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RESEARCH ARTICLE

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A rainfall interception model for inhomogeneous forest canopy

Abstract The process of rainfall interception by an inhomogeneous forest canopy composed of tree crowns with some gaps among them were considered, and the previous theoretical models of rainfall interception were modified to model an inhomogeneous canopy instead of a statistically homogeneous canopy. The paper deals with the following. First, the process of rainfall interception in tree crowns and that of rainfall in the gaps among them are studied respectively to acquire the average rainfall interception of a forest canopy. Based on the model derived by Liu (1987) and setting the canopy density value, both the relevant partial equations and a formula to estimate rainfall interception were derived. Moreover, the new model was solved through a numerical method and was illustrated with typical values of some ecological factors; three groups of curves were acquired by calculation with the VisualBasic program. A model of rainfall interception by an inhomogeneous forest canopy is classified as a multi-layer model, which is different from previous models (models where all the parameters represent the whole canopy). The results from the model in this paper could be used to determine the relationship between interception and each ecological factor in detail.

Keywords inhomogeneous canopy, canopy density, rainfall interception, theoretical model

1 Introduction

The interception of rainfall, including interdiction, adsorption and evaporation by the components of forest canopy, has great effect on the redistribution of water and reduction of the dynamics of raindrops. It is one of the important parts of forest ecology, and covered by forest meteorology, forest hydrology and water and soil conservation, etc. It has been studied for a long time, but there are still some theories waiting to be discovered.

Since Horton (1919) first put forward the easiest linear model of rainfall interception of forest canopies, succeeding models in the field have been greatly developed. The interception models can be divided into four types: conceptual model, empiric model (or the mathematical model) (Marriam, 1960; Leonard, 1965; Czarnowski and Olszewski, 1968; Aston, 1979; Massman, 1980), the theoretical model and the half-theoretical model (Rutter et al., 1971, 1975, 1977; Gash, 1979; Cui et al., 1980; Massman, 1983; Mulder, 1985; Wang, 1986; Liu, 1987, 1988; Liu, 1997; Liu et al., 2000). These models have advantages and disadvantages respectively.

The theoretical model of rainfall interception by Liu (1988) described the rainfall interception process. However, it was only applied in a homogeneous canopy. Since the distribution of twigs and leaves in a forest canopy is actually inhomogeneous, it was necessary to develop a model for an inhomogeneous canopy.

In the model (Liu, 1988), mathematical and physical methods and those in the theory were used for reference. The forest canopy was divided into many thin layers; the shading effect of twigs and leaves among each layer was considered; the amount of water intercepted, adsorbed, and evaporated by each layer of twigs and leaves was calculated; and the changes of both rainfall intensity and dry percentage were studied. Hence, it is a theoretical model describing the process of rainfall interception in more detail. Moreover, the new model was illustrated with typical values of some ecological factors. However, the subject depicted in the model was a horizontally homogeneous forest canopy, which agreed with the pure forests with high canopy density. Whereas for sparse forests or mingled forests, the distribution of their twigs and leaves is more complex, and most of them are inhomogeneous. Thus, theoretical development necessarily requires the

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establishment of a model of rainfall interception by an inhomogeneous forest canopy.

Therefore, in this paper, the process of rainfall interception by an inhomogeneous forest canopy was considered. First, the process of rainfall interception in tree crowns and that of rainfall in the gaps among them were studied respectively to acquire the average rainfall interception in the forest canopy. Next, when the value of the canopy density was set, and the relevant partial differential equations were derived, the new model was solved through numerical method. Then it was illustrated with typical values of some ecological factors. Finally, the results acquired through the new model were compared with measured data.

2 Derivation of partial differential equations

The model by Liu (1988) was composed of two partial differential equations. One decided the rainfall intensity in the forest canopy R, Eq. (1), and one determined the dry percentage of twigs and leaves D, Eq. (2). The boundary condition of the rainfall intensity and the initial condition of the dry percentage were Eqs. (3) and (4):

$$\frac{\partial R(z,t)}{\partial z} = -R(z,t)D(z,t)\overline{U}(z)G(z) \tag{1}$$

$$\frac{\partial D(z,t)}{\partial t} = -R(z,t)D(z,t)G(z)/\alpha(z) + [1-D(z,t)]V/\alpha(z) \tag{2}$$

$$R_0(t) = R(0,\ t) \tag{3}$$

$$D_0(z) = D(z,\ 0) \tag{4}$$

where R_0 is the rainfall intensity above the forest canopy, which equals to the rainfall intensity in the gaps among tree crowns; z is the depth in the forest canopy, the direction of axis z is perpendicularly downward, $z=0$ is at the top of the forest canopy, $z=H$ is at the bottom of the forest canopy, H is the thickness of the forest canopy; t is time; $\overline{U}$ is the average leaf area density; G is the average perpendicular projection rate of the leaf area; a is the adsorption rate of water by the leaf surface; V is the evaporation rate of twigs and leaves.

