# Soil Water Movement Resulting from Transpiration : The Influence of Soil Characteristics and Lower Boundary Conditions

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# Soil Water Movement Resulting from Transpiration
## —— The Influence of Soil Characteristics and Lower Boundary Conditions ——

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An experiment and a numerical simulation on soil column consisting of a root zone underlain by lower layers containing no roots were conducted under the same crop growth stage, root distribution and environmental conditions to evaluate the influence of soil characteristics (Masa and Kuroboku soils) and hydraulic conditions of lower boundary (water table and impervious layer) on soil moisture depletion distribution and upward capillary movement resulting from transpiration.

For the water table and impervious layer condition soil moisture distribution during the experiment was small for Kuroboku soil. Soil moisture distribution for Masa soil, especially for the impervious condition, was large.

Response of upward flux from the water table after start and upward flux deterioration after end of radiation were larger and quicker for Kuroboku soil compared with that of Masa soil. The simulation results were in good agreement with that of the experiment. The difference in the characteristics of soil moisture distribution and upward capillary movement between the soils could be explained by the difference in their water retentivity and hydraulic conductivity.

## INTRODUCTION

Following the application of water to soil by irrigation or rainfall, crop roots first extract soil moisture in the root zone before utilizing soil moisture in the deeper layers. This results in a decrease in soil moisture and consequently a decrease in matric potential in the root zone. Hence, soil water in the succeeding layers moves upward into the root zone where it is subsequently extracted by crop roots. The depth to which crop roots can remove soil moisture depends on factors such as root distribution, soil texture, depth of water table and transpiration rate.

In recent years the phenomena of upward capillary movement have been studied in order to extend the knowledge of the theory of water saving irrigation/reducing irrigation requirement. Upward capillary movement is large in volcanic soil but small in heavy clay and coarse sandy soil (Takenaka, 1964 ; JSIDRE Sub-committee of field irrigation, 1983).

In this study an experiment was conducted to evaluate the influence of soil characteristics and hydraulic boundary conditions of lower boundary on soil moisture depletion distribution and upward capillary movement. For soils with different characteristics Masa and Kuroboku soils were used. Water table and impervious layer were used to represent the different hydraulic conditions of lower boundary. Environmental factors such as temperature, humidity, wind speed and radiation were controlled, and crop factors such as crop type, growth stage and root distribution were kept the same in the experiment. Simulation on soil water movement was conducted by a numerical model under the same conditions, and the results of the experiment were examined in the light of that of the simulation.

## EXPERIMENTAL MATERIAL AND PROCEDURE

Short cylindrical acrylic columns ($\phi$ 10 cm x 10 cm) were packed with Masa soil to a dry bulk density of 1.25 $g/cm^3$ and were seeded to one cucumber plant ***(Cucumis sativus*** L. var. Hort. Chojitsu-Ochiai No. 2) each. The plants were cultivated in the phytotron glass room (air temperature 23± 1°C and relative humidity 70±5%) under unstressed condition. At the 5-leaf stage (20 days after seeding, leaf No. 1, 2 and 3 fully expanded) leaf No. 4 and 5 were excised, leaving leaf No. 1, 2 and 3 intact. The seeded short columns (root zone) were then joined to long cylindrical acrylic columns ($\phi$ 10 cm X *50* cm, lower layers) packed with Masa or Kuroboku soil to a dry bulk density of 1.25 and 0.68 $g/cm^3$, respectively. The experimental columns thus created were 60 cm tall, and consisted of an upper 10 cm root zone in which all the roots were artificially confined and the lower layers containing no roots. This method eliminated the uncertainty of root factors in soil moisture depletion. This system was used to simplify the root zone-lower layers system of the field, and was used to study the relation between soil moisture depletion distribution and transpiration.

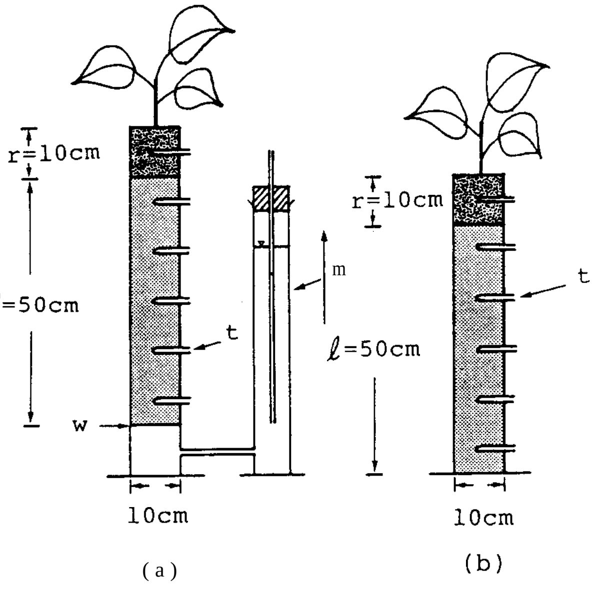


**Fig. 1.** Experimental pots for the water table (a) and impervious (b) lower boundary conditions : r, root zone packed with Masa soil ; *l*, lower layers packed with Masa or Kuroboku soil ; t, tensiometer ; w, water table ; m, mariotte siphon.

For each soil, the experiment on the effect of different lower hydraulic boundary conditions, i. e. water table and impervious layer, were conducted. The soil in the experimental column was well watered from the top until drainage occurred from the bottom of the column. For the water table condition a mariotte siphon was connected to create and to maintain the water table elevation (Fig. 1 (a)). For the impervious condition the bottom of the column was sealed to create an impervious layer (Fig. 1 (b)). Soil surface was covered with a vinyl sheet during the experiment to check soil surface evaporation.

