Soil-Root Interface Water Potential in Sweet Corn Affected by Organic Fertilization and Effective Microbes Applications

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Abstract

The main objective of this study is to examine effects of fertilizations of organic materials and applications of effective microbes (EM), which mainly include *Lactobacillus*, *Rhodopseudomonas*, *Streptomyces* and *Aspergillus* on soil-root interface water potential ($\Psi_{s\text{-}r}$) of sweet corn (*Zea mays* L. cv. Honey-Bantam). The contributions to $\Psi_{s\text{-}r}$ from root amount and root activity were analyzed using the Ohm's law. Plants were grown in 1/5000 a Wagner's pots each filled with a Andisols and six treatments were made as follows; 1) organic materials fermented anaerobically with EM added; 2) anaerobic organic materials; 3) organic materials fermented aerobically with EM added; 4) aerobic organic materials; 5) chemical fertilizers with EM applied; and 6) chemical fertilizers.

One month after sowing, as soil matric water potential decreased, $\Psi_{s\text{-}r}$ was maintained higher in plants with organic fertilizations than those with chemical fertilizations and also higher in plants with EM applications than those without EM treatments. The relatively higher $\Psi_{s\text{-}r}$ in those plants was contributed by both their larger root amount and higher root activity. As a consequence, photosynthetic rates under soil water deficit conditions were also maintained relatively high in these plants. This suggested that high maintenance of $\Psi_{s\text{-}r}$ favored plants to resist against water deficits. Moreover, the methodology adopted in this study is suggested as a practicable additional means to analyze the soil-plant water status under undisturbed conditions.

Introduction

Practices of organic farming have been proposed as alternatives of chemical agriculture in order to protect environment, decrease production cost and improve food quality. Practices of organic farming or nature farming have been adopted by farmers in Japan. Recently, a technology of applications of effective microbes (EM) is introduced to organic farming. The so-called EM here consists of a group of beneficial microbes containing about 50 species such as *Lactobacillus*, *Rhodopseudomonas*, *Streptomyces*, and *Aspergillus*. Researchers have shown that organic fertilizations improve soil physical properties, whereby the soil retains more water and the crops growing there resist to a stronger water stress compared with the cases of chemical fertilization (Letey, 1977).

However, there has been very few scientific reports to support the mechanisms of EM effects although farmers found that EM applications with organic fertilizations improved crop yield and quality (Higa, 1996). Recently, some documents show the trends that EM applications to crop production are more effective in drought regions (LI and Ni, 1996) than in humid areas, Therefore, EM effect might be associated with increased water stress resistance caused by root water uptake ability.

Moreover, in researches on plant responses to drought conditions, measurements of plant water status such as leaf water potential ($\Psi_{s\text{-}r}$) are suggested to be more appropriate for water stress indication than measurements of soil water conditions such as soil water potential ($\Psi_{s\text{-}r}$) and water content (Hsiao, 1973, Jackson, 1974). However, the fluctuation of environmental factors, for example at a hot-dry midday, can cause a short-term change in plant water status such as $\Psi_{s\text{-}r}$. On the other hand, some plants with very inadequate water supply can have the same $\Psi_{s\text{-}r}$ as in well watered control plants if stomata close efficiently in response to changes in environmental factors. This leads to a disadvantage in using $\Psi_{s\text{-}r}$ as an indicator of water stress. Fortunately, Jones (1983 a) proposed a method to estimate the $\Psi_{s\text{-}r}$ at the root surface or, so-called, soil-root interface water potential ($\Psi_{s\text{-}r}$) with the familiar Ohm's law. The $\Psi_{s\text{-}r}$ is associated with both soil physical properties and plant water root activity and water consumption. It can be considered as an appropriate indicator for the status of soil water that is available or ready to enter the plant. Therefore, in the present research, we estimated Ψ_{s-r} in sweet corn as well as the contribution to Ψ_{s-r} from root amount and root activity, and discussed the effects or organic fertilizations and EM applications.