The group of equations mentioned above can still be displayed in another form. If leaf area index or LAI (the leaf area within certain thickness of the forest canopy) is used to replace z (when $z=H$, $L=L_M$, is the maximum leaf area index: the leaf area in the whole forest canopy) while precipitation is used to replace t, then Eqs. (1) and (2) can be transformed into the following equations:

$$L(z) = \int_0^z \overline{U}(z')\mathrm{d}z' \quad \text{and} \quad \mathrm{d}L = \overline{U}(z)\mathrm{d}z \tag{5}$$

$$P(t) = \int_0^t R_0(t')\mathrm{d}t' \quad \text{and} \quad \mathrm{d}P = R_0(t)\mathrm{d}t \tag{6}$$

$$\frac{\partial R_r(L,P)}{\partial L} = -R_r(L,P)D(L,P)G(L) \tag{7}$$

$$\frac{\partial D(L,P)}{\partial P} = -R_r(L,P)D(L,P)G(L)/\alpha(L) + [1-D(L,P)]V/\alpha(L)R_0(P) \tag{8}$$

$$R_r(L,P) \equiv \frac{R(L,P)}{R_0(L,P)} \tag{9}$$

where $R_r(L,P)$ is relative rainfall rate.

As was mentioned above, this model can be applied in a horizontally homogeneous forest canopy. We should develop it for application in an inhomogeneous forest canopy.

It is assumed that the inhomogeneous forest canopy consists of cylindrical tree crowns with gaps among them and the canopy density is E, $0 < E \leqslant 1$. $E=1$ can be taken as a homogeneous canopy, and the twigs and leaves within each tree crown are homogeneously distributed (Fig. 1).

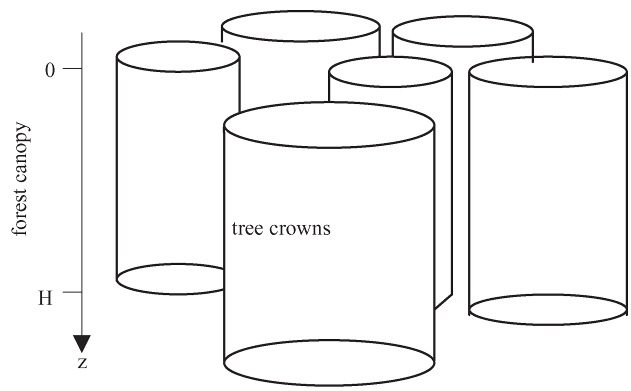

Fig. 1 Inhomogeneous forest canopy ($0 <$ canopy density $\leqslant 1$)

The rainfall intensity within the forest canopy is the average value of rainfall intensity of tree crowns and that in the gaps, thus the average rainfall intensity is:

$$R(L,P) = ER_C(L,P) + (1-E)R_0(P) \tag{10}$$

where R_C is the rainfall intensity within tree crowns; $ER_C(L,P)$ is the contribution of the rainfall intensity within tree crowns; $(1-E)R_0(P)$ is the contribution of the rainfall intensity in the gaps.

$$Eu = \overline{U} \tag{11}$$

where u is the leaf area density within tree crowns.

From Eqs. (5) and (6), we know that the LAI within tree crowns is multiplied with E equalizing the average LAI within the forest canopy.

$$\mathrm{d}L = u(z)\mathrm{d}z = [\overline{U}(z)/E]\mathrm{d}z = \mathrm{d}\overline{L}/E \tag{12}$$

Since it has been assumed that the twigs and leaves within each tree crown are homogeneously distributed, then Eqs. (7) to (9) can be applied to twigs and leaves within tree crowns. Considering Eq. (12), we can derive the equations as follows:

$$\frac{\partial R_{rc}(L,P)}{\partial L} = -R_{rc}(L,P)D(L,P)G(L)/E \tag{13}$$

$$\frac{\partial D(L,P)}{\partial P} = -R_{rc}(L,P)D(L,P)G(L)/\alpha(L) + [1-D(L,P)]V/\alpha(L)R_0(P) \tag{14}$$

where $R_{rc}(L,P)$ is the relative rainfall intensity within the forest canopy.