To control the atmospheric factors during the experiment, the cucumber plant was placed in the growth cabinet (ambient air temperature 25±0.5°C, relative humidity 40±5% and horizontal wind speed 0.3f0.05 m/s) and was then left in darkness for 12 hours. The leaves were spread out and held horizontally parallel to wind direction, and were subjected to vertical light radiation from tungsten light bulbs (total radiant flux density 171 $mW/cm^2$ in the range of 0.35-60 $\mu$m, short-wave radiant flux density 64 $mW/cm^2$ in 0.35-3 $\mu$m and long-wave radiant flux density 107 $mW/cm^2$ in 3-60 $\mu$m). Leaf temperature change was used to evaluate transpirational activity. Copper-Constantan thermocouples ($\phi$ 0.1 mm) were inserted in three locations of each leaf to measure leaf temperature change.

Change of matric potential was measured with porous cups inserted at 5, 15, 25, 35, 45 and 55 cm from the soil surface. The porous cups were connected to transistorized pressure sensors to automate measurement.

Radiation (daytime) and darkness (nighttime) cycle were 12 hours each to reproduce field conditions and were twice repeated. Continuous data logging was conducted for leaf temperature and soil moisture measurement, and the average for 5 minutes was assembled.

Transpiration rate ($g/cm^2/min$) was calculated by the leaf heat balance equation (Kitano *et al.*, 1983). Transpiration rate per minute per plant (g/min/plant) was obtained from this transpiration rate. Daily transpiration (mm/day) was also converted by dividing transpiration rate per minute per plant by soil surface area.

Upward flux from the water table was measured at 10 minute intervals and the data was smoothed by three-point moving average (20 min).

Table 1 shows the results of mechanical analysis of the soils used.

Table **1**. Classification of Masa and Kuroboku soils by the International standard.

| Soil type | gravel (%) 2mm< | coarse sand (%) 2-0.2mm | fine sand (%) 0.2-0.02mm | silt (%) 0.02-0.002mm | clay (%) <0.002mm | soil texture | bulk density |
|---|---|---|---|---|---|---|---|
| Masa | 0 | 64.92 | 23.63 | 10.3 | 1.15 | loamy sand | 1.25 |
| Kuroboku | 0 | 9.67 | 44.93 | 44.6 | 0.8 | loam | 0.68 |

Fig. 2 shows the soil moisture characteristic (drying process) and hydraulic conductivity (Jackson, 1972) curves of Masa (Loamy sand) and Kuroboku (Loam) soils. They indicate that for a given matric potential, moisture content and conductivity of Kuroboku soil are larger than that of Masa soil. In general, Kuroboku soil has a larger specific area and micro porosity compared with Masa soil. In addition to that, the large water content of Kuroboku soil is also attributed to its exceptionally great water affinity (Fujiwara and Baba, 1973).

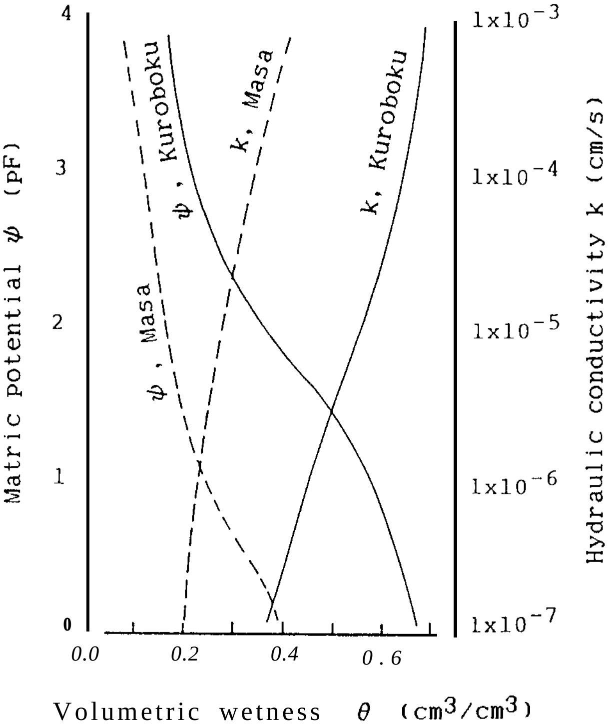


**Fig. 2.** Soil moisture characteristic (drying process) and hydraulic conductivity *k* (Jackson method) as a function of volumetric wetness *θ* for Masa (dashed lines) and Kuroboku (solid lines).

## EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 3 and Fig. 4 show the experimental results for Masa soil and Kuroboku soil under the water table condition, respectively. For both soils, change of moisture content in the root zone was great, whereas that of the depths below 15 cm showed, though slight, a decreasing trend of moisture throughout the experiment. For Masa soil, the decrease of matric potential in the root zone during daytime was larger than that of Kuroboku soil. During nighttime moisture of the root zone of both soils recovered ; Kuroboku soil showed quicker and larger recovery. For Kuroboku soil matric potentials at the depths measured at the end of experiment were almost the same as the outset values, whereas that of Masa soil became slightly smaller.

Upward flux from the water table occurred soon after start of radiation for Kuroboku soil, but was delayed for Masa soil. During nighttime upward flux of Masa soil took a longer time to deteriorate.

