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Dynamics of water and ion transport driven by corn canopy in the Yellow River basin

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Abstract: Water and ion balance in a corn field in the semi-arid region of the upper Yellow River basin (Inner Mongolia, China) was analyzed with special reference to transpiration stream and selective nutrient uptake driven by the crop canopy. During the crop development stage (June 7 to July 17, 2005), crop transpiration and soil evaporation were evaluated separately on a daily basis, and concentrations of NO_3^-, PO_4^{3-}, K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^- ions in the Yellow River water, irrigation water, ground water, soil of the root zone and xylem sap of the crop were analyzed.
The crop transpiration accounted for 83.4% of the evapotranspiration during the crop development stage. All ions except for Na^+ were highly concentrated in the xylem sap due to the active and selective uptake of nutrients by roots. In particular, extremely high concentrations of the major essential nutrients were found in the nighttime stem exudate, while these concentrations in the river water, the irrigation water, the ground water and the root-zone soil were lower. On the other hand, Na^+, which is not the essential element for crop growth, was scarcely absorbed by roots and was not highly concentrated in the xylem sap. Consequently, Na^+ remained in the ground water and the root-zone soil at higher concentrations. These results indicate that during the growing season, crop transpiration but not soil evaporation induces the most significant driving force for mass flow (capillary rise) transporting the ground water toward the rhizosphere, where the dynamics of ion balance largely depends on the active and selective nutrient uptake by roots.

Key words: active and selective uptake, transpiration stream, water and ion transport

Introduction

Water deficit and salt accumulation in the root zone are serious problems in crop fields in semi-arid regions, which are affected by dynamics of water and ion transport in the soil-plant-atmosphere continuum. Although water and ion transport in crop fields is driven through physical and physiological processes, the transport phenomena in the root zone have been studied mainly through physical processes because of the difficulties in quantitative analyses of root physiological functions (Hillel, 1998). Transpiration stream and nutrient uptake driven by crop canopy can be considered to largely depend on root physiological functions, where transport mechanisms such as pumps, channels and transporters in the root cell membranes play the important roles especially in the radial flow across root endodermis (Taiz & Zeiger, 2002). In this study, water and ion balance in a corn field in the semi-arid region of the upper Yellow River basin in Inner Mongolia, China, was analyzed with special reference to transpiration stream and selective nutrient uptake driven by crop canopy.

Material and methods

Experimental field and observations
Japan Science and Technology Agency (JST) and Institute of Agro-Environmental and Sustainable Development, CAAS, China established an experimental corn field, 55 m × 73 m in area, at Togtoh, Inner Mongolia, China (latitude 40°14.8′ N, longitude 111°11.0′ E, altitude 995 m a.s.l.) for conducting irrigation experiments to develop water-saving irrigation techniques. In this region, basin irrigation is applied two or three times a year with the water diverted from the Yellow River (Iwanaga et al., 2005; Yasutake et al., 2006b). Corn plants (*Zea mays* L. cv. Zhedan No. 7) were planted with a density of 6.11 plants m^{-2} at the end of April and harvested in the first ten days of October. A weather station with a 7 m high tower was installed at the center of the field, and meteorological elements were observed and recorded every hour (BST). The data obtained during the

crop development stage (as defined by Allen et al., 1998) of corn from June 7 to July 17, 2005 were analyzed.

Evaluation of crop transpiration

The rate of evapotranspiration from a well watered reference crop with dry surface of leaves is called the reference crop evapotranspiration and is denoted as ET_0 (mm d^{-1}). It can be calculated using the FAO Penman-Monteith equation on a daily basis (Allen et al., 1998) as

$$ET_0 = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma \dfrac{900}{T_\mathrm{A} + 273} u_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where R_n is the net radiation, G is the ground heat flux, T_A is the air temperature at 2 m above the plant canopy, u_2 is the wind speed at 2 m above the plant canopy, e_s is the saturation vapour pressure at T_A, e_a is the actual vapour pressure at 2 m above the plant canopy, Δ is the slope of vapour pressure curve and γ is the psychrometric constant. Since the magnitude of daily ground heat flux beneath the reference crop surface is relatively small, G in Eq. (1) was ignored in this study.

