

The Salt Accumulation Model on the Soil Surface by Evaporation, Transpiration and Rainfall

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ABSTRACT

The salt accumulation on the soil surface can be mathematically described. Although the movement of salts in soil solution is expressed in terms of mathematical model, which has certain limitations in practical application, except the exchangeable and absorbable state salts in soil solution.

This model is illustrated by analytical experiments in which evaporation from the bare soils, transpiration of plants and rainfall are required. Agreement between the model and the measured data was satisfactory, which validating the salt accumulation theory on the soil surface.

INTRODUCTION

Since liquid water and salts absorbed by plants move upward through a soil profile and vascular bundles, their burdens of dissolved salts move with water.

When the water evaporates at the soil surface, the salts remain in the soil. The salts absorbed by plants are accumulated in their above-ground parts, too. Evaporation, salination and absorption rates are thus very closely related.

Verhoeven (1950) and Richard et al. (1956) estimated evaporation by measuring the accumulation of salt in the surface layer and the concentration of salt in the soil solution moving into that surface layer.

Salts in solution also move by diffusion in response to concentration gradients which tend to move salts downward against the upward flow of liquid. If the flow is rapid and the water contains very low concentration of salt, the amount of salt that moves downward against the flow of water may be negligible in comparison to that which is transported upward. But if the water is saline, as ground water often is salt concentrations increase rapidly near the surface, and the resulting concentration gradients cause

significant amounts of salt to move downward. This is especially true in arid regions if soils remain for several months.

Soil solution phase and exchangeable phase are regarded as readily available in soils. The nonexchangeable phase generally represents slowly available forms of salt. The mineral phase, however, is often considered to be relatively unavailable and accounts for primary salt minerals. Applications of soluble salt fertilizer result in marked increases of salts in the soil-solution phase.

Under the natural conditions, practically all water and available salt absorption by rooted plants take place through the root system. The part of the roots where the most absorption takes place is the root hair zone. Soil solution diffuses into the root hair and, to a lesser degree, into other root epidermal cells, as a result of a water potential gradient. The most water and salt absorption occurs through the passive and active absorption. As a result, salts are absorbed by plant roots more upward through vascular bundle systems and accumulated in above-ground parts of plants on the soil surface.

Salts in the air fall on the soil surface with radinfall and snowfall. The velocity of fall

of the drops depends on the drop size. However, this state is limited within the rainy day.

This paper describes a theoretical model of salt accumulation on the soil surface by evaporation, transpiration and rainfall. The results are compared to an estimate obtained independently by the experiments which measured vertical distribution of salts in tide-land, grassland and forest soils.

MATHEMATICAL THEORY

The salt accumulation method for estimating evaporation and transpiration from soils in the presence of a water table, and for rainfall and snowfall is based upon the premise that salts which enter the soil profile can be accounted for by periodic samplings of the surface soil mass. Salt accumulation in the surface layer, salt movement by molecular diffusion, salt absorption and salt falling are all involved, but they can be evaluated independently.

The flow system is shown schematically in Fig. 1. As water in soils evaporates and transpires, salt accumulates at the surface, diffuses

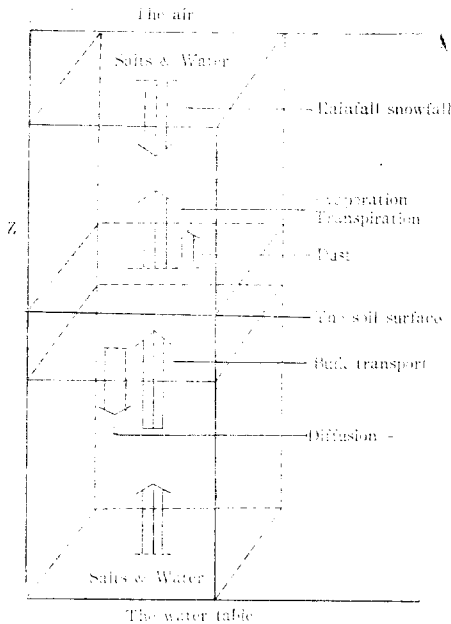


Fig. 1. Flow diagram for the movement of water and salt in a soil with a water table and the air.

downward in response to the concentration gradients that develop, while it rises in the air with dust.