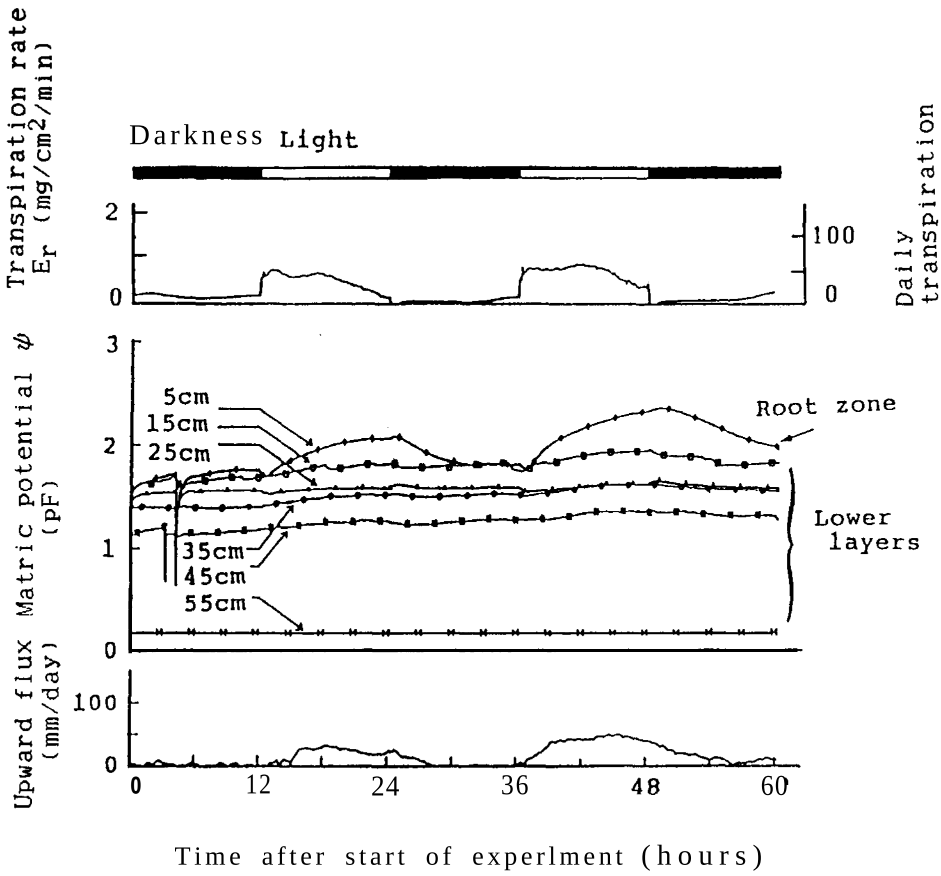


**Fig. 3.** Time course of transpiration rate $E_r$, daily transpiration $E_d$, matric potential $\psi$ of the root zone and lower layers, and upward flux from water table for Masa soil experiment under water table lower boundary condition.

The cucumber plants were grown with care to ensure no sample difference. Despite the efforts taken transpiration rate of Kuroboku soil experiment was larger than that of Masa soil. All the experiments were conducted under high root zone water content (soil moisture suction less than pF 2.5) and the difference in transpiration rate between the soils could not be due to root zone moisture stress.

From the transpiration rate curves, in spite of the fact that transpiration rate of Kuroboku soil experiment was much larger than that of Masa soil experiment, the change of matric potential of Kuroboku soil during and after end of radiation was smaller. This could be explained by the larger upward flux of Kuroboku soil.

Fig. 5 and Fig. 6 show the experimental results of the impervious condition for Masa soil and Kuroboku soil, respectively. The decrease of matric potential in the soil profile for both soils, particularly during the second radiation, was much larger than that of the water table condition. Transpiration rate was observed to decrease during

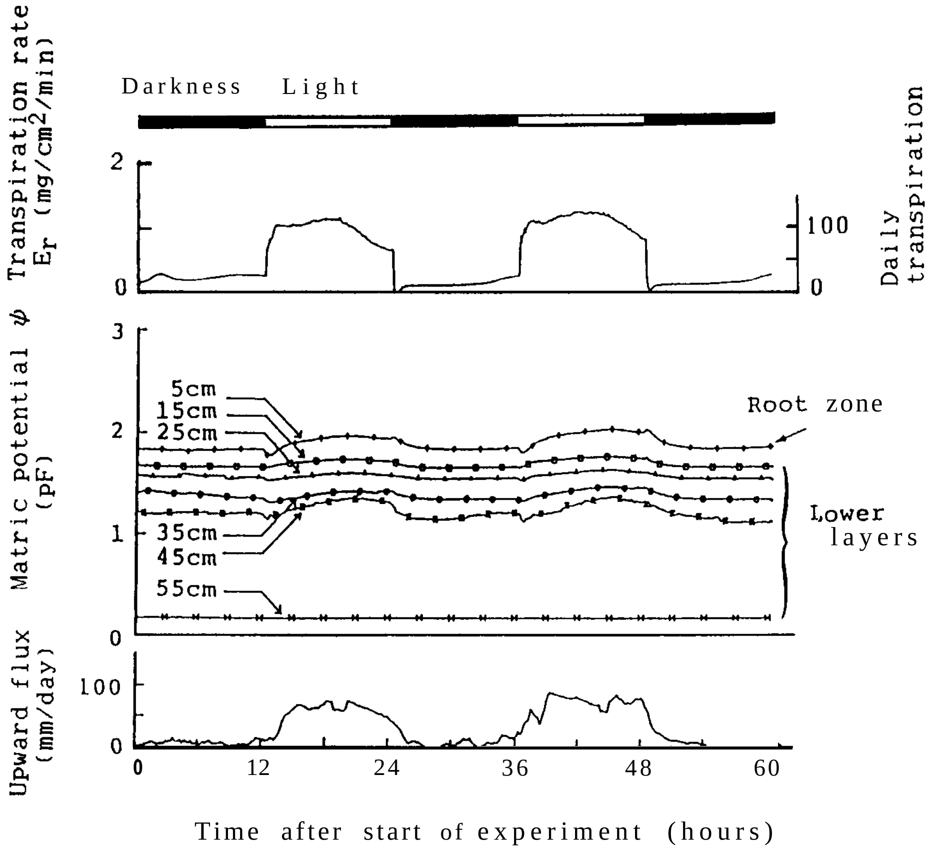


Fig. 4. Time course of transpiration rate $E_r$, daily transpiration $E_d$, matric potential $\psi$ of the root zone and lower layers, and upward flux from water table for Kuroboku soil experiment under water table lower boundary condition.