For evaluating crop transpiration and soil evaporation separately on a daily basis, the dual crop coefficient approach recommended by FAO (Allen et al., 1998) was applied (Yasutake et al., 2006b). Under conditions without soil water stress, daily crop transpiration rate (Tr) and daily soil evaporation rate (E) are given by

$$Tr = K_\mathrm{cb} ET_0 \quad (2)$$

$$E = K_\mathrm{e} ET_0 \quad (3)$$

where K_cb is the basal crop coefficient, which specifies the crop transpiration when the soil surface is dry but transpiration is occurring at a potential rate, and K_e is the soil evaporation coefficient. Furthermore, the effect of soil water stress on Tr can be quantified by multiplying the stress-free transpiration rate by the water stress coefficient K_s as

$$Tr = K_\mathrm{s} K_\mathrm{cb} ET_0 \quad (4)$$

The value of K_s is less than 1 during soil water stress and equal to 1 under the condition with no soil water stress. From Eqs (3) and (4), daily evapotranspiration (ET) from crop fields can be written as

$$ET = (K_\mathrm{s} K_\mathrm{cb} + K_\mathrm{e}) ET_0 \quad (5)$$

The three coefficients K_cb, K_e and K_s can be determined following the procedure given by FAO based on the type of soil, meteorological conditions, crop characteristics, etc. (Allen et al., 1998).

Furthermore, diurnal changes in crop transpiration and stomatal conductance of plant canopy were evaluated by using the proposed method in which abscisic acid (ABA), transpiration inhibiting plant hormone, was applied to roots (Yasutake et al., 2005). The effect of soil water stress on crop transpiration was also predicted from dynamics of the plant canopy stomatal conductance evaluated by the ABA method. Yasutake et al. (2006a) showed that the daily-accumulated crop transpiration rate evaluated by the ABA method was similar to Tr evaluated by Eq. (4) of the dual crop coefficient approach.

Analysis of ion transport

Roots can generate positive hydrostatic pressure (i.e. root pressure) in the nighttime by absorbing ions actively from the dilute soil solution and transporting them into the xylem, and if the stem of a plant is cut off just above the soil, the stump often exudes sap from the cut xylem for many hours (Kramer & Boyer, 1995; Taiz & Zeiger, 2002). Therefore, the ion composition of this stem stump exudates can be considered to reflect clearly the active and selective ion absorption by roots without the significant effect of dilution due to the transpiration stream. The xylem sap exuded from the stem stumps of three corn plants was collected during the nighttime on July 17 in the experimental corn field. The concentrations of the ions of different nutrients (NO_3^-, PO_4^{3-}, K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^-) were analyzed by using an ion chromatograph system (ICS-90, DIONEX, Osaka, Japan). The concentrations of the same ions in the samples of the Yellow River water, the irrigation water and the ground water under the corn field were also analyzed. The ground water was sampled from observation wells in the corn field where the ground water table lay between 1.76 and 2.25m below the ground surface. The electrical conductivity (EC) of the solutions was measured with an EC meter (B-173, HORIBA Ltd., Tokyo, Japan). Soils in the root zone were sampled from the depth of 15cm at three different spots in the field. The dissolved ion concentrations and $EC_{1:5}$ of the soil samples were measured with the ion chromatograph system and the EC meter, respectively, after the standard process of pretreatment. The whole shoots above the ground surface of three corn plants were sampled on June 7 and July 17, 2005 and fresh weight, dry weight and the content of ions K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^- in the sampled shoots were measured following the standard procedures. For measuring the ion content in the sampled shoots, the ash of each shoot was dissolved in dilute nitric (HNO_3) or hydrochloric (HCl) acid to achieve complete decomposition of organic matter (The contents of NO_3^- and PO_4^{3-} were not measured with this procedure). From the amounts of the respective ions accumulated in the corn shoots and the total amount of the transpiration over the crop development stage, the average concentrations of ions in the transpiration stream of xylem sap toward the shoot were estimated.