$$R_{rc}(L,P) \equiv \frac{R_C(L,P)}{R_0(L,P)} \tag{15}$$

The initial and boundary conditions respectively are:

$$R_0(P) = R(0,P) \tag{16}$$

$$D_0(L) = D(L,0) \tag{17}$$

According to Eqs. (2)–(18) from Liu (1988) and Eq. (10), we can have the equations to calculate the interception:

$$I(P) \equiv E\int [R_0(t') - R_c(H,t')]\mathrm{d}t' = E\int_0^t [1-R_{rc}(H,t')]R_0(t')\mathrm{d}t' = E\int_0^P [1-R_{rc}(L_M,P)]\mathrm{d}P \tag{18}$$

3 Validation of the new model

3.1 Calculation method

A group of typical data from Dong et al. (1987) and Luo et al. (1999) was used to validate the newly derived model.

Set the maximum LAI or $L_M = 6$, and the average perpendicular projection rate of leaf area $G = 0.5$ constant; the adsorption rate of water by leaf surface $\alpha = 2.0 \times 10^{-4}$ m a constant; canopy density $E = 1$ or 0.7; $V = 0$ or 0.18 mm/h; the boundary condition $R(0, P) = R_0 = 2.03 \times 10^{-3}$ m/h, indicating it was a constant rainfall; the initial condition $D(L, 0) = D_0 = 1$, indicating that the forest canopy was completely dry before it rains.

Then, the numerical method was employed to solve the partial differential Eqs. (13) and (14). First, both the forest canopy and each variable should be discrete. We can divide the forest canopy into N horizontal layers in the perpendicular direction, while setting the number of time steps as M. In this case, $R_{rc}(L, P)$ and $D(L, P)$ can be regarded as two two-dimensional numerical arrays: $R_{rc}(N, M)$ and $D(N, M)$. Eqs. (13) and (14) should be changed into difference equations.

The detailed steps are as follows: first draw on the initial condition $D(k, 0)$ and Eq. (13) to solve $R_{rc}(k, 0)$, where $k = 0, 1, 2,\ldots, N$; then, solve $D(k, 1)$ with already known $R_{rc}(k, 0)$ and Eq. (14), and using Eq. (13) solve $R_{rc}(k, 1)$; next, with the solved $R_{rc}(k, 1)$ and Eq. (14), $D(k, 2)$ is solved, and using Eq. (13) to solve $R_{rc}(k, 2)\ldots$, calculating in this way again and again until the M step is reached, then all $R_{rc}(L, P)$ and $D(L, P)$ in the process can be solved. With all the solved $R_{rc}(L, P)$ and Eq. (18), interception $I(P)$ can be directly solved. The results are shown in Figs. 2, 3 and 4.

3.2 Calibration

In Fig. 2 (a), when $P = 0$, since $D(L, 0) = 1$, as per Eq. (13), separate the variables and then integrate, from which we know that the curves of $R(P) - L$ (named as "isochrone" in the following dynamic changes of relative rainfall intensity R vs leaf area index L at a certain moment; such curves vary over time) should decline exponentially as L increases. Over time, the forest canopy gradually became more moist and the rainfall intensity in it gradually increased and the curves of $R(P) - L$ gradually shift from exponential decline to "converse S" shape. Until $P \to \infty$, the forest canopy turned completely wet, and the rainfall intensity in the forest canopy equals to R_0.

In Fig. 2(b), the rainfall within tree crowns differed from that in the gaps among tree crowns. When $P = 0$, since $D(L, 0) = 1$, the rainfall within tree crowns declined exponentially while that in the gaps stayed at R_0. Thereby, the average rainfall intensity when $P = 0$ (according to Eq. (10)) at the bottom of the forest canopy (especially where L was larger in value) was elevated to $R > (1 - E)R_0 = 0.3R_0$. Over time, tree crowns gradually turned wet, and until $P \to \infty$, the forest canopy was completely saturated, and the rainfall intensity in the forest canopy equaled to R_0. Another important difference between Figs. 2(b) and 2(a) was that the isochrone of the former was denser than that of the latter when $E = 0.7$. L_M of tree crowns was larger in value than the average value of the forest canopy (according to Eq. (12)). Therefore, it took more time for twigs and leaves in tree crowns to become moist than for those in a homogeneous canopy.

