Effect of Soil Water on Soil Temperature and Salt in Saline Soil with Undulate Surface in Hetao Irrigation District

Zhu Xue [1, 2] *, Takeo Akae[1], Haibin Shi [2] and Mari Ishida[2]

1. Graduate School of Environmental Science, Okayama University, Okayama 700-8530, Japan
2. Water Conservancy and Civil Engineering College of Inner Mongolia Agricultural University, Hohhot 010018, China

xuezhu_okayama@yahoo.com

Abstract: Field experiments were conducted to investigate the effect of soil water on soil temperature and salt in saline soil and its interactive influence. The variation of soil temperature along with soil profiles was continuously monitored on three undulate experimental sites (C+, 50 cm high from the reference level C, and C−, 50 cm low from reference level, respectively). Soil samples were collected from 10 cm to 150 cm depth on each soil profile at three sites to measure soil moisture content and electrical conductivity ($EC_{1:5}$) of soil in spring season (May, 2005). It was revealed the water content in soil profiles was in order of C−>C>C+, and the soil temperature was in order of C+>C>C−, and the $EC_{1:5}$ value was in order of C+>C>C−. Basing on the soil temperature model and diurnal variation in temperature data, we calculated the thermal parameters. Thermal diffusivity (D_T) is 0.024, 0.049, and 0.233 cm^2/s; the average thermal conductivity is 0.022, 0.051, and 0.246 cal/cm·s·℃ in C+, C, and C-sites, respectively. The soil heat fluxes were also calculated based on the Fourier's law. The variation range of soil heat flux at subsurface is in the order of C+>C>C−. This calculated results show that the calculated soil temperature values are in good agreement with the measured values for C+ site (low soil moisture content) but not so good for C− site (relatively higher soil moisture content) due to the effect of soil moisture content. The results suggest that in arid area like Hetao Irrigation District, China, water loss by evaporation should be reduced for preventing salt from accumulating on soil surface or rooting zone hazarded to seed germination and growth. [Journal of American Science 2010; 6(10):343-350]. (ISSN: 1545-1003).

Key words: saline soil, soil temperature, soil moisture content, electrical conductivity, undulate surface, arid area.

1. Introduction

The unscientific irrigation and poor natural drainage water induced salinity are the main causes of lands loss in irrigated areas in China and in the world. Up to 48% of farmland in the world is affected by salinity (Umali, 1993). Salinity resulted in reducing yield of crops, especially where irrigation water or soil contains large amounts of salt. Hetao Irrigation District is gaining 1.7 M ton of total dissolved salt annually (Wang, 2002). Akae et al. (2008) also found the risk of salinization is occurred mainly in the central drainage canal block in the same district. The salinity problem is increasing day by day in this district.

The agricultural productivity mainly depends on the irrigation water supplied from Yellow River in the district. In recent, the shortage of water resource and salt problem already hazarded the development of agricultural production in the district.

A common phenomenon of salinity problems is the accumulation of salts to the surface soil due to acute heavy evaporation and lack of leaching chance due to poor drainage. The salt moves with the movement of soil water. The poor drainage results to the groundwater table rising up shallow, which leads to the secondary salinization. The salt accumulations on surface soil make the surface soil become a white crust, which may be a common seen at spring season every year.

To avoid the accumulation of salt in the soil, leaching is very essential method. However, natural leaching of salts from irrigated agricultural fields is not possible in such arid areas as rainfall is generally insufficient. The fall irrigation is implemented to leach the excess salt from the agricultural land in every year, however, at the same time the fall irrigation brings a lot of salt (Wang, 2002).

Frequently irrigation, intensive evaporation, and high groundwater table are the main phenomenon in Hetao Irrigation District. Under such conditions, the water-salt content in the soil can change with spatial and temporal change. Moreover, the water-salt distribution in soil may be depend on the local topography because of water-salt movement attending by lateral flow of water and salt.