Materials and Methods

Plant Materials

Sweet corn (*Zea mays* L. cv. Honey-Bantam) was used as plant material. They were grown in Wagner's pots (dia. 16 cm x 20 cm high) in June, 1996. The pots, each with one plant remaining after thinning, were placed with a Latin Square design in a glasshouse.

Soil

A fine textured Andisols was collected from a field where soybean was previously cultivated. The total soil nitrogen, available phosphorus, and potassium were 3.4, 0.025 and 0.44 g kg^{-1}, respectively, with a C/N ratio of 13. The field capacity (or capillary capacity) was 80 percent on the gravimetric basis, ie., there was 80 g water in 100 g dry soil when it was saturated with water. Each pot was filled with 3 Kg fresh soil with a water content of 30 percent of the field capacity.

Fertilizers

Ammonium sulfate, superphosphate and potassium sulfate were used for chemical fertilization treatments and the quantities of N, P and K were equivalent to the total content in organic fertilization treatments as described below. Organic materials such as oilseed sludge, rice husk and fish-processing by-product were fermented anaerobically or aerobically with or without EM added. The total nitrogen, available phosphorus, and potassium concentrations were 58, 30 and 2 g Kg^{-1}, respectively, for both anaerobic and aerobic organic fertilizers.

Effective microbes

Effective microbes (EM) used in this study were a group of beneficial microorganisms that can exist together with each other in the same conditions. About 50 species were contained in the product liquid of EM. The main species included in EM are lactic acid bacteria such as *Lactobacillus*, *Streptococcus* and *Pediccoccus*, yeast such as *Acharaomyces* and *Candida*, photosynthetic bacteria such as *Rhodopseudomonas*, *Rhodospirillum*, *Chromatirum* and *Chlorobium*, *actinomyces* such as *Streptomyces*, *Propionibacteriium*, *Norcardia* and *Micromonospora*, and others such as *Aspergillus* and *Mucor*.

Treatments

Six fertilization treatments were designed as follows;

1) EM-Organic 1: anaerobically fermented organic materials 80g, in which EM was added to the materials before fermented;
2) Organic 1: anaerobically fermented organic materials 80g;
3) EM-Organic 2: aerobically fermented organic materials 80g, in which EM was added before fermented;
4) Organic 2: aerobically fermented organic materials 80g;
5) EM-Fertilizer: chemical fertilizers (ammonia sulfate 5.3g, LP coat-70 2.8g, superphosphate 13g and potassium sulfate 4.95g), with EM, 80 ml, applied into soil the same time before sowing, the total amounts of nitrogen, phosphorus and potassium were the same as in the above-mentioned organic material; and
6) Fertilizer: the same fertilizers as in 5).

Concept and Calculation of Ψ_{s-r} and Related Parameters

Fig. 1 shows an electric analogue of the pathway of water flow from soil through the plant to the atmosphere. The pathway is also called soil-plant-air continuum (Nobel and Jordan, 1983). With the exception of the tissue storage capacity (Cs) and resistance (Rs), which are not supposed to change easily with fertilizations within one species, other parameters in the analogue will be used to derive an equation to estimate Ψ_{s-r}. In this pathway, Ψ_{soil} Plays a dominant role in controlling plant water status and Ψ_{s-r} is proposed as a better indicator of the status of the water available or ready to enter the plant (Jones 1983ab) because it is related not only to soil hydraulic properties, which are determined by soil texture and physical properties, but also to plant root amount and water uptake ability. Usually, it is difficult to measure $\Psi_{s\text{-}r}$ routinely. However, it can be estimated using the concept of electrical circuit analogue (Fig. 1). In the present study we estimated $\Psi_{s\text{-}r}$ as proposed by Jones (1983a). According to the first equation of Ohm's Law,

$$V = V_1 + V_2 + \ldots + V_1 + \ldots V_n = I_1R_1 + I_2R_2 + \ldots + I_iR_i + \ldots + I_nR_{nj} \quad (1)$$