In Fig. 2 (c), evaporation rate $V = 0.18$ (mm/h); according to the above analysis, we know that when $P = 0$ at the bottom of the forest canopy was (especially where L was larger in value) elevated to $R > (1 - E) R_0 = 0.3R_0$. Over time, the rainfall intensity in the forest canopy gradually became larger in value; however, until $P \to \infty$, the rainfall intensity in the forest canopy cannot reach R_0. Although the rainfall intensity at the top of the forest canopy (where $L = 0$) was R_0, due to evaporation, the rainfall intensity declined linearly within the forest canopy as leaf area index L increased. With the increase

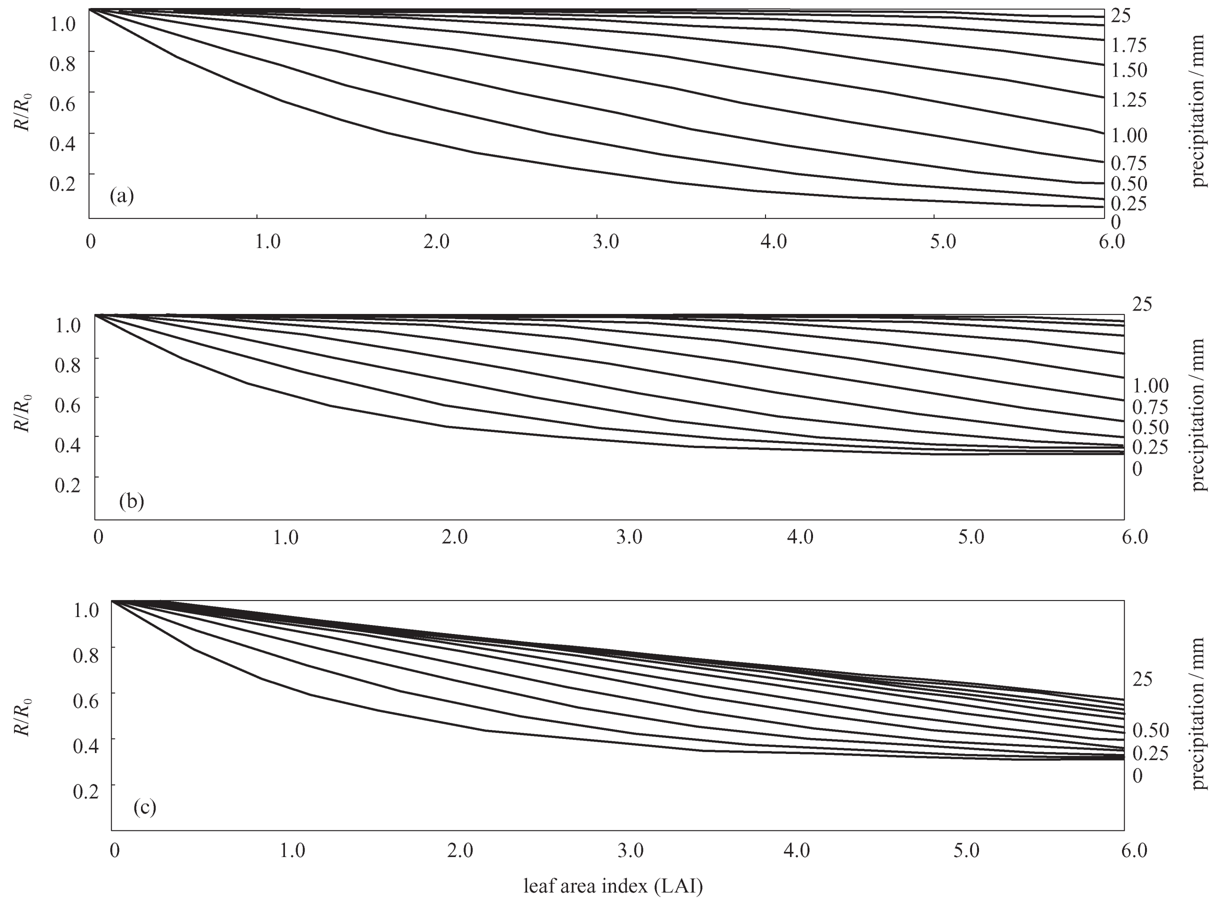

Fig. 2 Dynamic changes of the ration rainfall intensity and the initial rainfall intensity over leaf area depth and precipitation. Note: (a): $V = 0$, $E = 1$; (b): $V = 0$, $E = 40.7$; (c): $V = 0.18$(mm/h), $E = 0.7$. The same as below.

of L, the amount of water evaporated by the leaf surface increased and rainfall intensity decreased.

In Fig. 3(a), when $P = 0$, supposing the initial condition $D(L, 0) = 1$, we acquired a horizontal line. Over time, the forest canopy gradually became more moist and especially the upper part of the forest canopy (where L was smaller in value) first became wet, and the curves of $D(P)$–L gradually declined. Until $P \to \infty$, the forest canopy was completely saturated and the dry percentage was zero.