Results and discussion

Figure 1 shows daily changes in ET_0, K_e, $K_\mathrm{s}K_\mathrm{cb}$, ET, Tr and E during the crop development stage of corn plants from June 7 to July 17, where precipitation was observed on June 5 (14.5 mm d^{-1}) and June 26 (9.7 mm d^{-1}). ET_0 varied with the daytime weather conditions mainly depending on the net radiation. K_e depends on moisture condition of the top soil, and consequently the higher values of K_e and E were found only for several days after each precipitation. $K_\mathrm{s}K_\mathrm{cb}$ increased almost linearly with time until July 1 under the condition with no soil water stress ($K_\mathrm{s} = 1.0$), and the contribution of Tr to ET increased. The occurrence of soil water stress after July 1 decreased K_s from 1, and consequently $K_\mathrm{s}K_\mathrm{cb}$ leveled off at around 0.65. However, $K_\mathrm{s}K_\mathrm{cb}$ and therefore Tr were remarkably larger than K_e and E, respectively, except for a few days after

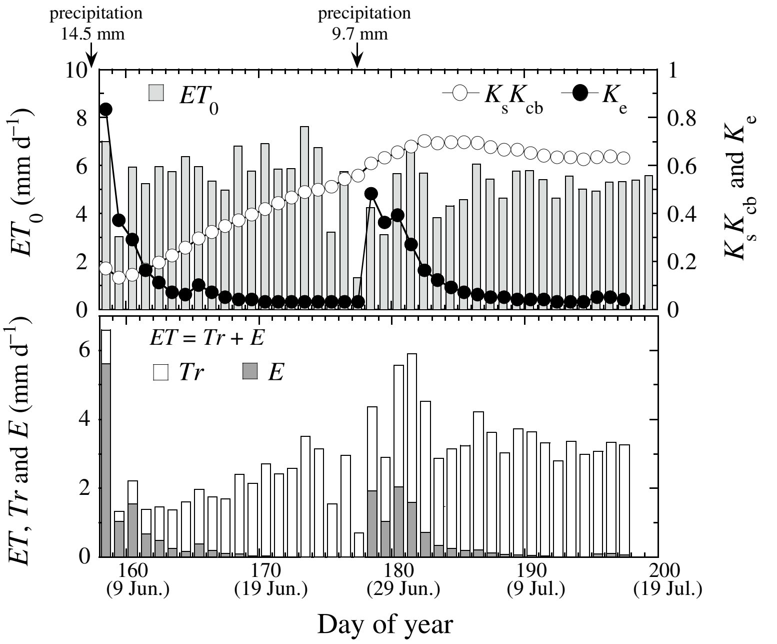

Fig. 1. Daily changes in reference potential evapotranspiration (ET_0), soil evaporation coefficient (K_e), basal crop coefficient (K_{cb}) corrected for soil water stress by multiplying water stress coefficient (K_s), evapotranspiration (ET), crop transpiration (Tr) and soil evaporation (E) during the crop development stage of corn from June 7 to July 17, 2005.

the precipitation at the beginning of the crop development stage. The total amounts of *Tr*, *E* and *ET* during the crop development stage from June 7 to July 17 were 98.7, 19.6 and 118.3 mm, respectively. This means that during the crop development stage in the corn field, the precipitation supplied only about 20% of water loss by the evapotranspiration, and the crop transpiration accounted for 83.4% of the evapotranspiration. These results suggest that crop transpiration induces the most significant driving force for mass flow (capillary rise) transporting the ground water toward the rhizosphere. Furthermore, diurnal changes in crop transpiration rate and stomatal conductance of the corn canopy evaluated by the ABA method on July 15 indicated that crop transpiration and stomatal conductance were depressed in the afternoon due to the occurrence of the midday stomatal closure by soil water stress (Yasutake et al., 2006a).