Where *V*, *I* and *R* are the electrical potential or voltage (Volt), current (Ampere) and resistance (Ohm) in an electric circuit. Accordingly, Ψ_{soil} and $\Psi_{s\text{-}r}$ can be expressed as follows;

$$\Psi_{soil} = \Psi_{s\text{-}r} + ER_{s\text{-}rj} \quad (2)$$

And

$$\Psi_{s\text{-}r} = \Psi_{xylem} + ER_{pj} \quad (3)$$

where *E* is the plant transpiration rate (Kg s^{-1}), corresponding to I_i in (1); $R_{s\text{-}r}$ and R_p are the hydraulic resistance between the soil and root or called soil-root interface hydraulic resistance (MPa sKg^{-1}) and the total plant hydraulic resistance (MPa sKg^{-1}), respectively, corresponding to R_i in (1); Ψ_{xylem} is leaf xylem water potential (MP a), corresponding to Vi in (1). Because $R_{s\text{-}r}$ cannot be measured directly, it is not possible to estimate $\Psi_{s\text{-}r}$ using Equation (2), although Ψ_{soil} and E can be determined. Therefore, Equation (3) should be considered. It is known that transpiration rate per unit of leaf area, E_A(Kgm^{-2} s^{-1}), is proportional to water vapor concentration difference, (θ_s- θ_a)(Kg m^{-3}), between the evaporating surface and the ambient air. According to the Ohm's law, it can be expressed as follows;

$$E_A = (\theta_s - \theta_a)/\pi \quad (4) \text{ or}$$

$$E_A = (\theta_s - \theta_a) = g \quad (5)$$

Where π (sm^{-1}) is the leaf resistance and g (m s^{-1}) is leaf conductance shown as the reciprocal of π Substituting (5) into (3) gives the following equation:

$$\Psi_{s\text{-}r} = \Psi_{s\text{-}r} + (\theta_s - \theta_a)gAR_p \quad (6)$$

Where *A* is the total leaf area (m^2) of the plant. Because R_p and *A* cannot be easily measured, comparison with the well watered control plant is used to eliminate these variables in the equation. First, for convenience, let $b = (\theta_s - \theta_a)AR_p$, and then

$$\Psi_{s\text{-}r} = \Psi_{xylem} + gb \quad (7)$$

If $\Psi_{s\text{-}r}$ is assumed as zero for a well watered plant, equation (7) will be

$$\Psi_{xylem(W)} = -bg[w] \quad (8)$$

where the subscript [W] refer to a well watered control plant. Because (θ_s- θ_a), *A* and R_p do not change between droughted (D) and well watered plants during a short term, *b* is the same for the former and later. Consequently, the following equation is derived from (7) and (8):

$$\Psi_{s\text{-}r(D)} = \Psi_{xylem(W)} - \Psi_{xylem(W)g(D)/g(W)} \quad (9)$$

Equation (9) can be used to estimate $\Psi_{s\text{-}r(D)}$ using only *g* and Ψ_{xylem} without disturbing or damaging the plant and soil, except a half leaf blade is cut for Ψ_{xylem} measurement.

Moreover, the soil-root interface hydraulic resistance, $R_{s\text{-}r}$ (MPa M^2s g^{-1}), in relations to total root surface area, S_{root} (m^2), root activity-related resistivity, $p_{s\text{-}r}$ (MPa M^2s g^{-1}), and soil-root interface distance, $L_{s\text{-}r}$ (m), were analyzed according the second equation of Ohm's laws:

$$R = \rho \iota / S \quad (10)$$

Where, ρ, ι and *S* are the resistivity, conductor length, and conductor crosscut section surface area, respectively. Therefore, in the case of soil-root interface,

$$R_{s\text{-}r} = \rho_{s\text{-}r} \iota_{s\text{-}r} / S_{s\text{-}r} \quad (11)$$

