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EFFECTS OF SOIL NUTRITION AND WATER CONTENT ON SEEDLING GROWTH OF *DACRYDIUM PIERREI* HICKEL IN CHINA

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Abstract

How soil nutrition availability affects the density, height, and ground diameter of seedling of *Dacrydium pierrei* Hickel was investigated in three selected National Nature Reserve of China using mixed model approaches. Results showed that the soil nutrient content in the studied area was significantly different; the relationship between six nutrient elements and the density, height, and ground diameter of seedling were almost in exponent and logarithm; ground diameter is the best seedling growth factors for modeling by soil nutrition availability; models ((14)-(16)) are the best models for simulating the relationship between them; *D. pierrei* seedlings growth has a specific distribution range in altitude, latitude, and longitude. It was observed that increasing soil fertility, cleaning litter under the forest appropriately, healthy seeds obtainment, artificial cultivation and breeding seedlings may take protective and management measures for *D. pierrei*.

Introduction

Soil nutrients play an important role in soil fertility and environmental condition of plant growth and development (Camenzind *et al.* 2018, Uriarte *et al.* 2018). The condition of seed germination, seedling establishment, growth and reproduction during tree recruitment (Collin *et al.* 2018), the composition, development, spatial patterns, and geographical distribution of species (Wang *et al.* 2018), and ecosystem stability are mainly affected by soil nutrient availability. Most researches of soil nutrition have focused on the effects of alkaline nitrogen, available phosphorus, available potassium, and water content on plant growth (Mackay *et al.* 2017) effecting the ecosystem community structure (Waldrop *et al.* 2017). Thus, finding out the relationship between soil nutrients and seedling growth is important to the protection and management of rare and endangered species.

Model can describe the relationship between seedling growth and environment (Gibert *et al.* 2016). Experts have conducted many model studies on soil nutrients. Soil nutrients can be well estimated by principal component analysis, gray correlation analysis, fuzzy comprehensive evaluation, and index method (Ebrahimi *et al.* 2017). However, most of these models can only be applied to a certain research object. Therefore, exploring a suitable model to evaluate the effects of soil nutrients with different quality on the seedling recruitment of rare and endangered tree species remains a significant challenge.

D. pierrei is the only species of genus *Dacrydium* belongs to Podocarpaceae in China. *D. pierrei* is a third-class rate-endangered plant species under the China red data book classification (Chen *et al.* 2014). The main purpose of this study was to create a generalized NLME model for the quantitative description of the relationship between seedling growth and comprehensive effect

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of soil nutrient in natural forest. Thus an attempt was made to identify the effects of soil nutrient on seedling growth, identify the soil nutrients and other factors which have significant impact on seedling density (D) and also to explore the influences of that on the tree height (H) and ground diameter (GD).

Materials and Methods

National Nature Reserve in China, namely the Bawangling, the Jianfengling and the Diaoluoshan where *D. pierrei* grows, were chosen as the study sites (Chen *et al.* 2014). A total of 150 seedling plots (in all three sites) were selected, and one typical seedling was taken as the center for each plot.

Soil samples were collected from the center and four corners of each plot in all 150 seedling plots in March, 2016. Five samples (20 cm depth) from each plot were mixed together and 150 g soil was taken, dried, sieved, and kept in laboratory for further analysis. The soil nutrient grading standard of the second national soil census in China was used as the soil nutrient quality criterion, taking soil organic matter (SOM), total nitrogen (N), alkali-hydrolyzable nitrogen (N), available phosphorus (P), rapidly available potassium (K) and total phosphorus (P), total potassium (K) and water content (W) as indicators. The plot size, canopy density, altitude, longitude, latitude, slope, aspect, litter thickness, shrub coverage and herb coverage of each plot were measured. The species name, GD, and H and number of seedlings were recorded.

Four types of models used for the relationship between soil nutrient and seedling growth. W, N, SOM, AN, RP and RK were chosen as predictor variables in model. The NlME process of R software was used to fit the 300 trees, and the 30 trees were validated. After several times of calculation, the best basic model was chosen depending on the result of four statistical criteria (Fu *et al.* 2017).

The total P (P_2O_5), total K (K_2O), canopy density (CD) and litter thickness (LT) were put into the models to consider the influence of other factors from survive environment on seedling. Then, the new Y models were established.

