2. Parameter estimates and model validity of the logistic growth equation for different treatments

Treatment	Parameter estimation				Characteristic parameter				
	K	a	b	R^2	X_0	X_1	X_2	X_{max}	V_{max}
RC20	46.1	27.55	0.0523	0.980	63.2	38.1	88.4	119.5	0.60
CK20	44.1	29.86	0.0524	0.987	64.7	39.6	89.9	120.9	0.58
RC30	40.3	101.2	0.0646	0.991	71.4	51.0	91.7	116.9	0.65
CK30	42.7	82.90	0.0637	0.995	69.2	48.6	89.9	115.4	0.68
RC40	32.2	295.3	0.0751	0.983	75.7	58.2	93.2	114.9	0.60
CK40	35.2	290.8	0.0781	0.981	72.6	55.7	89.4	110.2	0.68

K – theoretical maximum dry matter mass, with a and b as parameters of the equation; X_0 – time corresponding to the maximum DMA rate; X_1 – start time of rapid DMA; X_2 – end time of rapid DMA; X_{max} – denotes the growing period; V_{max} – maximum DMA rate; RC – root-pruned CK – control

The main characteristic parameters of DMA for each treatment were calculated using Eq. (2), and the results are presented in Table 2. Different root pruning treatments affected the start and end times of rapid DMA, the maximum growth rate, the time to reach the maximum rate, and the rice growth cycle. RC20 and CK20 entered the rapid growth phase during the re-greening stage, while RC30, CK30, RC40, and CK40 entered during the jointing stage, delaying entry by 12.9 to 20.0 days compared to RC20. All treatments concluded rapid growth during the milk maturity stage, with RC40 ending the latest at 1.5 to 4.9 days later than the others. Each treatment reached its fastest DMA rate during the booting-to-heading transition, but the rates varied among treatments. The rice growth cycle ranged from 110.29 to 120.96 days, depending on the treatment.

To analyse the interactive effects of seedling age and root pruning on DMA, contour plots were generated using Origin 9.0 (Figures 5E–I). The maximum start time of rapid DMA (X_1) was in mature seedlings with root pruning, and it was advanced in younger seedlings and delayed in older seedlings (Figure 5E). The end time of rapid accumulation (X_2) was also longest under mature seedling age with root pruning, ending earlier in younger seedlings and later in older seedlings (Figure 5F). The time of maximum accumulation rate (X_0) was highest in mature seedlings with pruning, and it was advanced in younger seedlings and delayed in older seedlings (Figure 5G). The longest crop growth cycle (X_{max}) occurred in young seedlings without pruning, and it was shortened by pruning in younger seedlings and extended by pruning in older seedlings (Figure 5H). The highest growth rate (V_{max}) was observed without pruning, and it increased in younger seedlings with pruning but decreased in seedlings with pruning older than 30 days (Figure 5I).

Figure 6 shows the sensitivity coefficients of DMA characteristics in response to root pruning. The absolute value of the sensitivity coefficient indicates the degree of change in the parameters per unit change in root pruning; positive values indicate an increase, while negative values indicate a decrease. At the 20-day seedling age, the sensitivity coefficients decreased in the following order: maximum growth rate (V_{max}), start time of rapid accumulation (X_1), time of maximum accumulation rate (X_0), end time of rapid accumulation (X_2), and duration of the growth period (X_{max}). The sensitivity coefficient for V_{max} was positive at 0.061, suggesting a 0.061 unit increase in growth rate per unit increase in root pruning. The

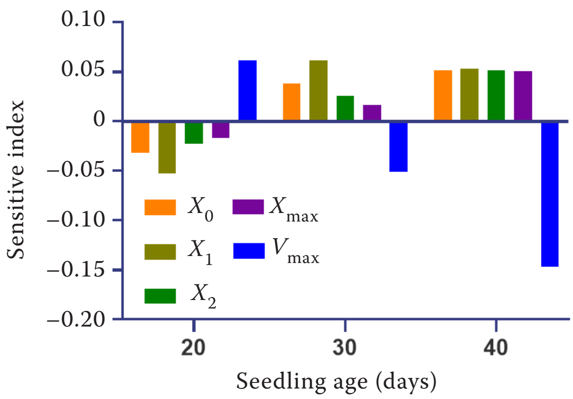

Figure 6. Sensitivity coefficient of characteristic parameters. X_0 – time corresponding to the maximum dry matter accumulation (DMA) rate; X_1 – start time of rapid DMA; X_2 – end time of rapid DMA; X_{max} – denotes the growing period; V_{max} – maximum DMA rate