Where $S_{s\text{-}r}$, (m^2) is the total contacting surface area between the soil and root and equal to S_{root}. Therefore, (11) will be

$$R_{s\text{-}r} = \rho_{s\text{-}r} \iota_{s\text{-}r} / S_{root} \quad (12)$$

The reciprocal $\rho_{s\text{-}r}$ of named as the soil-root interface hydraulic conductivity, $\Gamma_{s\text{-}r}$ (gm Mpa^{-1} m^{-2}

s^{-1}), was used to show the contribution to from the soil-root interface properties (the root activity and soil physical properties). It is expressed as follows;

$$\Gamma_{s\text{-}r} = 1/\rho_{s\text{-}r} = \iota_{s\text{-}r} / R_{s\text{-}r} S_{root} \quad (13)$$

Here, $\Gamma_{s\text{-}r}$ is different in definition from both the reciprocal of $R_{s\text{-}r}$ (hydraulic conductance) and the soil hydraulic conductivity obtained from the desorpotion curve (Hillel, 1980). Then $\Psi_{s\text{-}r}$ can be written as

$$\Psi_{soil} - \Psi_{s\text{-}r} = E R_{s\text{-}r} = E \Gamma_{s\text{-}r} S_{root} / \iota_{s\text{-}r} \quad (14)$$

The soil-root interface distance, $\iota_{s\text{-}r}$ is assumed as the same for the same species with the same soil. If the variance of $\Psi_{s\text{-}r}$ and E which is on a relative basis of shoot size are neglected, $\Psi_{s\text{-}r}$ is determined by $\Gamma_{s\text{-}r}$ and S_{root}. The is estimated from the root volume (V_{root}) as follows;

$$S_{root} = V_{root}^{23} \quad (15)$$

V_{root} is estimated from the root biomass on a relative basis. Because many parameters cannot be easily measured or cannot be measured under undisturbed conditions, the variables such as V_{root}, S_{root}, $R_{s\text{-}r}$, $\rho_{s\text{-}r}$ and $\Gamma_{s\text{-}r}$ are expressed on the relative basis with those of the control plant as 1 for easy comparisons.

Measurements of Leaf Photosynthesis and Leaf Conductance

Photosynthetic rates (PN) in the leaf just above the ear were measured using a gas exchange system (LI-6400, LI-COR, Inc., Lincoln, Nebraska, USA) under different soil water conditions. The relative value of PN Was used to show photosynthetic maintenance ability. Leaf conductance was measured the same time as photosynthetic measurement.

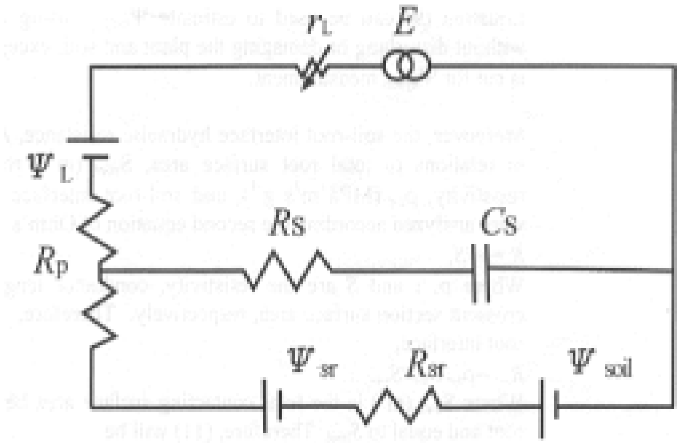

Fig 1. An Electric Circuit Analogue for Water Flow from the soil through the Plant to the Air. Ψ_{soil} Soil water potential; $\Psi_{s\text{-}r}$ soil-root interface water potential; $R_{s\text{-}r}$ soil-root interface hydraulic resistance; Rp, the total hydraulic resistance within the plants; Ψ_{xylem} leaf xylem water potential; π leaf resistance; E total plant transpiration; Rs water storage resistance; Cs water storage capacitance.