The flow is upward and downward in the Z-direction. Analysis is based upon a column which has a unit cross-sectional area and which extends from the air and the water table to the soil surface. Depth is represented by Z increasing from the soil surface and C is the salt concentration in the water which enters the bottom and the air of the column. The rate at which salt enters the profile from below and upper, dF/dt , is given by

$$\frac{dF}{dt} = Cq_i \dots\dots\dots(1)$$

where q_i is the volume rate of inflow of water from the water table and air. Since the salts remain in the soil when the water evaporates and transpires from the surface, there is an accumulation of salts in the profile.

If there is no evaporation, transpiration and rainfall, the equation (1) is a

$$\frac{dF}{dt} = 0 \dots\dots\dots(2)$$

In this case, the concentrations of salts in the surface soils are equal in subsoils.

The change in salt content ΔF , between times t_1 and t_2 is

$$\Delta F = \int_{t_1}^{t_2} dF = C \int_{t_1}^{t_2} q_i dt \dots\dots\dots(3)$$

where C is constant.

The continuity principle requires that inflow minus outflow must equal storage. This applies for both salt and water. For water, this relationship is

$$V_i = V_o + V_s = (V_e + V_t + V_f) + V_s \dots\dots(4)$$

where V is expressed in units of volume per unit area, and the subscripts i, o, e, t, f and s denote inflow, outflow, evaporation, transpiration, raining and storage, respectively. But

$$V = \int q dt \dots\dots\dots(5)$$

so

$$\begin{aligned} V_i &= \int_{t_1}^{t_2} q_i dt = \int_{t_1}^{t_2} q_o dt + \int_{t_1}^{t_2} q_e dt \\ &= \int_{t_1}^{t_2} (q_o + q_e + q_f) dt + \int_{t_1}^{t_2} q_s dt \dots\dots(6) \end{aligned}$$

If θ is the average water content of the soil,

column in milliliters per unit volume, the amount of water stored between t_1 and t_2 is

$$Z \int_{t_1}^{t_2} d\theta = \int_{t_1}^{t_2} q_s dt \dots\dots\dots(7)$$

After substituting equations (3) and (7) into (5), differentiating and rearranging terms we have

$$q_o = \frac{1}{c} \frac{dF}{dt} \Big|_{q_e+q_t+q_f} - Z \frac{d\theta}{dt} \dots\dots\dots(8)$$

where q_o , q_e , q_t , and q_f are the volume rates of outflow, evaporation, transpiration, and rainfall, respectively. When there is no vegetation on the soil surface, the equation (8) is given by

$$q_o = q_e = \frac{1}{c} \frac{dF}{dt} \Big|_{q_e} - Z \frac{d\theta}{dt} \dots\dots\dots(9)$$

In the case of the grassland and forest soils, the equation (8) is approximately

$$q_o = q_t = \frac{1}{c} \frac{dF}{dt} \Big|_{q_t} - Z \frac{d\theta}{dt} \dots\dots\dots(10)$$

On rainy days, the equation (8) is defined as

$$q_o = q_f = \frac{1}{c} \frac{dF}{dt} \Big|_{q_f} - Z \frac{d\theta}{dt} \dots\dots\dots(11)$$

If the water-table depth remains constant, steady flow will result when the flow is controlled by the capacity of the soil to transmit water upward and by the activity of salt absorption and translocation of plants. Under these conditions, the rate at which water flows upward will be the same at all depths in the profile, whether the profile is homogeneous or composed of layers of different textures. For steady flow throughout the profile, $\frac{d\theta}{dt} = 0$, and the last term in the equation (8) vanishes:

$$q_o = q_e = \frac{1}{c} \frac{dF}{dt} \Big|_{q_e+q_t+q_f} \dots\dots\dots(12)$$

In the naked soils the equation (12) can be integrated to give the mirror image of the drainage rate out of the profile, (Youngs, 1960; Gardner, 1962) according to the expression.

$$q_o = q_e = \frac{1}{c} \frac{dF}{dt} \Big|_{q_e} = \frac{1}{c} A(1 - e^{-Bs}) = a(1 - e^{-Bs}) \dots\dots\dots(13)$$

where A and a are constants and S denotes salt concentrations.