In Fig. 3(b), when $P = 0$, supposing the initial condition $D(L, 0) = 1$, a horizontal line was acquired. Over time, tree crowns gradually became wet until $P \to \infty$; the forest canopy is totally drenched and the rainfall intensity in the forest canopy equals R_0, which resembles the tendency of curves in Fig. 3(a). Nevertheless, there exists a great difference: the isochrones in Fig. 3(b) are denser than those in Fig. 3 (a) in that when $E = 0.7$, L_M of tree crowns is larger in value than the average L_M of the forest canopy (according to Eq. (12)), in this case, it should take more time for twigs and leaves in tree crowns than for those in a homogeneous canopy to become moist.

In Fig. 3(c), the isochrones were also denser than those in Fig. 3(a), or it took more time to become moist for the forest canopy in Fig. 3(c) than that in Fig. 3(a). However, when $P \to \infty$, the dry percentage D was not zero but a positive value depending on the rainfall intensity and the evaporation rate due to evaporation.

In Fig. 4(a), saturated interception was proportional to L_M in that the larger the value of L_M, the more water the forest canopy adsorbed. Besides, it takes more time for the forest canopy to become saturated because the larger the value of L_M, the more difficult for the twigs and leaves in the lower part to be soaked and more time should be needed before the forest canopy reaches saturation.

In Fig. 4(b), although the canopy density was different from that in Fig. 4(a), the same average L_M should correspond to the same saturated interception in that the forest canopies with the same average L_M should have the same total leaf area. The larger the value of L_M, the longer it should be before interception reached saturation, and even more time should be taken to reach saturation than for the interception of the forest canopy in Fig. 4(a) with the same thickness. According to Eq. (12), when $E = 0.7$, the L_M within tree crowns was larger in value than the average L_M of the forest canopy (or L_M when $E = 1$). In this case, it took more time for denser tree crowns to be saturated than for sparser ones. When $P \to 0$, the gradient of interception curves with different