Measurements of Root Respiration Rate

Root samples each with 1 g of fresh mass for respiration measurement were collected by cutting the root at 5 cm from the tip. The respiration rate was measured using the same gas exchange system as that for photosynthetic measurement. The root respiration at 25°C was used to indicate root activity.

Measurements of Leaf Xylem Water Potential

Because the leaf blade of corn is much broader and longer than those of other cereal crops such as wheat and rice, a particular procedure was adopted for the measurement. The tip half part of the leaf blade after photosynthetic measurement was cut for leaf xylem water potential measurement. The leaf blade was aligned on the gluey surface of a 60 cm wide Scotch tape and folded along the main vein. The leaf blade was then enclosed in the Scotch tape to prevent evaporation water loss and the pressure gas penetration into the tissue. The prepared leaf blade sample was set in a pressure chamber (Model 3000, Soilmoisture Ltd., California, USA). The tip of the leaf blade with the tape was cut and the cut end was left 1 cm over the rubber stop. Other processes were the same as in usual cases as mentioned by Turner (1988).

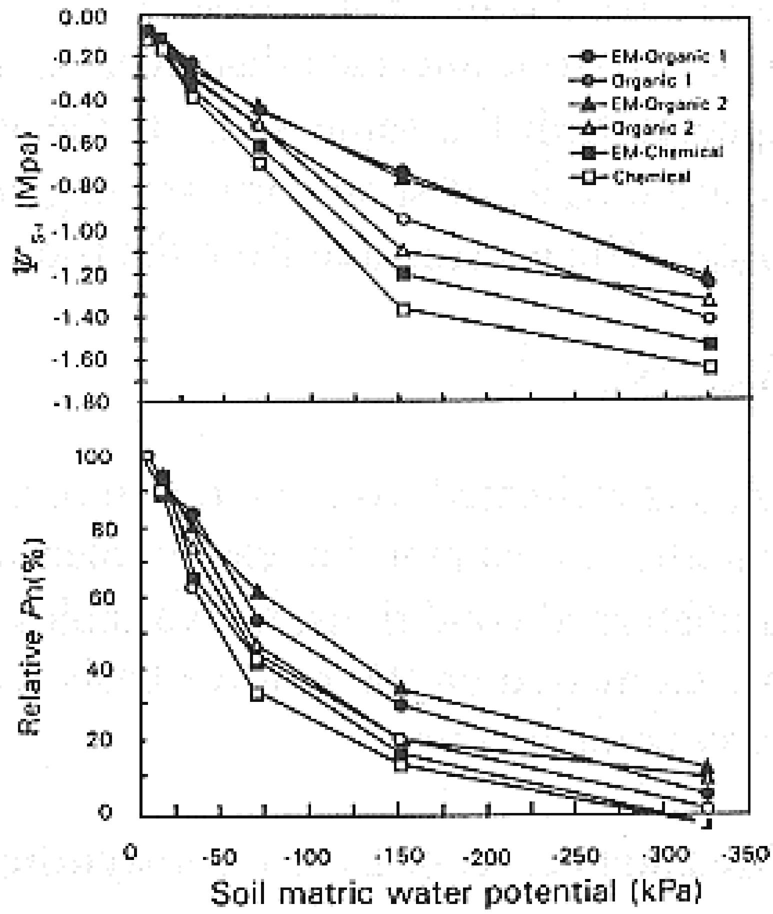

Fig 2. Maintenance of Soil-Root Interface Water Potential ($\Psi_{s\text{-}r}$) and Relative New Photosynthetic Rate (P_N) in Sweet Corn Plants Grown with Different Fertilizations as Soil Matric Water Potential Decreased.