In the grassland and forest soils, the equation (12) is obtained by

$$q_o = q_t = \frac{1}{c} \frac{dF}{dt} \Big|_{q_t} = \frac{1}{c} \frac{FS}{K+S}$$

$$= \frac{F_m S}{K+S} \dots\dots\dots(14)$$

where $FS/k+S$ is the absorption rate of salt by plant roots (Epstein, 1962).

In the air, the flow is controlled by the velocity of the drops, the so-called terminal velocity, which depends on the drop size. The equation (12) is defined by the terminal velocity of the falling drops (Byers, 1974)

$$q_o = q_f = \frac{1}{c} \frac{dF}{dt} \Big|_{q_f} = \frac{1}{c} \frac{2}{9} \frac{\rho_L - \rho}{\eta} g r^2 \dots\dots\dots(15)$$

where ρ_L , ρ , η , g , and r are the density of droplets, the density of air, viscosity, gravity and radius of droplets, respectively. However, $C_f q_f$ is the lowest value of $C_e q_e$, $C_t q_t$ and $C_f q_f$:

$$C_e q_e \gg C_t q_t \gg C_f q_f$$

so

$$C_e q_o = C_e q_e + C_t q_t + C_f q_f = C_e q_e + C_t q_t \dots\dots\dots(16)$$

As evaporation and transpiration progresses, the salts which are transported upward concentrate at or near the surface. Then concentration gradients develop which cause salt to move downward against the liquid flow by molecular diffusion.

Figure 2 also points out the hazard of using the salt concentration in the soil solution at some relatively shallow depth Z_1 , instead of using the salt concentration in the ground water to estimate evaporation and transpiration at the surface from measured salt accumulation above Z_1 . Except for a short time after the upward flow is initiated, the salt concentration in the soil solution at Z_1 increases with time, even though the amount of salt entering the system from the water table remains constant. As a result the evaporation and transpiration rate tends to be underestimated.

If we select Z_1 , that evaporation and transpiration actually occur at depths less than Z_1 , we can express the rate of salt accumulation in the layer above Z_1 by solving equation (8) for dF/dt and adding a term to account for the downward diffusion of salt at Z_1 . Hence

$$\frac{dF}{dt} \Big|_{q_e+q_t+q_f} = C(q_e+q_t+q_f) + CZ_1 \frac{d\theta}{dt} + D_e \frac{dB}{dZ} \Big|_{z_1} \dots\dots\dots(17)$$

can express the rate of salt accumulation in the layer above Z_1 by solving equation (8) for dF/dt and adding a term to account for the downward diffusion of salt at Z_1 . Hence,

$$\frac{dF}{dt} = Cq_e + C_{z_1} \frac{d\theta}{dt} + D_e \frac{dB}{dZ} \Big|_{z_1} \dots\dots\dots(18)$$

where D_e is the effective coefficient of molecular diffusion (cm^2/day) and takes into account the coefficient of molecular diffusion for the salt in aqueous solution, the water content of the soil, the tortuosity of the diffusion path, the viscosity of the solution, etc. q_e is sum of the evaporation, transpiration and rainfall rates (cm/day), dB/dZ concentration gradient (me./ml. cm.) in soil solution at Z_1 , C is the salt concentration in the ground (mc/an^3), and $d\theta/dt$ is the rate change of the average water content ($\text{ml}/\text{cm}^3 \cdot \text{day}$) in the soil above depth Z_1 . After transposing terms and expressing the derivatives as differences, equation (15) becomes

$$q_e = \frac{\Delta F}{C \Delta t} \Big|_{q_e+q_t+q_f} - \frac{D_e}{C} \frac{\Delta B}{\Delta Z} \Big|_{z_1} - Z_1 \frac{\Delta \theta}{\Delta t} \dots\dots\dots(19)$$

D_e can be experimentally established, and all of the remaining quantities on the right can be evaluated under field conditions, thus giving a measure of evaporation, transpiration and falling rates.

The salts in the soil surface enter the air against the rainfall by molecular diffusion of gases and winds with the dust.