Figure 2 shows the electrical conductivity (EC) and concentrations of the respective ions of NO_3^-, PO_4^{3-}, K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^- in the Yellow River, the irrigation water, the ground water and the nighttime exudate from the corn stem stump on July 17, and Fig. 3 shows the electrical conductivity and concentrations of the dissolved ions at a depth of 15cm in the soil of the corn field on June 7 and July 17, 2005. The nighttime exudate of xylem sap can be considered to indicate clearly the active and selective uptake of nutrients by roots without the significant effect of dilution with the transpiration stream (Kramer & Boyer, 1995; Taiz & Zeiger, 2002). Ions except for Na^+ were highly concentrated in the nighttime xylem sap due to the active and selective nutrients uptake by roots, and in particular, extremely high concentrations of the major essential nutrients such as NO_3^-, PO_4^{3-} and K^+ were found, while these concentrations in the river water, the irrigation water, the ground water and the root-zone soil were remarkably lower. This clearly indicates that transport mechanisms in roots facilitate the active and selective uptake of the major essential nutrients from the lower concentrated solution of the rhizosphere. On the other hand, Na^+, which is not the essential element for crop growth, was scarcely absorbed by roots and therefore was not highly concentrated in the xylem sap. Consequently, Na^+ remained in the ground water and the root-zone soil with higher concentrations, and Na^+ concentration in the root-zone soil increased during the crop development stage.

The total amount of *Tr* during the crop development stage from June 7 to July 17, 2005 were evaluated as 98.7 mm in depth (Fig. 1), which can be converted into the total volume of transpired water as 16.2 L plant^{-1} by using the plant density of 6.11 plant m^{-2}. By using this total volume of *Tr* and the total amount of each ion accumulated into the shoot during the crop development stage, the average concentration of each ion in the transpiration stream of xylem sap toward the shoot was estimated. Table 1 shows the ion accumulation in the shoot and the average ion concentrations in the transpiration stream toward the shoot between June 7 and July 17, 2005. The average ion concentrations in the transpiration stream of xylem sap were considered to reflect the selective ion uptake by roots, although these concentrations became lower due to the dilution effect of the transpiration stream as compared with those in the nighttime stump exudation. Ions ex-