Measurement of Soil Matric Water Potential

Soil matric water potential was measured using tensiometers (Hirose-Rika Ltd., Tokyo). Three tensiometers were placed with the sensor heads in different places within the soil volume of the sampled pots. The average value of the tensiometer readings was recorded as the soil matric water potential. Pots were weighed at the time when photosynthesis and leaf conductance were measured. The correlation ($y=7011.9E^{-0.0767x}$; r2=0.83; n=28) between soil matric water potential (y) and soil water content (x) was obtained. It has to be pointed out that the soil matric water potential measured *in situ* here does not represent Ψ_{soil} in the analogue of Fig. l because Ψ_{soil} includes osmotic potential and pressure potential in addition to the matric potential. In the present study, we used the *in situ* measured soil matric water potential just to show the decreasing extent of soil water. If soil water potential is involved in the calculation and analysis, the one measured with psychrometer should be used.

Results

Soil-Root Interface Water Potential

As soil matric water potential decreased, soil-root interface water potential ($\Psi_{s\text{-}r}$) maintained higher in organic fertilized sweet corn plants than in chemical fertilized ones (Fig. 2). For example, at the soil matric water potential of 70 kPa, $\Psi_{s\text{-}r}$ decreased to -0.61 MPa in chemical fertilized plants while it maintained at -0.45 and -0.43 MPa in plants fertilized with anaerobic and aerobic organic materials, respectively (Table 1). There was no difference in $\Psi_{s\text{-}r}$ found between anaerobic and aerobic organic fertilizations. Under both organic and chemical fertilization conditions, $\Psi_{s\text{-}r}$ Was 0.08 MPa higher in plants with EM applications than in those without EM applications. This result suggests that EM applications diminished decreases in $\Psi_{s\text{-}r}$ under soil water deficit conditions although the differences between plants with EM application and without EM were not as large as those between chemical and organic fertilizations. There were only simply additive effects without synergistic interactions between the treatments of organic fertilization and EM application.

Table 1. Soil -Root Interface Water Potential ($\Psi_{s\text{-}r}$ MPa) and Related Parameters on Relative Basis with Control as 1.

Fertilization	Ψ_{root}	R/T	V_{root}	S_{root}	$R_{s\text{-}r}$	$\rho_{s\text{-}r}$	$\Gamma_{s\text{-}r}$
EM organic 1	-0.45a	0.27a	1.53a	1.33a	0.60a	0.80a	1.25a
Organic 1	-0.52b	0.24b	1.35b	1.22b	0.72b	0.88b	1.14b
EM organic 2	-0.43a	0.28a	1.55a	1.34a	0.57a	0.76a	1.32a
Organic 2	-0.51b	0.24b	1.33b	1.21b	0.70b	0.85b	1.18b
EM chemical	-0.61c	0.20c	1.11c	1.07c	0.87c	0.93c	1.08c
Chemical	-0.69d	0.18d	1.00d	1.00d	1.00d	1.00d	1.00c

R/T. root/top ratio on dry mass basis (%); V_{root} , root volume; S_{root} , root surface area; $R_{s\text{-}r}$, soil-root interface resistance; $\rho_{s\text{-}r}$, soil root interface resistivity, $\Gamma_{s\text{-}r}$, soil-root interface hydraulic conductivity. The data followed by the same letter are not significantly different with each other according to Waller-Duncan comparison.

Contributions of Root Amount and Root Activity to $\Psi_{s\text{-}r}$

The contributions to $\Psi_{s\text{-}r}$ from root amount and root activity were analyzed using the second equation ($R = \rho\ \iota /S$) of Ohim's law. First, we found that root/top ratio of biomass was higher for organic fertilized plants than chemical fertilized plants and also higher for plants with EM applications than for those without EM applications (Table l). On the relative basis, root volume is logically higher in plants with a higher root/top ratio and consequently the total root surface area on the relative basis can be estimated from the relative root volume If the soil-root interface hydraulic resistance ($R_{s\text{-}r}$) is assumed to be inversely proportional to $\Psi_{s\text{-}r}$ using plants under chemical fertilization without EM application as control on a relative basis, the hydraulic resistivity ($\rho_{s\text{-}r}$) of the soil-root interface conductor is smaller for organic fertilized plants than chemical fertilized plants and also smaller for plants with EM applications than for those without EM applications. If the results of $\rho_{s\text{-}r}$ is shown by its reciprocal, the soil-root interface hydraulic conductivity ($\Gamma_{s\text{-}r}$), it is easier to understand the contribution to $\Psi_{s\text{-}r}$ from the soil-root interface properties, which is determined by both root activity on one side and soil physical properties on the other side.