the radiations owing to the smaller matric potential of the root zone. Root zone moisture of both soils showed incomplete recovery during nighttime of the first cycle and no recovery was observed after the second (simulation results showed recovery, vid. Numerical simulation and discussion). This could be explained by the fact that in the experiment matric potential of the root zone during the second radiation decreased beyond the measurable range of the tensiometric method.

The difference of matric potential at the points measured for Kuroboku soil was smaller than that of Masa soil. This shows that water used consumptively by the cucumber plant was extracted not only from the root zone but also from the layers lower in the soil column. For Masa soil, change of matric potential was large to a depth of 15 cm during daytime whereas the deeper layers showed a gradual change throughout the experiment. This shows that for Masa soil most of the water transpired by the plant was withdrawn from the root zone.

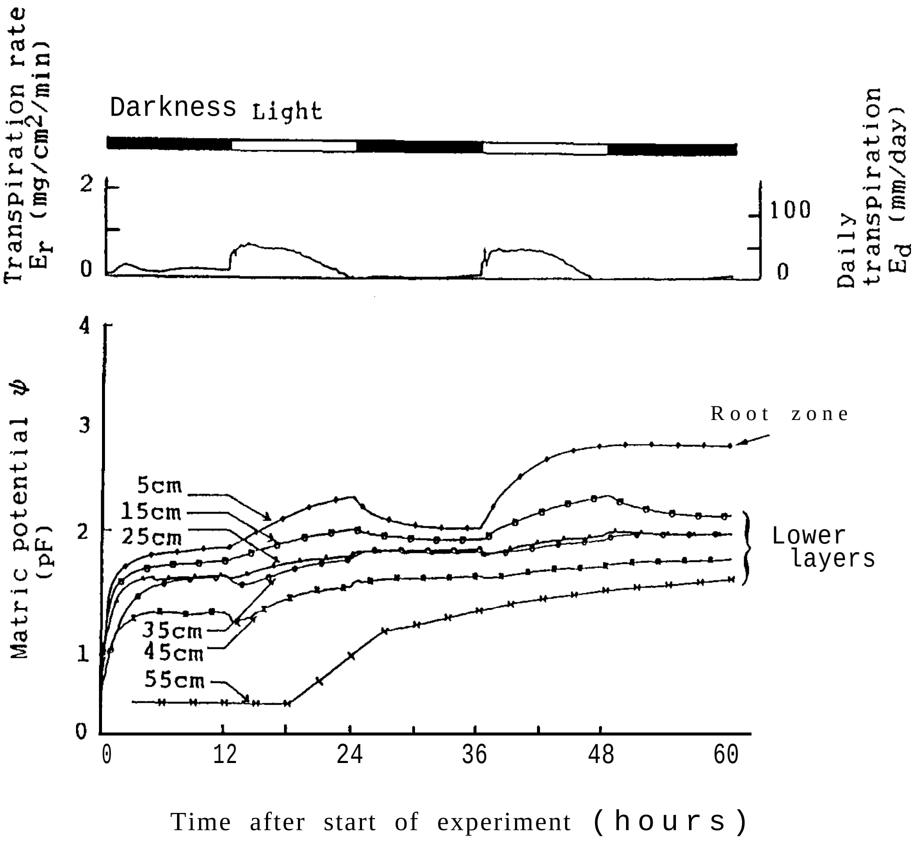


Fig. 5. Time course of transpiration rate R,, daily transpiration *E*,,, and matric potential $\psi$ of the root zone and lower layers for Masa soil experiment under impervious lower boundary condition.

## NUMERICAL SIMULATION AND DISCUSSION

A numerical model on soil water movement (Hillel et *al.*, 1976) was used to simulate the effect of soil characteristics and hydraulic conditions of lower boundary on soil moisture depletion distribution and upward capillary movement resulting from root water uptake. In the experiment, the soil column was 60 cm tall consisting of an upper 10 cm root zone and a 50 cm lower layers containing no roots. This system was used to simplify the root zone-lower layers system under natural condition. In the simulation, the 60 cm soil column was divided into equal compartments of thickness 1 cm with the top 10 compartments taken to be the root zone with constant root density. The amount transpired from the leaves was assumed to be uniformly absorbed from the root zone. The initial soil moisture condition was taken to be the state when the matric potential of each layer equaled the negative height from the water table, i. e., when there was no soil water movement. The simulation time step was 1 second.