As time progresses, the salt concentration in the soil solution increases at greater depths in the profile as a result of that molecular diffusion (Fig.2). Even though the initial salt concentration in the water entering the profile from below is constant, the concentration gradient at a particular depth will increase with time unless precipitation of salt occurs. It is therefore conceivable that the rate of salt movement downward by molecular diffusion could eventually equal the rate of transport upward by liquid flow, and no salt accumulation would occur anywhere in the profile.

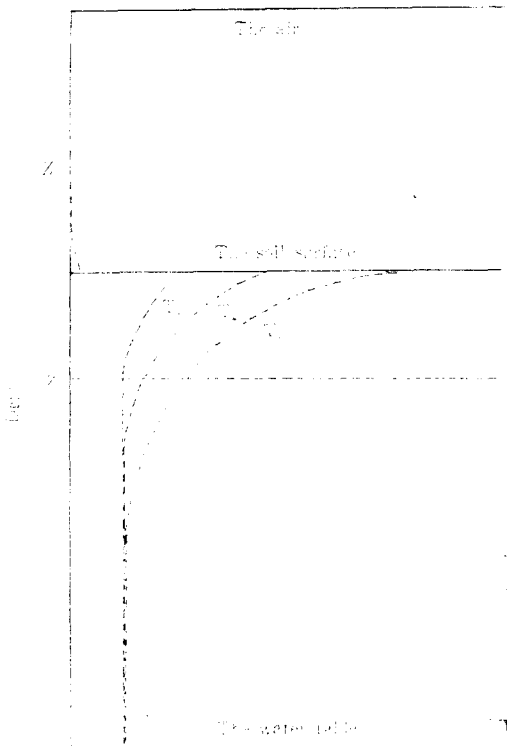


Fig. 2. Time sequence of soil solution concentrations as a function of depth that result from the steady evaporation, transpiration and falling of water from the soil and the air.

EXPERIMENTAL METHODS

The sites selected for this study are on tidal area in the bay of Namyang, grasslands in Moonheri and Seungilkyo in Cheolwon in Korea.

The upper 30cm of the soil profile of tidal area in the bay of Namyang consists of silty-clay layers. The top silty-clay layer contains less clay than second layer. The remainder of the profile is essentially homogeneous silt loam.

The grasslands at Moonheri and Seungilkyo in Cheolwon are characterized by *Medicago denticulata* and *Arundinella hirta* which are dominant species, respectively. The forest types chosen in Kwangnung plantation stand are *Pinus densiflora* and *Quercus mongolica*. The soils under these grasslands and forests are used in this experiments

Each plot was $5 \times 10\text{m}$ in size and had 50 sampling sites located at the intersections of 1-

meter grid.

Five sites, one randomly selected from each longitudinal row, were sampled on each of several sampling dates at depth increments of L, F, H, A₀, 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 45-50, 50-55, 55-60, 60-65, 65-70, 70-75, 75-80, 80-85, 85-90, 90-95 and 95-100cm.

During late August of 1977, all the sample plots were visited and the soil samples were collected. All samples were air-dried and were sieved through a stainless steel 2mm mesh to determine the amounts of total N, available P and exchangeable K. Nitrogen was determined in duplicate or occasionally triplicate by the micro-kjeldahl method and expressed as a percentage of the oven-dry weight of soil. The amount of available phosphorus was determined colorimetrically by the stannous-reduced molybdophosphoric blue method (Dickman and Bray 1940). Exchangeable K in soil were extracted with 1 N NH₄ OAC of pH 7.00 and were determined by flame photometer.

The chloride ion concentrations in the tide-land soils were determined by titration with mercuric nitrate.

All results are expressed as a percentage of the oven-dry soil.

The amounts of N, P and K in the monthly rainfall in Mt. Kwanak were determined in accordance with methods for chemical analysis of fresh waters edited by Golterman (1971).

RESULTS AND DISCUSSION

For illustrative purposes of the model of salt accumulation on the soil surface, this experiments were carried out and the results were presented in Figs 3, 4, 5 and 6. The concentrations in the tide-land soil solution are shown in Fig. 3 as a function of depth at various times. The chloride concentrations in soils of the surface layer are greater in the dry-season than in the rain-season. This result suggests that near the surface, the chloride ions are leached by the rain-water and decreased.