The parameter effect, the covariance structure of the variance within-sample plot, and the variance covariance structure of random effects were determined (Jordan *et al.* 2005).

The fitting and validation results were evaluated by the following statistics and indicators: R^2, $\bar{e}$, σ_e^2 and root mean square error (RMSE) calculated by Eqs. (1 - 4) using the fitting and validation data sets. The fixed-effect part test of the mixed effects model was the same as the traditional; the random effect part test requires subsampling to calculate the random parameter value.

$$R^2 = 1 - \sum\left(Y_t - \hat{Y}_t\right)^2 \Big/ \sum\left(Y_t - \bar{Y}\right)^2 \quad (1)$$

$$\bar{e} = \sum e_t \Big/ N = \sum\left(Y_t - \hat{Y}_t\right) \Big/ N \quad (2)$$

$$\sigma_e^2 = \sum\left(e_t - \bar{e}\right)^2 \Big/ (N-1) \quad (3)$$

$$RMSE = \sqrt{\bar{e}^2 + \sigma_e^2} \quad (4)$$

Results and Discussion

The soil nutrient quality grade was significantly differently in all three regions. In the Bawangling National Nature Reserve, only a little plot has soil nutrient quality in the higher grade and high grade, and that of the medium and less medium grade were more than the high grade, which indicated that the soil nutrition of the site was relatively poor. That of the Jianfengling, most of the soil nutrient quality was concentrated on the medium grade, and soil nutrient quality grade of some plots were the higher or less medium.

The relationship between the six nutrient elements and seedling D (Fig. 1), GD (Fig. 2), and H (Fig. 3) were significantly different. The relationship between RK, AN, SOM, W, N, and D were the exponential function, and that of RP was logarithmic function. The R^2 value of that of RK, RP, AN, SOM, W and N was 0.8526, 0.7149, 0.7211, 0.6990, 0.3349 and 0.5514, respectively. The relationship between RK, AN, W and GD was the linear function, and that of SOM and N were the exponential function, and that of RP was logarithmic function. The R^2 value of that of RK, RP, AN, SOM, W and N was 0.8526, 0.7149, 0.7211, 0.6990, 0.3349 and 0.5514, respectively.

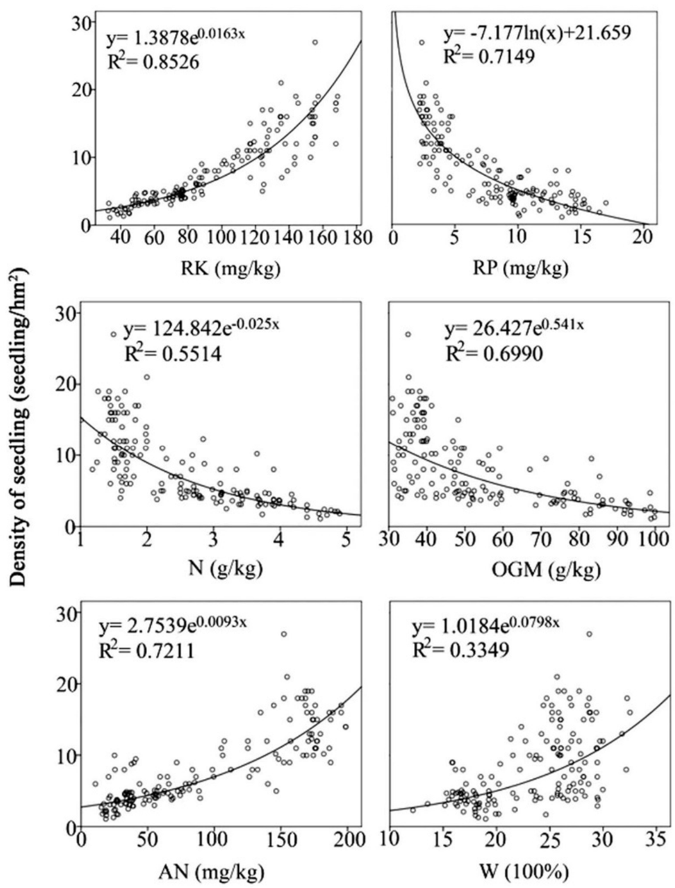

Fig. 1. The relationship between six soil nutrient elements and the density of seedling.