Root Respiration Activity

The respiration rate in the tip part of the root measured at $25^{o}C$ was higher in organic fertilized plants than chemical fertilized plants and higher for plants with EM application than those without EM application (Table 2). This result is consistent with that of $\Gamma_{s\text{-}r}$ analyzed using Ohm's law. This suggests that the relatively high $\Psi_{s\text{-}r}$ in organic fertilized plants or on EM applied plants is attributed, at least in part, to the relatively high root physiological activity.

Table 2. The Maximum Photosynthetic Rate Under Well Watered Conditions (P_{max}), Photosynthetic Rate at Soil Matric Potential of 70 kPa ($P_{R(70)}$) and Relative Value of $P_{N(70)}$ ($P_{N(70)}$) and Dark Respiration Rate of the Root 25°C at (D_{max}) in Leaves of Sweet Corn Plants with Different Fertilization Treatments.

Treatment	Pmax (μ mol $m^{-2}S^{-1}$)	PN(70) (μ mol $m^{-2}S^{-1}$)	PR(70) (%)	Dmax(25) (μ mol $kg^{-2}S^{-1}$)
EM organic 1	25.8bc	14.1b	54.5b	5.2c
Organic 1	24.8c	10.9d	43.9d	5.8b
EM organic 2	26.6b	16.6a	62.4a	6.0b
Organic 2	23.8c	11.3cd	47.7cd	6.8a
EM chemical	29.0a	12.4c	4.8dc	4.8dc
Chemical	26.8b	9.0e	33.7e	5.4c

Photosynthetic Maintenance Under Soil Water Deficit Conditions

Since Ψ_{s-r} maintained higher in organic fertilized and EM applied plants as soil matric water potential decreased, photosynthetic rate (P_N) was consequently higher in these plants with higher Ψ_{s-r} on both absolute and relative bases (Fig 2, Table 2). The proportional association between Ψ_{s-r} and P_N was only apparent when soil matric water potential decreased, ie. P_N is not in relation to Ψ_{s-r} under well watered conditions.