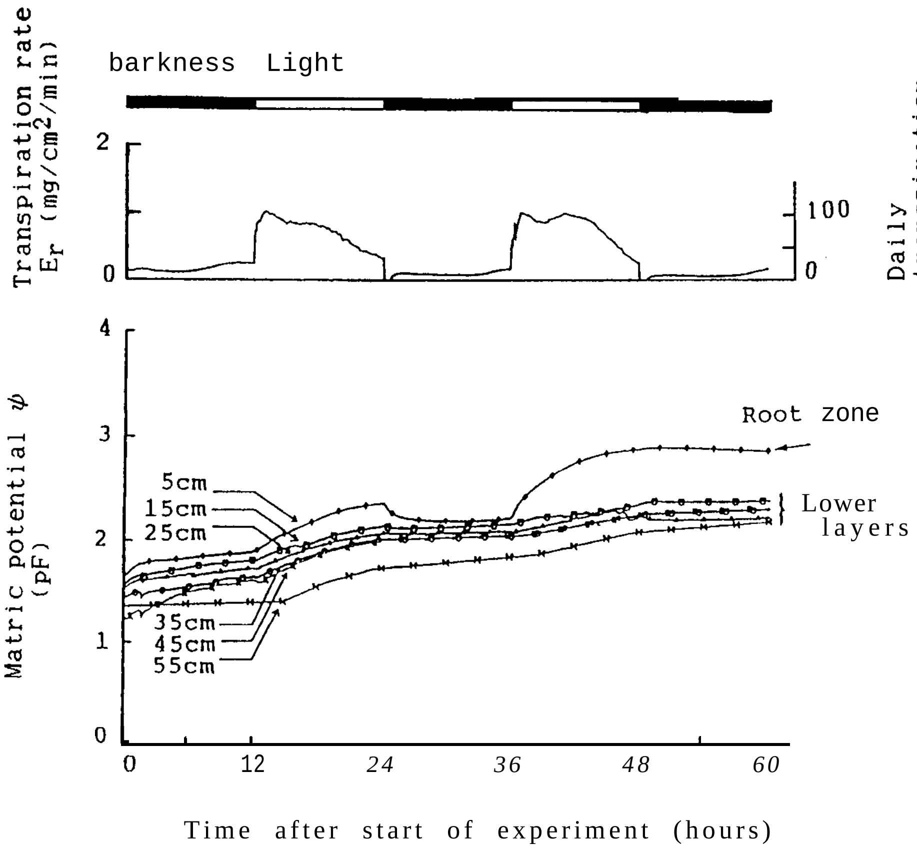
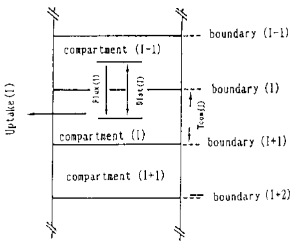


Fig. 6. Time course of transpiration rate $E_r$, daily transpiration $E_d$ and matric potential $\psi$ of the root zone and lower layers for Kuroboku soil experiment under impervious lower boundary condition.

Fig 7 shows the algorithm of calculating the water balance of the compartments.

The focus of the simulation was on the effect of soil characteristics such as Masa and Kuroboku soils and hydraulic conditions of lower boundary on soil water movement. In the simulation, in order to use the transpiration rate obtained by the leaf heat balance equation, transpiration rate per minute per plant (cm$^3$/min/plant) was obtained by multiplying transpiration rate (g/cm$^2$/min) by total leaf area. Transpiration rate per minute per plant was then divided by soil surface area to convert to daily transpiration (mm/day).

Experiment on the short column consisting of the root zone (10 cm) directly underlain by a water table was conducted to check the accuracy of converting transpiration rate (g/cm$^2$/min) obtained by the leaf heat balance equation to daily transpiration (mm/day). Since no change of root zone moisture was observed during the experiment, daily transpiration was equal to the upward flux from the water table in this experimental setup. Calculation of total upward flux from the water table during radiation showed that it was about 1.1 times larger than transpiration rate calculated



$$\frac{\Delta w\ (\mathrm{I})}{\Delta t} = \mathrm{Flux}\ (\mathrm{I}) - \mathrm{Flux}(\mathrm{I}+1) - \mathrm{Uptake}(\mathrm{I})$$

$$\mathrm{Flux}\ (\mathrm{I}) = -\mathrm{Cond}\ \frac{\mathrm{Pot}\ (\mathrm{I}) - \mathrm{Pot}\ (\mathrm{I}-1)}{\mathrm{Dist}\ (\mathrm{I})}$$

$$\mathrm{Uptake}\ (\mathrm{I}) = \frac{\mathrm{Trans}}{0.1}\ \mathrm{Tcom}\ (\mathrm{I})$$

$\Delta w$ (I): Change of moisture of compartment (I) (m)
$\Delta t$: Time step (s)
Cond: Average hydraulic conductivity between compartment (I) and (I 1)
Dist (I): Flow distance between compartments (m)
Flux (I): Flow into compartment (I) (m/s)
Pot (I): Total head of compartment (I) (m)
Trans: Transpiration (m/s)
Tcom (I): Thickness of compartment (I) (m)
Uptake (I): Root uptake in compartment (I) (m/s)

**Fig. 7.** Geometric scheme for simulating one-dimensional vertical moisture flux between the soil compartments.

by the equation. The accuracy of this conversion was, therefore, considered adequate for the purpose of the experiment.

In the simulation, total daily transpiration was assumed to be 25 mm, which was the average of total daily transpiration of the experiment. The average value of 25 mm of the total daily transpiration, which was much larger than the normal daily values found in the field, could be produced under the experimental conditions with the small-sized pots. In the simulation 25 mm was used to emphasize and to facilitate soil moisture movement analysis. Daily transpiration was assumed to occur at a constant rate of 10 mm/day and 40 mm/day during nighttime and daytime, respectively.

The water balance of the compartments was calculated by the basic equation describing unsaturated flow

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(k\frac{\partial\psi}{\partial z} - k\right) - S_w \qquad \text{(1)}$$

wherein $\theta$ is volumetric wetness, $\psi$ is matric potential, $k$ is hydraulic conductivity, $z$ is depth from soil surface, $t$ is time, and $S_w$ is a sink term representing root extraction.