N is total nitrogen, OGM is organic matter content, AN is alkali-hydrolysable nitrogen, RP is available phosphorus, RK is rapidly available potassium, W is water content, R^2 is coefficient of determination, y is density of seedling and x is the independent variable corresponding to the horizontal axis.

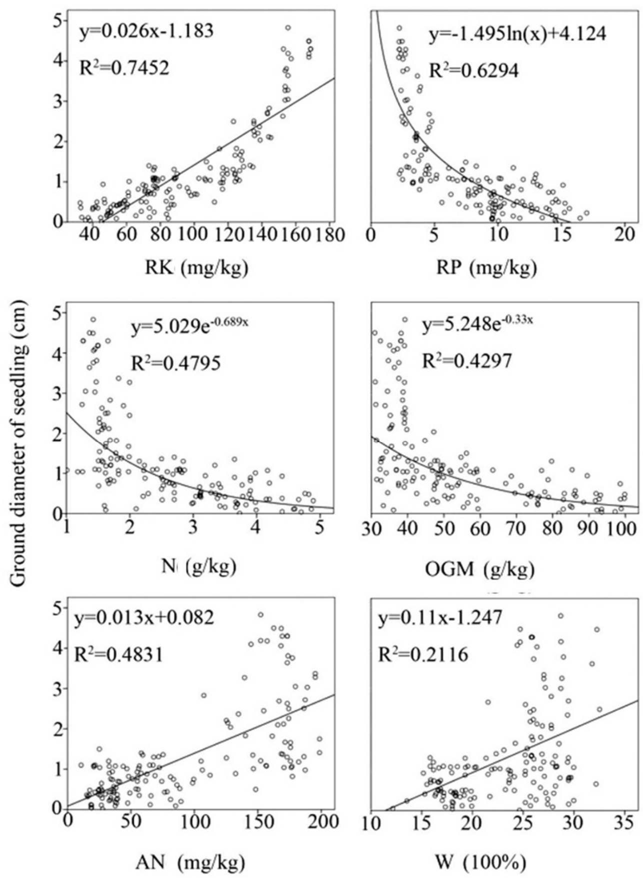

Fig. 2. The relationship between six soil nutrient elements and the ground diameter of seedling.
N is total nitrogen, OGM is organic matter content, AN is alkali-hydrolysable nitrogen, RP is available phosphorus, RK is rapidly available potassium, W is water content, R^2 is coefficient of determination, y is density of seedling and x is the independent variable corresponding to the horizontal axis.

The Model IIIc was most suitable for the density of seedlings modeling compared to other models (Table 1).

Table 1. Performance statistics of converged base models for both model fitting and validation.

Model	Data for model fitting				Data for model validation		
	$\bar{e}$	σ_e^2	RMSE	R^2	$\bar{e}$	σ_e^2	RMSE
Ia	0.168	5.987	2.453	0.518	0.210	13.174	3.635
IIb	0.137	5.687	2.389	0.725	0.201	7.517	2.749
IIIc	0.052	5.347	2.313	0.770	0.146	6.419	2.538
IVd	0.043	5.874	2.424	0.753	0.062	6.887	2.625

R^2 is coefficient of determination, $\bar{e}$ is mean bias, σ_e^2 is bias variance, RMSE is root mean square error, it combines mean bias and bias variance and provides a robust measure of the overall model accuracy, Ⅰa, Ⅱb, Ⅲc, and Ⅳd is model numbering.

For seedling GD (Table 2), the ε value of Model IVd was the minimum, the value of δ_e^2 and RMSE of the model validation were the minimum, and the value of R^2 of the model fit was the maximum. Thus, model Ⅳd was most suitable for the ground diameter of seedlings modeling compared to other models.

Table 2. Performance statistics of converged base models for both model fitting and validation.