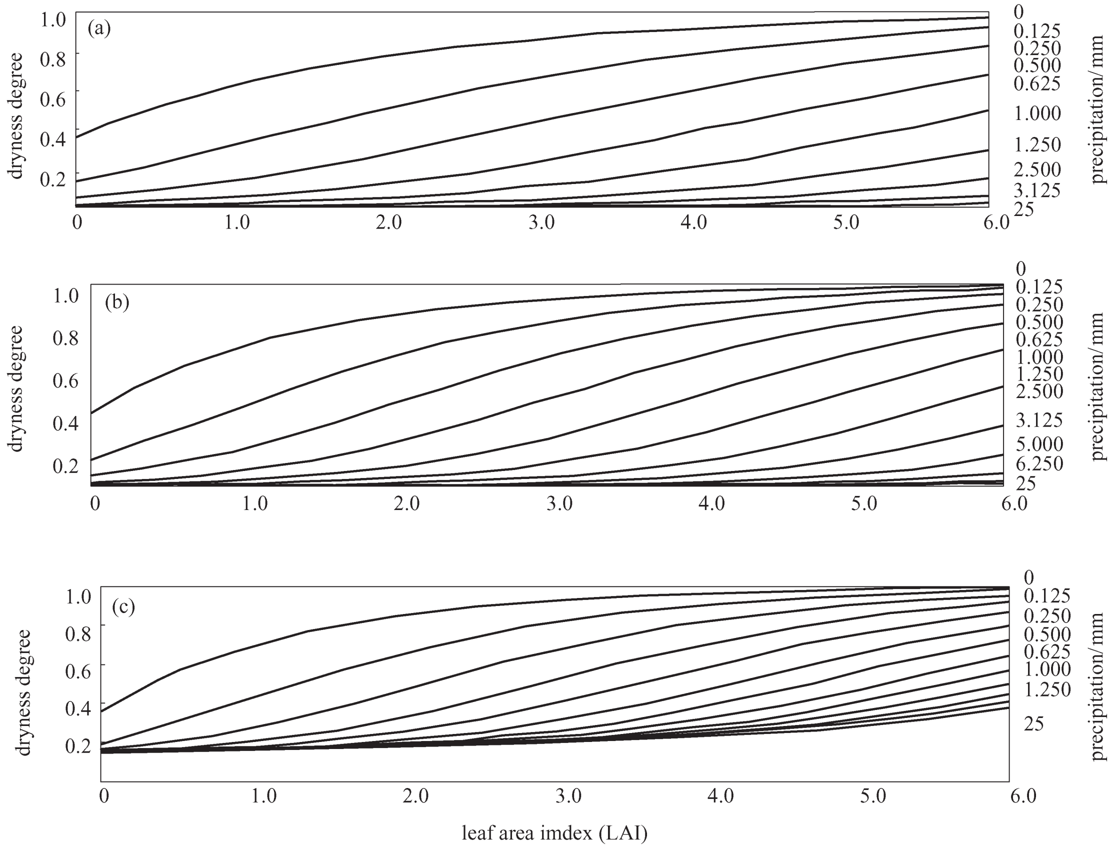

Fig. 3 Dynamic changes of dryness degree over leaf area depth and precipitation

$L_{\mathrm{M}}-\left(\frac{\mathrm{d}I}{\mathrm{d}t}\right)_{P=0}$ was smaller in value than that in Fig. 4(a) in that when $E=0.7$, the L_{M} within tree crowns was larger in value than the average L_{M} of the forest canopy (or L_{M} when $E=1$), even when $P\rightarrow 0$.

In Fig. 4(c), due to evaporation, $I\ (L_{\mathrm{M}})-P$ curves went up over time and they cannot reach saturation (or there was no climax); instead, they all tend to be lines with certain slopes. The larger the magnitude of L_{M}, the larger the gradient. This is because not only twigs and

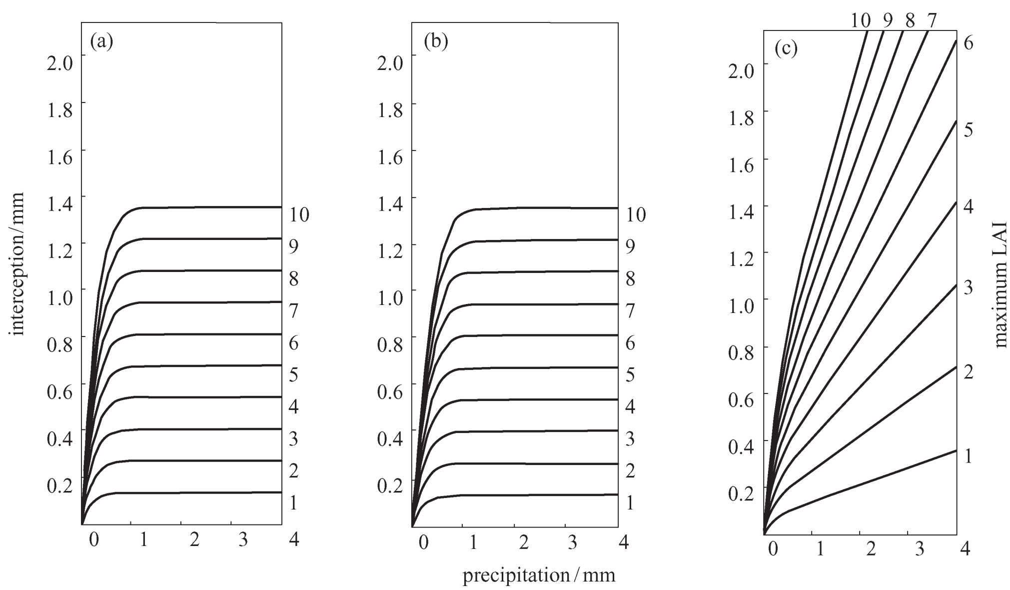

Fig. 4 Dynamic changes of interception over leaf area index and precipitation

leaves can adsorb water, but evaporation can also contribute to interception. Moreover, the contribution of the former was limited while that of the latter increased linearly over time. The larger the forest canopy's L_M in magnitude, the larger the total leaf area in value; the larger the evaporation rate in magnitude, the larger the slope in value. Finally, when $P \to 0$, the gradient of interception curves with different L_M $-\left(\frac{dI}{dt}\right)_{P=0}$ was smaller in value than that in Fig. 4(a) when $E = 0.7$. L_M within tree crowns was larger in value than the average L_M of the forest canopy (or L_M when $E = 1$). However, the gradient equalizes that in Fig. 4(b) in that when $P \to 0$, there was hardly any twig and leaf area drenched by rainfall or the additional interception brought about by evaporation can be ignored, although evaporation did not occur at that time.

4 Validation of measured data

Dong et al. (1987) published measured data of *Pinus tabulaeformis* they acquired in Hebei Province, including throughfall rate, throughfall, interception rate and interception amount etc. Validation results (Fig. 5) can be obtained with the new model derived in this paper (Table 1).