Fig. 8 and Fig. 9 show the simulation results for Masa soil and Kuroboku soil under the water table condition, respectively. For Masa soil, change of matric potential in the root zone was larger than that in the deeper compartments. Root zone moisture was depleted during the daytime and recovered due to upward capillary movement from the water table during the nighttime. After 60 hours, the moisture of the root zone and that of 25 cm did not recover to the outset values. The matric potential curves showed no depletion in the compartments below 35 cm.

For Kuroboku soil, change of water content was large to a depth of 25 cm with little depletion in the deeper compartments during the daytime. After 60 hours, soil moisture of the upper 25 cm, including the root zone, recovered to the outset values.

The response of upward flux from the water table after start and flux deterioration after end of radiation of Masa soil were smaller than that of Kuroboku soil. For Kuroboku soil, upward flux from the water table started soon after radiation and

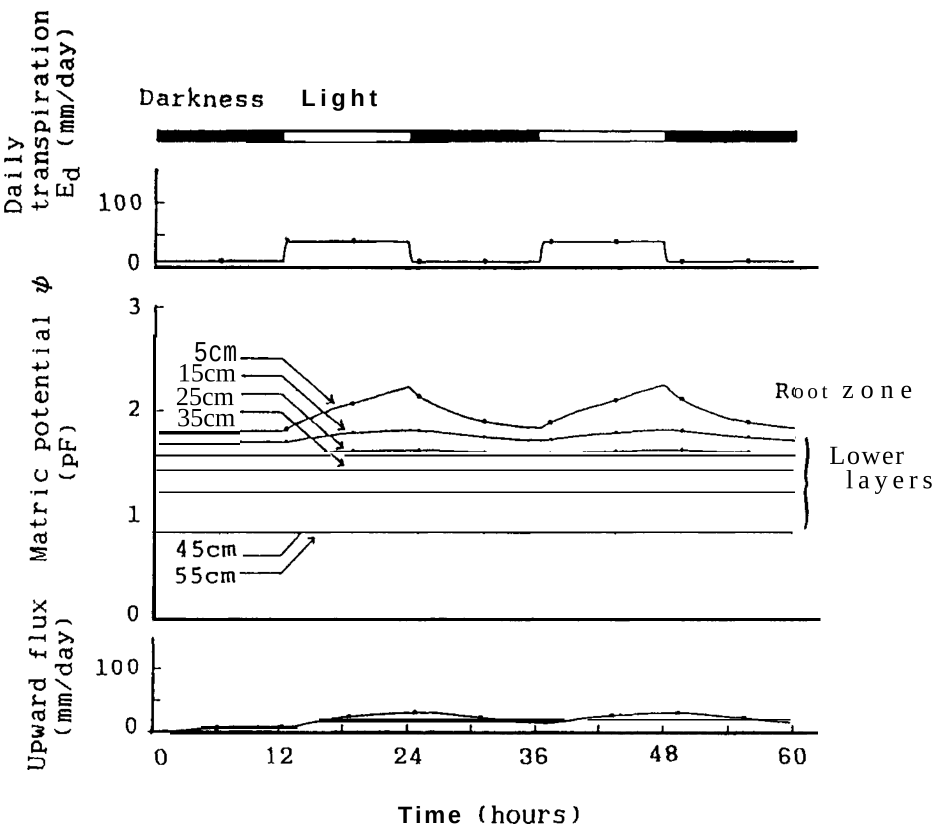


Fig. 8. Simulated matric potential $\psi$ of the root zone and lower layers, and upward flux from water table for Masa soil under water table lower boundary condition. In the simulation daily transpiration $E_d$ was taken to be 25 mm/day.

followed the trend of moisture depletion of the root zone; increased during the daytime and decreased during the nighttime.

Fig. 10 and Fig. 11 show the simulation results of the impervious condition for Masa soil and Kuroboku soil, respectively. Depletion of moisture occurred in all the compartments for both soils.

For Masa soil, the root zone showed marked depletion of moisture compared with the succeeding compartments. This indicates that most of the depletion of moisture occurred in the root zone. Root zone moisture showed large recovery after the second radiation but not to a value below pF 3.

For Kuroboku soil, more water was depleted from the upper compartments during daytime and slight moisture recovery was observed during nighttime. The difference of moisture between the compartments was small as indicated by the closer matric potential curves. This shows that soil moisture of Kuroboku soil was more uniformly depleted.