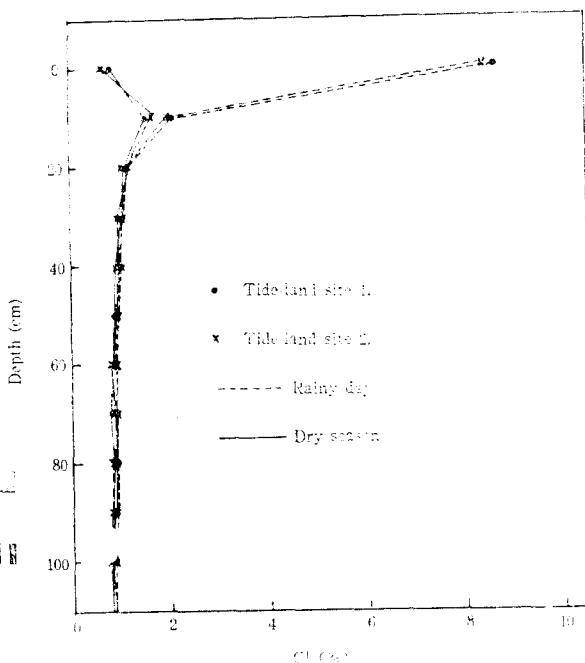


Fig. 3. The chloride concentrations in the tide-land soils in the bay of Namyang as a function of depth.

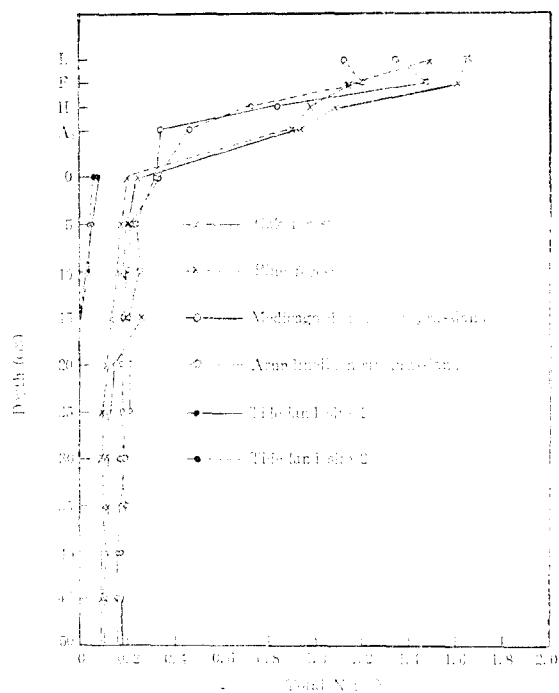


Fig. 4. Total N contents in soils of tide-land in the bay of Namyang, grasslands in Cheolwon and forests in Kwangnung as a function of depth.

From Fig. 3, it is also evident that the chloride concentration gradients below the 30cm depth increased with the decreasing depth.

The contents of total N, available P, and exchangeable K in tide-land, grassland and forest soils as a function of depth are presented in Figs. 4, 5 and 6, respectively.

In salt accumulation and distribution in the naked soils such as tide-land and fallow soils, evaporation and salination rates are very closely related.

The results of Figs. 3, 4, 5 and 6, the contents of total N, available P and exchangeable K near the surface of tide-land soils decreased with depth.

In the cases of grassland and forest soils, the salt accumulation mainly depends on the absorption of salts by plant by the roots of grasses and forest trees. According to the results of Figs 4, 5 and 6, the equation (13) might be acceptable for the present experiments.

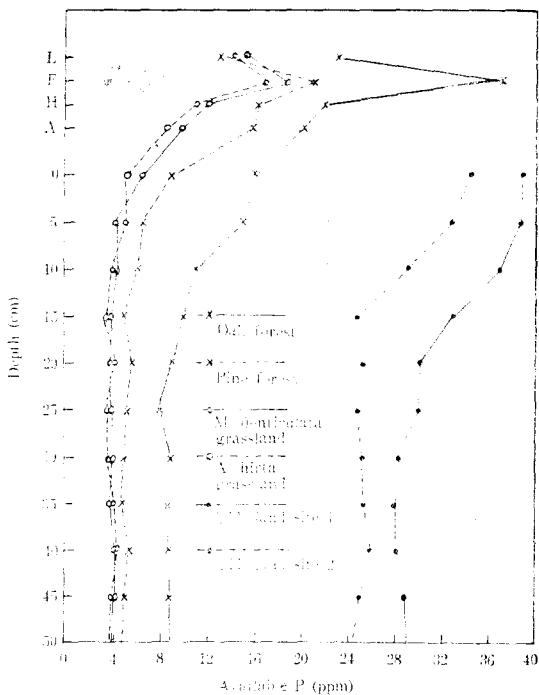


Fig. 5. Available P concentrations in soils of tide-land in the bay of Namyang, grasslands in Cheolwon and forests in Kwang-nung as a function of depth.