4.1 Formula derivation

According to the above discussion, the formula of throughfall rate, throughfall, interception rate and interception can be derived according to pertinent definitions. Evidently, the throughfall rate of the forest canopy is the ratio of the rainfall intensity at the bottom of the forest canopy to that at the top of it:

$$Tr(P) \equiv \frac{R(L_M,P)}{R_0(P)} = \frac{ER_C(L_M,P) + (1-E)R_0(P)}{R_0(P)} = (1-E) + E\frac{R_C(L_M,P)}{R_0(P)} = (1-E) + ER_{rc}(L_M,P) \quad (19)$$

The throughfall of the forest canopy is:

$$T(P) \equiv \int_0^t R_0(t')Tr(t')dt' = \int_0^P Tr(P')dP' = (1-E)P + E\int_0^P R_{rc}(L_M,P)dP \quad (20)$$

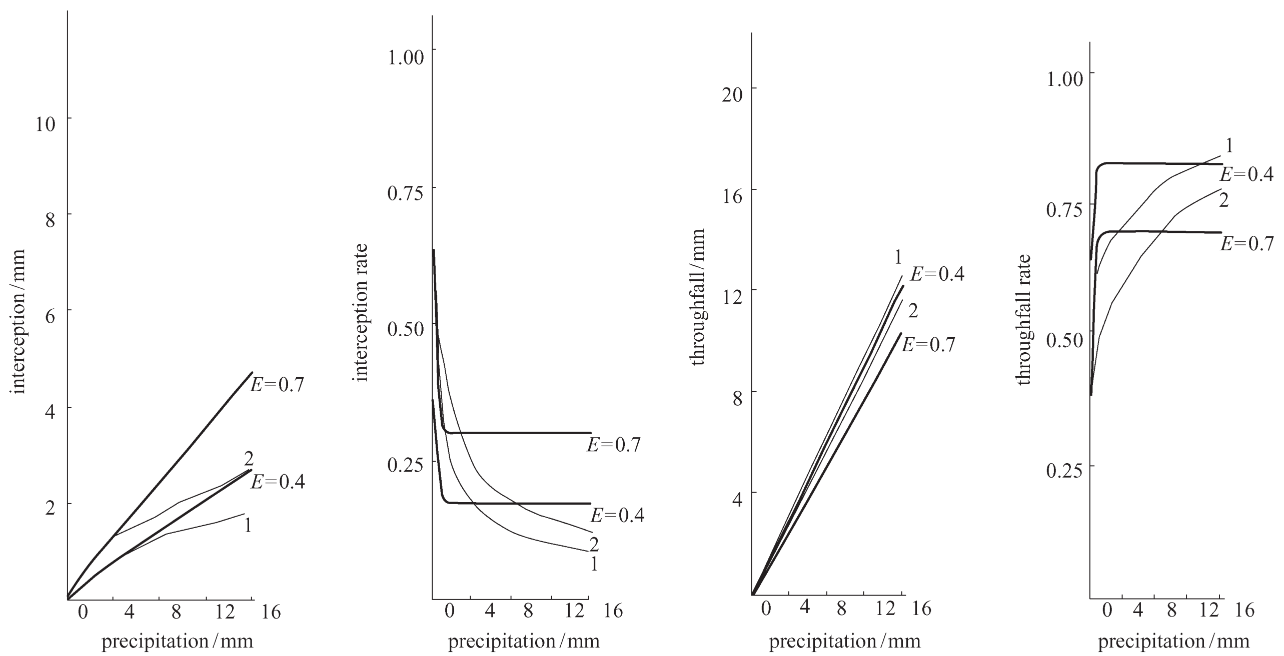

Fig. 5 Validation of interception, interception rate, throughfall and throughfall rate by the new model
Thick line: validation by the new model; thin line: data from Dong et al. (1987)

Table 1 Parameters applied to calculate throughfall rate, throughfall, interception rate and interception

plot	initial rainfall intensity (R_0)/mm·h^{-1}	canopy density (E)	evaporation rate (V)/mm·h^{-1}	adsorption rate of the needles (A)/mm*	leaf area projection rate (G)*	maximum leaf area index (L_M)	initial dry percentage (D_0)
plot 1	2.03	0.70	0.18	0.20	0.5	4.0	1.0
plot 4	2.03	0.40	0.15	0.20	0.5	3.0	1.0

Note: the parameters cited from Dong et al. (1987). Data marked by * were commonly used.