Model	Data for model fitting				Data for model validation		
	$\bar{e}$	δ_e^2	RMSE	R^2	$\bar{e}$	δ_e^2	RMSE
Ia	1.396	5.875	2.797	0.561	1.653	14.765	4.183
IIb	0.636	6.437	2.616	0.691	0.986	8.654	3.103
IIIc	1.073	7.047	2.863	0.352	1.013	7.875	2.983
IVd	0.831	5.477	2.484	0.727	0.654	7.982	2.900

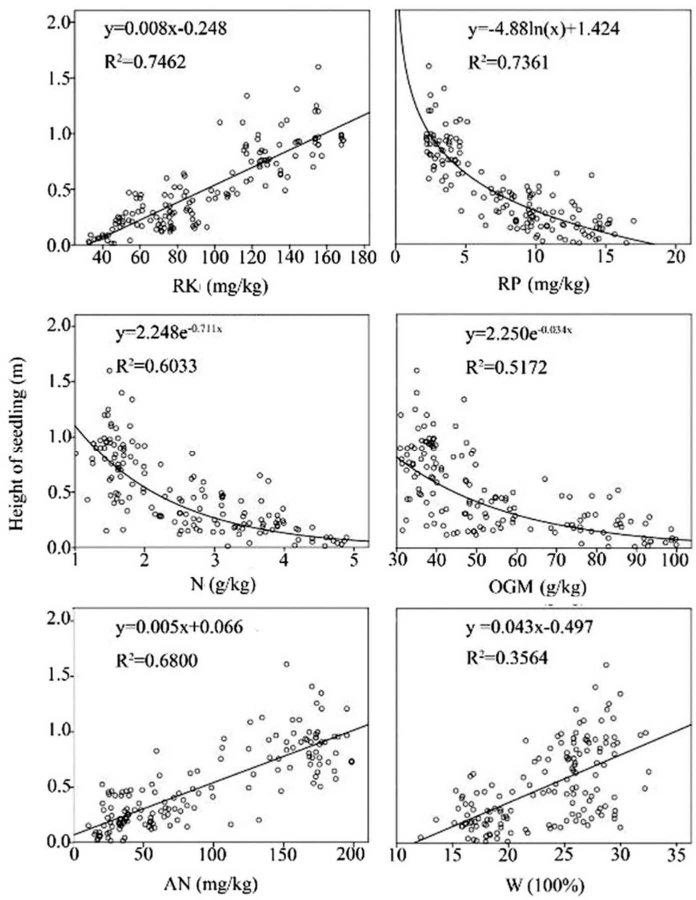

Fig. 3. The relationship between six soil nutrient elements and the height of seedling.

N is total nitrogen, OGM is organic matter content, AN is alkali-hydrolysable nitrogen, RP is available phosphorus, RK is rapidly available potassium, W is water content, R^2 is coefficient of determination, y is density of seedling and x is the independent variable corresponding to the horizontal axis.

For seedling H (Table 3), the Model IIIc and IVd were selected as the best performance model for model developing to fit the relationship between the D, H and GD of seedling and soil nutrient availability.

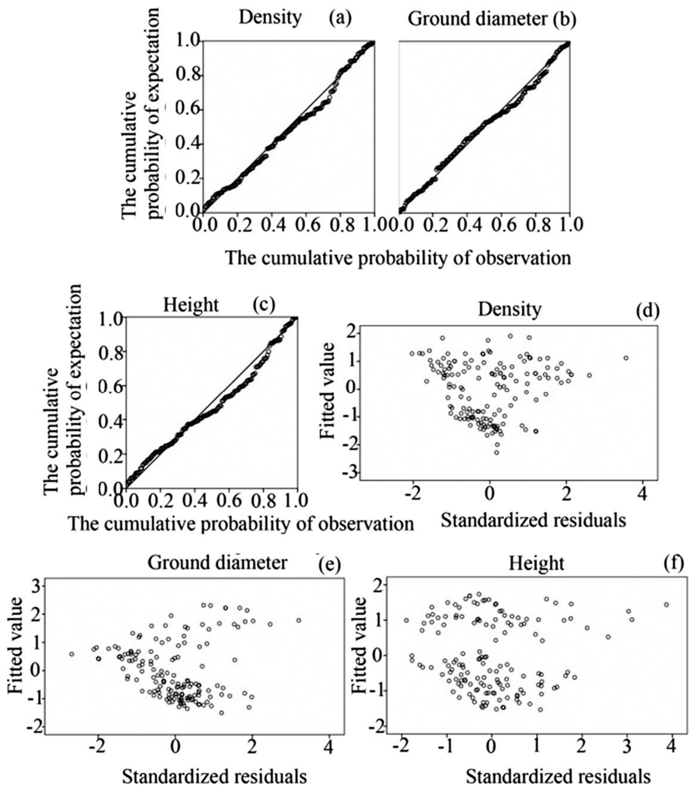

Fig. 4. The residuals distribution and P - P plots.