Discussion

In the pathway of water flow from soil through the plant to the atmosphere or soil-plant-air continuum (SPAC), Ψ_{soil} Plays a dominant role in controlling plant water status (Nobel and Jordan, 1983). However, in some specific cases, whether or not plants can absorb sufficient water from the soil is not only dependent on water amount in the soil but also dependent on the water uptake ability and the ability of the soil to transfer water from the soil to the root surface. The soil-root-interface water potential (Ψ_{s-r}) is not only related to soil properties but also associated to plant root activity and plant water consumption. That is why Ψ_{s-r} is considered as a better indicator of soil water available to the plants (Jones 1983a). As mentioned by Jones (1983a), Ψ_{s-r} is actually the average water potential or effective soil water potential at the root surface. It shows the status of water that is available or ready to enter the plant. In magnitude, Ψ_{s-r} is close to plant water potential at predawn bur far lower than especially Ψ_{soil} that measured with tensiometer. The results of the present study indicated that the calculated Ψ_{s-r} can be a useful additional method to estimate plant water stress. In every treatment, measurements are made on comparable leaves of water stressed and well watered control plants that errors from the Ψ_{xylem} and *g* could be minimized. The results showed a good trend among the treatments. Ψ_{s-r} was higher for both anaerobic and aerobic organic fertilizers than chemical fertilizers. In both organic and chemical plots, EM application increased Ψ_{s-r} almost equally. The relatively high Ψ_{s-r} in organic fertilized plants or in plants applied with EM was attributed to both the relatively large root surface area and relatively high soil-root interface hydraulic conductivity (Γ_{s-r}). By inferences as shown in equation (12) from Ohm's law, if plant transpiration is assumed unchanged on a relative basis to the shoot size, Ψ_{s-r} is determined by three factors, the length of the soil-root interface conductor, the root surface area and the soil-root interface hydraulic conductivity (its reciprocal is called resistivity). The length of the soil-root interface is actually the distance from the soil to root surface and associated with the contact between soil and root. It may be affected by the soil texture and root morphology. In the present study we used a soil with uniform soil texture and the same species of plant materials. Therefore, the distance between soil and root is not supposed to vary with fertilization treatments, Then, only S_{root} and Γ_{s-r} remain as the factors determining Ψ_{s-r}. We found that root/top ratio of biomass was higher for organic fertilized plants than chemical fertilized plants and also higher for plants with EM applications that for those without EM applications. Therefore, it is logical to assume that the root volume on the relative basis is proportional to root biomass. Consequently, the total root surface area on the relative basis can be estimated from the relative root volume. Therefore, from the results S_{root}, it is concluded that the relatively high Ψ_{s-r} in organic fertilized plants or in EM applied plants is attributed, on one hand, to the promoted root amount. Another factor that contribute to Ψ_{s-r} is the soil-root interface hydraulic resistivity (Γ_{s-r}), which is determined by the properties of the soil-root interface conductor. One of the terminals of the conducting pathway of the soil-root interface is the soil and the other is the root of the plant. Therefore, Γ_{s-r} is determined by both soil physical properties and root activities. With plants under chemical, fertilization without EM application as control on a relative basis, Γ_{s-r} is larger for organic fertilized plants than chemical fertilized plants and also larger for plants with EM applications than for those without EM applications. We measured root respiration rate, which is supposed to be an indicator of the physiological activity in the root (Huck, 1982). It was found that root respiration rate at 25^{o}C was relatively high in organic fertilized or EM applied plants. Respiration rate in the root indicates the physiological activity for ion and water uptake (Huck, 1982; Lauchi, 1982). This result is consistent with the result of Γ_{s-r} with analysis of Ohm’s law. Another factor associated with Γ_{s-r} might be the physical properties, which determine the easiness of water to flow onto the root surface. In the present study, we did not measure the physical properties of the soil. So, we do not know whether just one season of fertilization with a small quantity of organic materials or application of EM can change soil physical properties. From our results, however, it can be concluded that Ψ_{s-r} is attributed to the developed root system and promoted root activity. In methodology, the analysis with the second equation of Ohm’s law showed good results for the experiment although many assumptions and relative values were used.

Because of higher Ψ_{s-r} under soil water deficit conditions, plants fertilized with organic materials and applied with EM maintained higher P_N than plants fertilized with chemicals and those without EM applications. It is logical that, compared to that of a small root system, a plant with a large root system and high root activity shows a higher water stress resistance ability. This result also supports that EM is more effective to crops under conditions of water deficit and under other stresses (Li and Ni, 1996).

It has been known that long-term fertilizations with organic materials improve soil physical, chemical and biological properties (Hillel, 1980). Growth and activity of the root system are promoted by the improved soil properties and as a consequence the plants become more resistant to soil water deficits by their strong root system (Jones, 1983b). Up to now, there have been many researches on organic fertilizations (Harwood, 1984; Lockeretz and Kohl, 1981; U.S.D.A, 1980; Vogtmann, 1984). However, the mechanism of EM effect has not been clear in many aspects. For example, we do not know whether EM applications affect soil physical properties and how they are affected if any. It is also not clear whether the effect are from the microbes themselves or from the substances produced by microbes during the product manufacture or after it is applied. Therefore, further studies are needed to elucidate the mechanistic basis for the effects of EM on soil physical properties and plant characteristics associated with root water uptake.

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