The interception rate (the percentage of the interception by the forest canopy in the rainfall intensity above the forest canopy) or subtract the throughfall rate from one:

$$Ir(P) \equiv 1 - Tr(P) = E[1 - R_{rc}(L_M, P)] \quad (21)$$

According to Eq. (21), we can calculate interception by:

$$I(P) \equiv \int_0^t R_0(t')Ir(t')\mathrm{d}t' = E\int_0^P [1 - R_{rc}(L_M, P)]\mathrm{d}P \quad (22)$$

4.2 Validation

From Fig. 5, we know that the performance of the new model is better. However, there exist several differences, because the curves of Dong et al. (1987) were acquired by simulating the measured data with exponential functional models. The measured data were indeed dispersed spots or not all of them located near the curves.

Take the interception curves for instance. After the forest canopy became saturated, the dry percentage should almost be constant; in this case, the additional interception should increase linearly as rainfall increased, rather than increase exponentially. In addition, the amount of leaves of the forest canopy with canopy density $E = 0.7$ was 75% more than that of the forest canopy with canopy density $E = 0.4$ ($(0.7 - 0.4)/0.4 = 75\%$). Correspondingly, after the forest canopy became saturated, the interception of the former should be 75% more than that of the latter, while the distance between the two curves in the work of Dong et al. (1987) was relatively smaller.

Another example is the interception rate curves. When $P \rightarrow 0$ (or when it just began to rain), the interception rate should be $E[1 - \exp(-GD_0L_M)]$ (according to Eq. (7); and in Fig. 5, when $E = 0.4$, the interception rate is 0.39, while at $E = 0.7$, the interception rate is 0.68), instead of positive infinity (the new model used for simulation) or 100% (relevant curves of Dong et al. (1987)); additionally, by reason of evaporation, the interception rate should at first decrease and then tend to stabilize as precipitation increased, rather than decrease in accordance with the model used for simulation (Otherwise, the interception rate will become zero as precipitation increase constantly, which disagrees with the fact that evaporation always exist in the forest canopy). Similarly, when $P \rightarrow 0$ (or when it begins to rain), owing to the gaps in the forest canopy, the throughfall rate should be $1 - E + E\exp(-GD_0L_M)]$ (according to Eq. (7); and in Fig. 5, when $E = 0.4$, the interception rate is 0.61; when $E = 0.7$, the interception rate is 0.32), instead of zero. Besides, by virtue of evaporation, the throughfall rate should at first increase and then tend to stabilize as precipitation increase but should not reach 100%, rather than increasing logarithmically (Otherwise, the throughfall rate will become 100% or even surpass 100% as precipitation increas constantly).

5 Conclusions and discussion

The previous theoretical model of rainfall interception (Liu, 1988) had been modified from a statistically homogeneous canopy to an inhomogeneous canopy. This expands the extent within which the theoretical model can be applied and revealed many more important detailed features during the process of rainfall interception by forest canopy. Among them, some agreed with the acquired knowledge, such as when canopy density $E < 1$, the rainfall intensity at the bottom of the forest canopy at first was a little over $(1 - E)$ R_0 (or the initial throughfall rate was a little more than $1 - E$), while some have not been discovered in previous studies. For example, if evaporation was considered, when $P \rightarrow \infty$, the dry percentage D cannot reach zero, or the forest canopy cannot be fully soaked; if the average leaf area index of the forest canopy was constant, it took more time for the interception I to become stable or saturated as the canopy density E decreased; and if evaporation was considered, when $P \rightarrow \infty$, the rainfall intensity in the forest canopy was smaller than R_0 in value.

Historically, there had been quite a few interception equations, most of them were integrated models: the parameters in them represented the whole forest canopy (Horton, 1919; Merriam, 1960; Aston, 1979; Calder et al., 1979; Cui et al., 1980; Wang, 1986; Liu, 1997). They reflect the process of interception on certain conditions. Among them, the model of Liu (1997) involves the merits of other models and in fact the latter is a particular form of the former in special situations. The new model derived in this paper belongs to the multi-layer type. However, the results through validation showed that the new model can replace the integrated models. The new model presented more detailed descriptions on the relationship between interception and each ecological factor.

However, there are two deficiencies in the new model: on the one hand, the twigs and leaves within each tree crown are still assumed to be homogeneously distributed, which is just approximate to the actual conditions; on the other hand, except for the gaps among tree crowns, there were still other variables that cause the inhomogeneity of the forest canopy. They provide the subjects for future research. In spite of this, the model of rainfall interception by an inhomogeneous forest canopy composed of tree crowns with gaps among them is still a good approximation under many circumstances and provide a foundation for further revisions.

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