Table 3. Performance statistics of converged base models for both model fitting and validation.

Model	Data for model fitting				Data for model validation		
	$\bar{e}$	δ_e^2	RMSE	R^2	$\bar{e}$	δ_e^2	RMSE
Ia	1.053	10.965	3.475	0.380	1.847	10.984	3.794
IIb	0.738	9.037	3.095	0.525	1.367	8.873	3.277
IIIc	0.514	7.687	2.820	0.624	0.853	7.847	2.928
IVd	0.519	8.589	2.976	0.614	0.945	8.173	3.011

The selected base models were follows:

$$Y_D = \frac{\alpha_1}{1 + exp[\alpha_2 + \alpha_3 \lg \quad (x)]} \tag{5}$$

$$Y_H = \frac{\alpha_1}{1 + exp[\alpha_2 + \alpha_3 \lg \quad (x)]} \tag{6}$$

$$Y_{GD} = \alpha_1 \exp\left(\frac{-\alpha_2}{x^{\alpha_3}}\right) \quad (7)$$

where Y_D, Y_H and Y_{GD} is the D, H, and GD of seedling respectively, x is soil nutrient element or other factors, α_1, α_2, and α_3 are parameters.

And then change the × into the five variables:

$$Y_D = \frac{\alpha_1}{1 + exp[\alpha_2 + \alpha_3 \lg(x_W + x_{RK} + x_{RP} + x_{AN} + x_N + x_{SOM})]} + \varepsilon \quad (8)$$

$$Y_H = \frac{\alpha_1}{1 + exp[\alpha_2 + \alpha_3 \lg(x_W + x_{RK} + x_{RP} + x_{AN} + x_N + x_{SOM})]} + \varepsilon \quad (9)$$

$$Y_{GD} = \alpha_1 \exp\left(\frac{-\alpha_2}{(x_W + x_{RK} + x_{RP} + x_{AN} + x_N + x_{SOM})^{\alpha_3}}\right) + \varepsilon \quad (10)$$

where Y_D, Y_H and Y_{GD} is the D, GD, and H of seedling respectively, x_W, x_{RK}, x_{RP}, x_{AN}, x_N and x_{SOM} is W, RK, RP, AN, N, and SOM of soil respectively, α_1, α_2, and α_3 are model parameters, ε is an error term.

For the other factors:

$$\boldsymbol{Y_D = \frac{\alpha_1}{1 + exp[\alpha_2 + \alpha_3\, lg(x_{CD} + x_{LT})]} + \varepsilon} \quad (11)$$

$$Y_H = \frac{\alpha_1}{1 + exp[\alpha_2 + \alpha_3 \lg(x_{CD} + x_{LT})]} + \varepsilon \quad (12)$$

$$Y_{GD} = \alpha_1 \exp\left(\frac{-\alpha_2}{(x_{CD} + x_{LT})^{\alpha_3}}\right) + \varepsilon \quad (13)$$

where Y_D, Y_H and Y_{GD} is the D, H, and GD of seedling respectively, x_{CD} and x_{LT} are the canopy density (CD) and litter thickness (LT) of the plot, $\alpha_1, \alpha_2, \alpha_3, \eta$, and g, are parameters, ε is error term.

Parameter calculation: After substitution of estimated parameters, those models were as follows:

$$Y_D = \frac{8.737}{1 + exp[1.712 - 1.044 \lg(x_W + x_{RK} + x_{RP} + x_{AN} + x_N + x_{SOM})]} + 0.138 \quad (14)$$

$$Y_H = \frac{1.312}{1 + exp[19.687 - 15.220 \lg(x_W + x_{RK} + x_{RP} + x_{AN} + x_N + x_{SOM})]} + 0.254 \quad (15)$$

$$Y_{GD} = 3.37 \exp\left(\frac{-841.4}{(x_W + x_{RK} + x_{RP} + x_{AN} + x_N + x_{SOM})^{6.816}}\right) + 0.762 \quad (16)$$

where Y_D, Y_H and Y_{GD} is the D, H, and GD of seedling respectively, x_W, x_{RK}, x_{RP}, x_{AN}, x_N, and x_{SOM} is W, RK, RP, AN, N, SOM, respectively.