The simulated soil water depletion and upward flux from water table in the

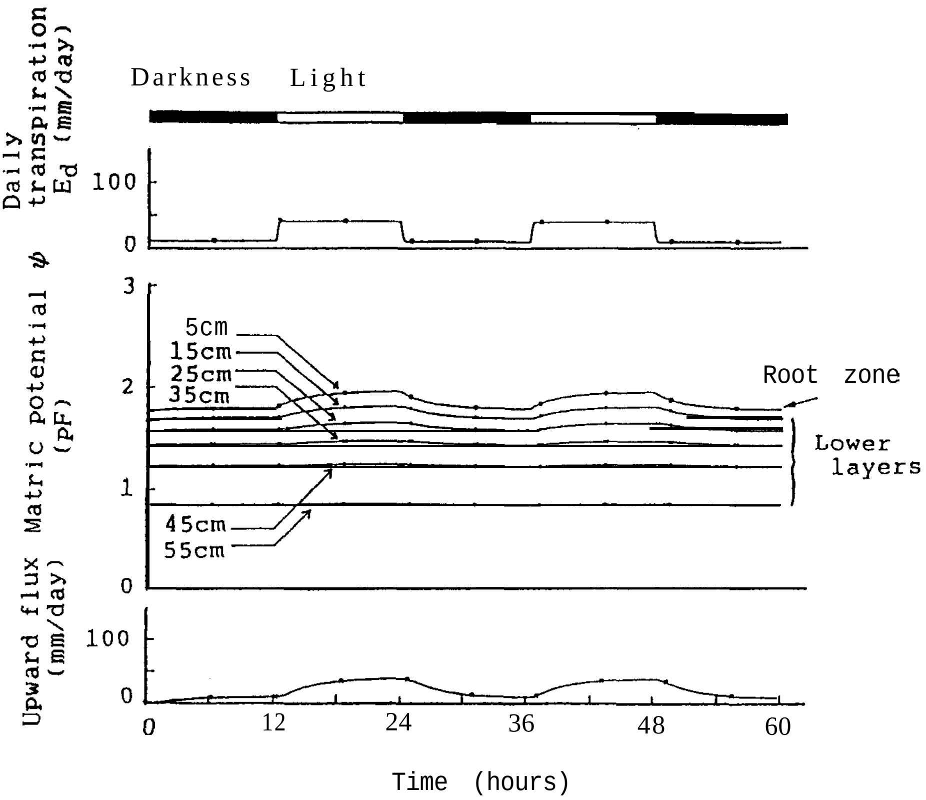


Fig. 9. Simulated matric potentials $\psi$ of the root zone and lower layers, and upward flux from water table for Kuroboku soil under water table lower boundary condition. In the simulation daily transpiration $E_d$ was taken to be 25 mm/day.

simulation agreed qualitatively with that of the experiment.

The difference in the characteristics of moisture distribution and upward capillary movement of the soils in the experiment and simulation is not self-evident from the difference in their hydraulic conductivity-matric potential-volumetric wetness relationship. Tanaka and Cho (1987), using soil water retentivity ($\Theta$), hydraulic conductivity ($K$) and response ($\Upsilon$) index, have shown that for soils with the same $\Theta$, the response of upward flux of moisture from the lower layers or water table to moisture stress in the upper layers is quicker for soil with a large $\Upsilon$ and the time needed for attainment of a steady state is shorter. These indices were used here to evaluate the difference in soil moisture depletion and upward capillary movement.

Table 2 shows the values of the indices of the soils used in the experiment. $\Upsilon$ of Kuroboku soil was about 1.5 times that of Masa soil, and therefore the response to moisture stress in the surface layers was quicker and as a result upward flux from lower layers or water table occurred sooner. Also, $K$ of Kuroboku was larger than that of Masa. This explains why that during the experiments moisture distribution of Kuroboku soil was smaller than that of Masa soil. Since $\Upsilon$ of Masa soil was smaller

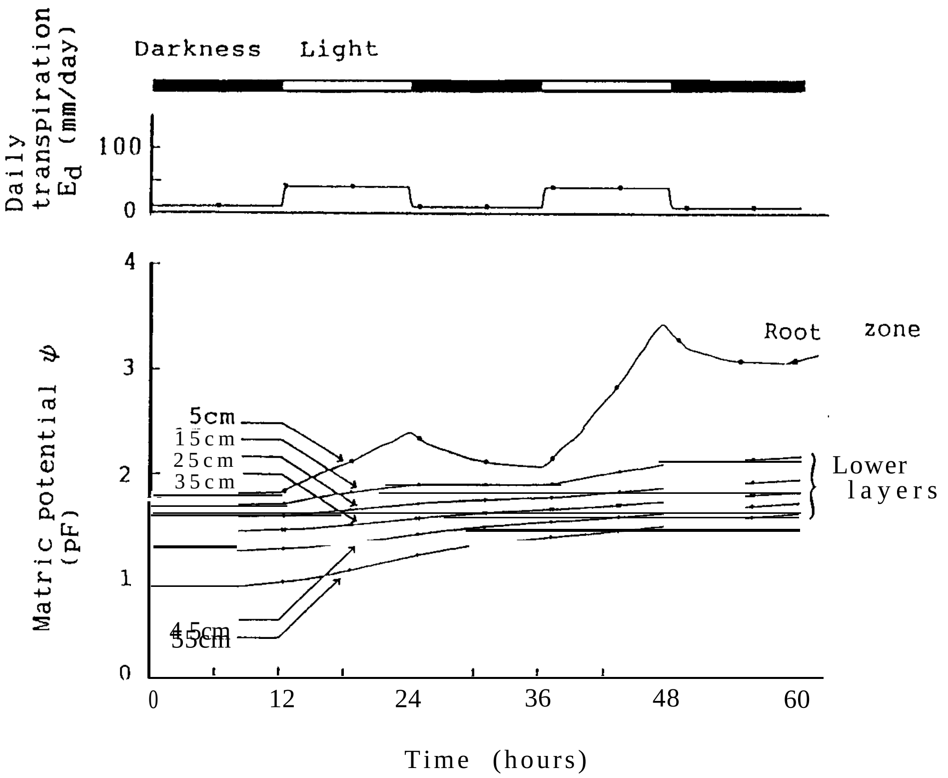


**Fig. 10.** Simulated matric potential $\psi$ of the root zone and lower layers for Masa soil under impervious lower boundary condition. In the simulation daily transpiration $E_d$ was taken to be 25 mm/day.

than that of Kuroboku soil, upward flux from water table of Masa soil at the end of radiation took a longer time to deteriorate compared with that of Kuroboku soil.

Soil moisture, besides being depleted by direct root absorption in the root zone, is also depleted when it moves from one layer into another. Soil moisture absorption distribution due to direct root absorption is defined here as real water uptake distribution. Soil moisture depleted in areas having no roots is therefore different from real water uptake distribution, and is defined here as apparent water uptake distribution.