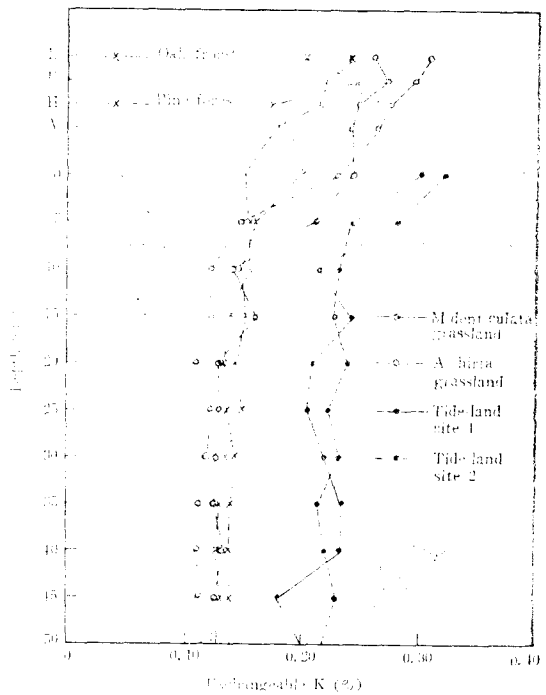


Fig. 6. Exchangeable K concentrations in soils of tide-land in the bay of Namyang, grasslands in Cheolwon and forests in Kwang-nung as a function of depth.

Yun et. al. (1969) and Chang & Yoshida (1973) reported that total N, available P, exchangeable K, Ca and Mg contents in grassland soils decreased with depth, respectively. Kim et. al. (1965) and Chae & Kim (1977) observed that total N, available P and exchangeable K contents in forest soils decreased with depth, too. In this connection, as well as the results in Figs 3, 4, 5 and 6, it is indicated that salts are accumulated by evaporation in the naked soil such as the tide-land and by transpiration throughout plants such as grasses and forest trees.

Amounts of total N, P and K nutrients falling with rainfall in the air in Mt. Kwanak are shown in Table 1.

As shown in Figs. 4, 5, 6 and Table 1, the contents of total N, P and K are greater in soils than in rainfall. Consequently, available salts in soils and in the air are accumulated on the earth's surface by evaporation, transpiration and rainfall as modified in the equation (8), (12),

Table. 1. Composition of rainfall and amounts of mineral nutrients falling in the open in Mt. Kwanak.

Month	Rainfall (mm)(1977)	Total N (ppm)	Total P (ppm)	Total K (ppm)
Apr.	228.8	0.55	0.043	1.39
May	63.7	0.21	0.030	1.36
June.	46.4	0.88	0.026	1.42
July	405.4	0.34	0.022	0.88
Aug.	101.1	0.40	0.029	0.65
Sep.	96.2	0.67	0.015	1.01
Oct.	15.7	0.73	0.021	0.67

(13), (14) and (15). Therefore, the theoretical models of salt accumulation on the soil surface might be confirmed with experimental result.

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要 約

蒸發, 蒸散 및 降雨에 의한 地表面上的 鹽類의 蓄積에 관한 理論

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蒸發, 蒸散 및 降雨에 의하여 鹽類가 地表面에 蓄積하는 현상을 數式 model로 表現하였다. 이 鹽類蓄積 model은 土壤溶液中에 可液狀態로 存在하고 있는 鹽類에 限定되어 適用될 수 있다.

우리나라에서 裸地인 干潟地에서의 蒸發, 植物群落에서의 蒸散 및 空氣에서의 降雨에 대한 N, P 및 K의 蓄積實驗結果는 理論値와 만족하리만큼 一致하였다.

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