For the other factors:

$$\boldsymbol{Y_D} = \frac{\mathbf{12.681}}{\mathbf{1} + \boldsymbol{exp}[\mathbf{0.863} - \mathbf{2.474}\,\boldsymbol{lg}(\boldsymbol{x_{CD}} + \boldsymbol{x_{LT}})]} + \mathbf{0.357} \tag{17}$$

$$Y_H = \frac{9.472}{1 + exp[5.839 - 1.485\lg(x_{CD} + x_{LT})]} + 0.480 \tag{18}$$

$$Y_{GD} = 4.51\exp\left(\frac{-41.4}{(x_{CD} + x_{LT})^{4.159}}\right) + 0.047 \tag{19}$$

where Y_D , Y_H and Y_{GD} are the D, H, and GD of seedling respectively, and x_{CD} and x_{LT} is the canopy density (CD) and litter thickness (LT), respectively.

The NLME models Eqs. (14) - (19) in each alternative showed steadily increasing prediction accuracy of D, H, GD when a larger number of sample trees were used for estimation of the random effects. Therefore, using four randomly selected trees to estimate the random effects could result in the most cost-effective and accurate predictions of the NLME model Eqs. (14)-(19).

The results (Table 4) showed that R^2 values of three models fitting were 0.806, 0.792, 0.753, 0.814, 0.807, 0.801, respectively, which mint other factors also have effect on the seedling growth.

Table 4. Validate statistics of density, ground diameter and height of seedling predictions by the three models.

Factors	Dependent variable	Data for model fitting				Data for model validation		
		$\bar{e}$	σ_e^2	RMSE	R^2	$\bar{e}$	σ_e^2	RMSE
W, RK, RP, AN, N, SOM.	D	0.050	5.543	2.355	0.806	0.168	5.987	2.453
	H	0.654	5.982	2.532	0.792	0.854	7.582	2.883
	GD	0.413	6.025	2.489	0.753	0.813	8.244	2.984
CD, LT.	D	0.053	5.419	2.417	0.814	0.144	5.845	2.256
	H	0.572	5.672	2.485	0.807	0.752	7.367	2.567
	GD	0.402	5.684	2.413	0.801	0.736	8.135	2.683

The P - P plots of the three models (Eqs. 14 - 16) showed linear relationship for the residuals, while the Eq. (16) (ground diameter) of that was more obvious compared to that of the Eq. (17) (density) and Eq. (15) (height) (Fig. 4).

The results showed that soil nutrients have great influence on the D, GD and H of seedling. This was same as in previous studies (Uriarte *et al.* 2018) that different water retention capacity of soil made the growth status different. Changing in soil P, K, Zn and Mn concentrations affect soil nutrient availability and reduces soil mineral ion absorbed by seedlings (Bagheri *et al.* 2012, Bachelot *et al.* 2016, Iraj *et al.* 2018). Therefore, artificial rainfall and other measures can be used to improve the soil dryness, and then improve seed germination and seedling growth environment. In addition, five soil nutrient indicators, measuring soil nutrient quality grade, shows significant contributions to the variation of D, GD and H of seedling.

Some other factors together with soil nutrients were found to determine the seedling growth was found in this study. Altitude, latitude, longitude and litter thickness did not have much contribution to model fitting, but they have still important effects on the seedlings growth. So, appropriate artificial breeding and planting seedling measures can be carried out at these regions, adapting to *D. pierrei* growth, in order to improve its endangered phenomenon.

Results showed that *D. pierrei* seedlings growth condition in tropical rainfall forest in China can be explained by soil nutrition availability. Soil nutrition and other factors in places where *D. pierrei* seedlings grow have a great impact on their establishment. Therefore, artificially cultivated and bred seedlings measures can be taken by obtaining healthy seeds in *D. pierrei* regious where *D. pierrei* grows.. What's more, increasing the soil fertility and appropriate remove litter under the forest are also appropriate me asures. Present findings are more strongly explained the reason why the number of *D. pierrei* seedlings growth is decreasing in China. The seedlings can survive and reproduce in the limited soil nutrients availability condition; it is not merely as it is having strong regional growth character. These results provide critical information about the effects of soil nutrition condition on seedling cluster processes of *D. pierrei* in China. However, there also exists deficiencies and shortcomings in the model used in this study that needs further study.

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