In the experimental setup, the roots were restricted to the root zone and only in it real water uptake distribution could occurred. Since the experimental and simulation results showed that soil moisture depletion also occurred in the lower layers, it apparently seems that soil moisture in the lower layer was also depleted by direct root extraction. Both the experimental and simulation results showed that soil moisture of Kuroboku soil was more uniformly depleted compared with that of Masa soil. Therefore, the difference between real water uptake distribution and apparent water uptake distribution was greater for Kuroboku soil. Generally, the difference between real water uptake distribution and apparent water uptake distribution is greater for soils having larger hydraulic conductivity.

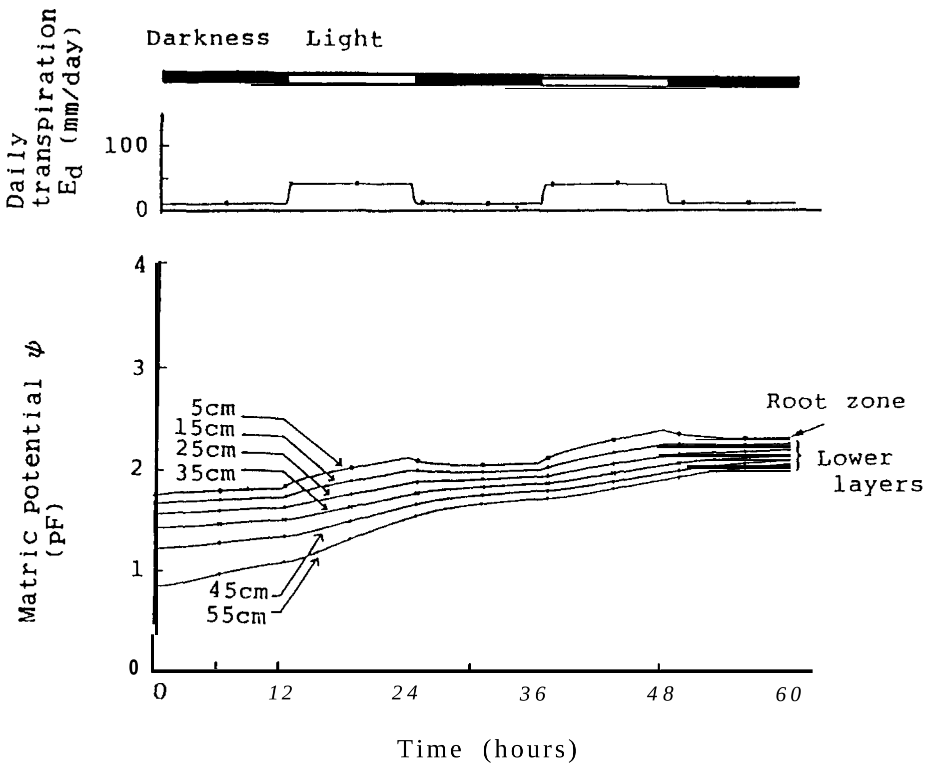


Fig. 11. Simulated matric potential $\psi$ of the root zone and lower layers for Kuroboku soil under impervious lower boundary condition. In the simulation daily transpiration $E_d$ was taken to be 25 mm/day.

Table 2. Physical characteristics of Masa and Kuroboku soils : $\Theta$, Water retentivity index ; $K$, Hydraulic conductivity index and $\Gamma$, Response index.

| Soil type | $\Theta$ (cm$^3$/cm$^3$) | $K$ (cm/day) | $\Gamma$ (cm/day) |
|---|---|---|---|
| Masa | 0.08 | 0.02 | 0.25 |
| Kuroboku | 0.23 | 0.09 | 0.39 |

In field irrigation, effective soil layer is an important parameter that must be determined. Effective soil layer is normally defined as the depth to the layer or point where there is no or little change in soil moisture content resulting from evapotranspiration. Experimental and simulation results indicated that depletion occurred (1) in the root zone of both soils for the water table condition, and (2) in the upper 15 cm of Masa soil and in all the layers of Kuroboku soil for the impervious condition. Therefore, effective soil layer is (1) shallow for Masa soil and deep for Kuroboku soil, and (2) shallow when there is a water table and deep when the lower layer is impervious.

## CONCLUSION

In this study experimental and simulation approach were used to demonstrate the effect of soil characteristics and hydraulic conditions of lower boundary on soil water movement and upward capillary movement. For soils with different characteristics Masa and Kuroboku soils were used. Water table and impervious layer were used to represent different hydraulic conditions of lower boundary.

For the water table condition (1) for Masa soil, the decrease of root zone matric potential during radiation was larger than that of Kuroboku soil ; (2) for Kurbboku soil, matric potentials at the depths measured at 60 hours were almost the same as the outset values, whereas that of Masa soil became slightly smaller ; and (3) the response of upward flux from water table of Kuroboku soil to transpiration was quicker than that of Masa soil.

For the impervious condition (1) for Kuroboku soil, the difference of matric potential at the points measured was smaller than that of Masa soil ; and (2) for Masa soil, more water was depleted from the upper 15 cm than from the layers further below, whereas for Kuroboku soil, depletion was more uniform in all the layers.

Simulation results by the numerical model were in good agreement with that of the experiment. Both the experimental and simulation results showed that for soils having small hydraulic conductivity, the response of soil moisture in the deeper layers or from water table to moisture stress in the upper layers was slow and soil moisture distribution was large. The difference in soil moisture movement and upward capillary movement between the soils could be explained by the difference in the water retentivity and hydraulic conductivity.

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