https://doi.org/10.17221/327/2023-PSE

coefficients for the other parameters were negative (–0.0529 for X_1, –0.0321 for X_0, –0.0229 for X_2, and –0.0168 for X_{max}), which indicated earlier onset and end times of rapid accumulation and earlier maximum rate time with each unit increase in root pruning. At the 30-day seedling age, the absolute values of sensitivity coefficients had the following order: X_1, V_{max}, X_0, X_1, and X_{max}. There was a negative coefficient for V_{max} and a positive for others. The pattern remained consistent at the 40-day seedling stage.

DISCUSSION

Effect of seedling age on seedling quality

Rice seedling quality at transplanting, including the number of green leaves, tiller numbers, height, root vitality, and DMA, significantly impacts early growth in the field (Zhang et al. 2008). The present study used the logistic growth model to simulate DMA during the seedling stage (Figure 3), revealing a gradual growth phase post-emergence, transitioning to rapid growth on day 17 and slow growth starting on day 40. As seedling age increased from 20 to 40 days, the plant height, dry weight, and stem base width significantly increased. DMA rate, which is closely related to root vitality (Cui et al. 2002), peaked at 28 days, indicating maximum root vitality. At 20 days, the seedlings experienced minimal root injury and rapid regrowth when transplanted. At 30 days, the seedlings experienced high root vitality but severe water loss, which led to a prolonged recovery and negatively impacted yield. At 40 days, the seedlings experienced weaker root vitality and severe water loss, significantly affecting yield.

Rice seedling quality at the time of transplanting refers to various indicators, including the number of green leaves, tiller numbers, seedling height, root system vitality, and DMA, all of which have an impact on the initial growth of rice in the field (Zhang et al. 2008). The age of seedlings is one of the important factors affecting seedling quality. In the present study, the logistic growth model was used to simulate the process of DMA in rice during the seedling stage (Figure 3). The simulation results showed that the rice plants entered the gradual growth phase after emergence and then transitioned to the rapid growth phase on the 17^{th} day after emergence. The rice plants finally entered the slow growth phase on the 40^{th} day after emergence. As the seedling age increased from 20 to 40 days, rice seedlings' height, individual plant dry weight, and stem base width significantly increased. However, with a further increase in seedling age, the dry weight of the seedlings may not continue to increase and may even exhibit a decreasing trend (Qiu et al. 2021). The present findings indicated that the slow-growth phase of rice will continue until the 53^{rd} day, and the 40-day seedling age may not have reached the critical seedling age, which leads to a decrease in seedling dry weight. Therefore, during this stage, the dry weight showed an increasing trend (Figure 3). The DMA rate is closely related to root vitality (Cui et al. 2002). In the present study, the DMA rate of seedlings reached a maximum of 28 days, indicating the strongest root vitality at this stage. When transplanted at 20 days, the root vitality was moderate, with fewer aboveground leaves and lower transpiration rates, resulting in minimal root injury and rapid regrowth. However, when transplanted at 30 days, the root vitality was high, but at the same time, there were more aboveground leaves and higher transpiration rates, leading to more severe water loss after root injury and a prolonged recovery period, which negatively affected the yield. When transplanted at 40 days, the root vitality was weaker, and there were more aboveground leaves, resulting in severe water loss after root injury and an extended recovery period, significantly impacting the yield.

Effect of root pruning at different seedling ages on root growth during the re-greening stage

Root pruning affects the root morphology of rice. Previous studies have shown that root pruning in rice and wheat results in reduced root volume, root surface area, number of secondary roots, and total root length compared to the non-pruned control group (Yu et al. 1985, Tong et al. 2011, Fang et al. 2015). The present results showed that on the 9^{th} day after root pruning, the total root length, root volume, root surface area, and root dry weight of rice were significantly reduced (Figure 4). These findings indicated that root pruning at different stages significantly decreased the root length, root volume, and root surface area, among other root morphological characteristics, in rice. The present study found that the effects of root pruning on rice root morphological characteristics varied among different seedling ages. Specifically, for young seedlings, root pruning they had a relatively minor impact on root morphological characteristics (Figure 4). However, for older seedlings, root pruning significantly in-