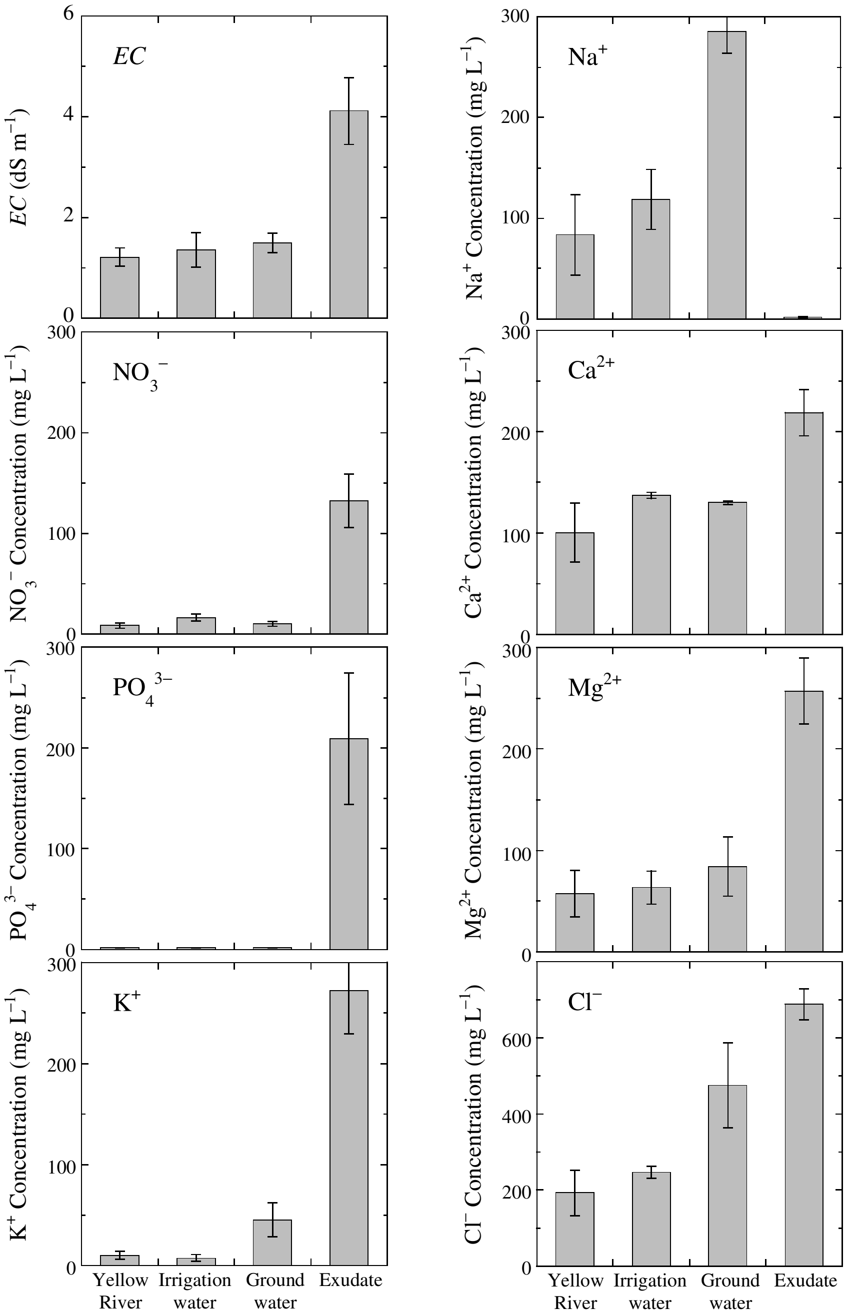

Fig. 2. Electrical conductivity (EC) and concentrations of the ions of NO_3^-, PO_4^{3-}, K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^- in the Yellow River, irrigation water, ground water and the nighttime exudate from the corn stem stump on July 17, 2005. Means of three samples are shown with the standard deviations.

Table 1. Ion accumulations in shoot and average ion concentrations in transpiration stream to shoot between June 7 and July 17, 2005.

	units	K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-
Ion contents in shoot						
7 June	(mg shoot^{-1})	99.2	6.7	17.2	32.2	28.1
17 July	(mg shoot^{-1})	1389.7	84.2	329.1	867.0	573.2
Ion accumulations in shoot (7 Jun.–17Jul.)	(mg shoot^{-1})	1290.5	77.5	311.9	834.8	545.1
Ion concentrations in transpiration stream	(mg L^{-1})	79.7	4.8	19.3	51.5	33.6

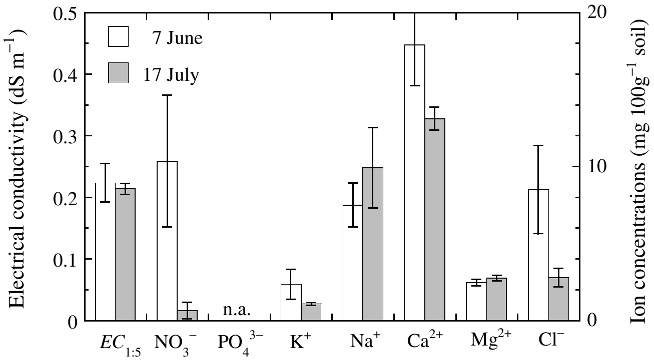

Fig. 3. Electrical conductivity ($EC_{1:5}$) and concentrations of the dissolved ions of NO_3^-, PO_4^{3-}, K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^- of the root-zone soil at 15cm depth in the corn field on June 7 and July 17, 2005. Means of three samples are shown with the standard deviations.

cept for Na^+ and Ca^{2+} were highly concentrated into the transpiration stream and distributed to the shoot. Na^+ is not the essential element for crop growth, and Ca^{2+} is the major essential element but has immobility in transport processes in plants. Therefore, it can be considered these ions were not highly concentrated into the transpiration stream toward the shoot.

These results indicate that during the crop growing season, it is the crop transpiration but not the soil evaporation that induces the most significant driving force for mass flow transporting the ground water toward the rhizosphere, where dynamics of ion balance largely depends on the active and selective nutrient uptake by roots. Therefore, root physiological functions affecting transport of water and ions in the soil-plant-atmosphere continuum should be taken into consideration for analyses and managements of water deficit and salinization in crop fields.

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