https://doi.org/10.17221/327/2023-PSE

hibited root growth, which was consistent with the findings of Li et al. (2016a). Li et al. (2015) observed that on the 7th and 14th days after root pruning, the total root length and root surface area of rice plants in the unpruned control group were significantly greater than those in the heavily pruned group, in which roots were cut at one-third of their length. Ren et al. (2007) showed that total pruning of the root system significantly inhibits new root and tiller production, as well as reduces DMA in rice plants. Figure 4 shows that rice plants of different seedling ages exhibited varying resistance mechanisms when subjected to root pruning. Young seedlings rapidly recovered and initiated lateral root growth to cope with root injury, while older seedlings required longer to restore root growth. These findings suggested that different seedling ages display differentiated resistance responses to root system injury.

Effect of root pruning on growth parameters at different seedling ages

Dry matter production is the foundation of rice yield formation, and the process of rice yield formation essentially involves producing and allocating dry matter (Hu et al. 2019). Previous studies have shown that the DMA process in rice is influenced by genotype and environmental factors, which are reflected in the variation of parameters in the logistic model (Drazic et al. 2017). Establishing a logistic model to simulate the rice growth process is beneficial for understanding the characteristics and differences in DMA of rice at different seedling ages after transplanting. Because the DMA process in rice varies due to differences in seedling age, utilising the logistic model helps to gain insights into the specific features and variations in this process.

The present results demonstrated that the DMA process in rice for both root-pruned and non-root-pruned treatments at 20, 30, and 40 days of seedling age followed a sigmoidal growth curve ("S" – shaped). However, their characteristic values differed, including the onset, peak, and end of rapid DMA, as well as the accumulation rate and total accumulation. Each treatment exhibited unique characteristics in these aspects. There were differences in the timing of rapid DMA among rice of different seedling ages. Specifically, for rice with a seedling age of 20 days, the rapid DMA stage occurred between 38 and 88 days after transplantation. For rice with a seedling age of 30 days, the rapid growth stage occurred between 40 and 90 days after transplantation. For rice with a seedling age of 40 days, the rapid growth stage occurred between 51 and 92 days after transplantation. Of note, the rapid DMA began earlier for rice with a seedling age of 20 days, while for rice with a seedling age of 30 and 40 days, it started later, which may be related to growth inhibition during the early seedling stage. The growth of seedlings is suppressed by competition for light and nutrients among plants, and this competition intensifies with the increase of seedling age (Lee et al. 2021). Young seedlings transplanted at an early stage experience a shorter period of suppression, characterised by strong root vitality and vigorous metabolic activities within the plants, which enables them to rapidly tiller and enter the re-greening stage, initiating the process of rapid DMA. Root pruning promotes lateral root growth, leading to an earlier start of rapid DMA. In contrast, mature seedlings experience a longer period of suppression with weaker root vitality, resulting in slower regrowth and growth of rice plants, which leads to a slower rate of DMA. Root pruning delayed the regrowth period, causing a postponement in the start of rapid DMA (Figure 5E). The peak period of DMA in rice varied among different treatments, occurring on different days after transplanting, but it consistently corresponded to the reproductive growth stage, which agreed with the conclusions of Wei et al. (2021). After root pruning at the 30-day seedling age, the rice seedlings exhibited a higher DMA rate, possibly attributed to their higher growth rate in the nursery (Figure 5A). Despite experiencing water stress during the early transplanting stage, the seedlings recovered and developed more lateral roots, which enhanced their ability to absorb water and nitrogen from the soil, resulting in a higher growth rate during the reproductive stage (Figure 5I). However, due to the shorter duration of the rapid growth phase, the yield was relatively lower compared to the 20-day seedling age rice seedlings.

Patel et al. (2019) suggested that extending the rice seedling stage and delaying the transplanting time may lead to an elongation of the overall rice growth cycle but may result in a reduction of the rice growth stage in the field. In the present study, the sensitivity coefficient average was utilised to describe the extent and direction of seedling age and root pruning effects on various characteristic parameters. The results showed that root pruning significantly impacted the rapid growth rate of DMA and the start time of the rapid growth stage. Under

https://doi.org/10.17221/327/2023-PSE

the condition of young seedling age, root pruning had a positive effect on the maximum growth rate of DMA, while under the condition of mature seedling age, it exhibited a negative effect. Additionally, root pruning had a negative effect on the start time of the rapid growth stage under the condition of young seedling age, while it had a positive effect under the condition of mature seedling age.

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