Soil temperature also is one of the most critical factors that influence physical, chemical, and biological processes in soil and plant science (William, 2004). The distribution and variation of soil temperature affect soil water movement at most aspects. For example, soil temperature influence physical and chemical properties, consequently influence soil matric potential, osmotic potential and so on. On the other hand, the soil water status also determines the soil thermal parameters. The phase transition of water is one of most important factors in heat balance, such influence often occurs in cold-arid region. In practice, the soil water-heat movement is interactive and coupled effect. Therefore, the issue of soil water-salt movement is very complex basing on taking into account many influence factors.

To further understand the mechanism of water-salt movement, we selected the waste saline lands as subjects to investigate the distribution and movement of soil water in salt-affected soil under undulate surface conditions.

Above this background, the two major objectives of this study are (a) to determine the soil water-salt distributions in salt-affected soil under undulate surface conditions and (b) to evaluate the effect of soil water on soil temperature and salt distribution in saline soil with undulate surface.

2. Materials and Methods

2.1 Experimental Site

This study was conduced in Shahaoqu Experimental Station (40° 55′ N, 107° 09′ E) in Hetao Irrigation District, China, it is shown in Figure1.

Hetao Irrigation District is located in the middle of Yellow River Basin, a typical arid region with continental monsoon climate. The district is one of the three largest gravity irrigation district in China and is the 250 km of length from West to East and 50 km of width from North to South. The terrain in entire district slopes gently, the ground slope is about 1/5000~1/8000 from West to East and 1/4000~1/8000 from North to South.

The average annual precipitation is about 150 mm; average annual potential evaporation is about 2,164 mm; mean annual temperature is 6.3~7.7 ℃. The precipitation is mainly occurred between May to September in every year.

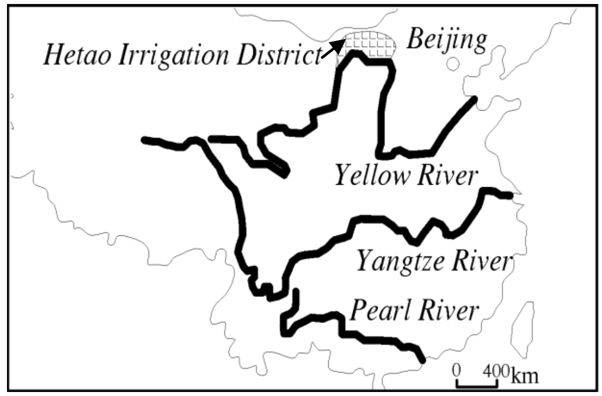

Figure 1 Schematic location of Hetao Irrigation District in China

The physical properties of soil have been listed on Table 1. Most of soil samples were collected at C+, C, and C− sites on May 4, 2005 to measure the soil moisture content, electrical conductivity ($EC_{1:5}$).

Table 1 Fundamental physical properties of study area

Site	Particle density ρ_s (g/cm^3)	Saturated water content θ_s (m^3/m^3)	Residual water content θ_v (m^3/m^3)	Soil texture
C+	2.72	33.7	21.9	Silty clay
C	2.74	33.6	20.7	
C−	2.73	35.2	17.9	

2.2 Experimental Design

The experimental sites were divided and indicated by different capital letters and have been built since 1996. This study was carried out in C site under controlled field site conditions. The investigated site was constructed by artificial excavation of 50cm lower than reference level (C−); and pile up of 50cm higher than reference level (C+), and reference level (C), natural soil surface as shown in Figure 2.

Soil temperature sensors were embedded at depth of 5cm, 20cm, 40cm, 50cm, 60cm, 70cm, 90cm, and 125cm in the three sites (C+, C and C−) respectively to measure continuously the temperature of topsoil to deeper soil. On May 4, 2005, most of soil samples were collected from soil profiles at depth of these sites to measure soil moisture content by using the gravitational method.

The disturbed soil samples were air-dried and mixed with distilled water at the ratio of 1:5 by weight.

The Electrical conductivity of soil solution was measured using portable electrical conductivity meter (B-173; Horiba Ltd.).

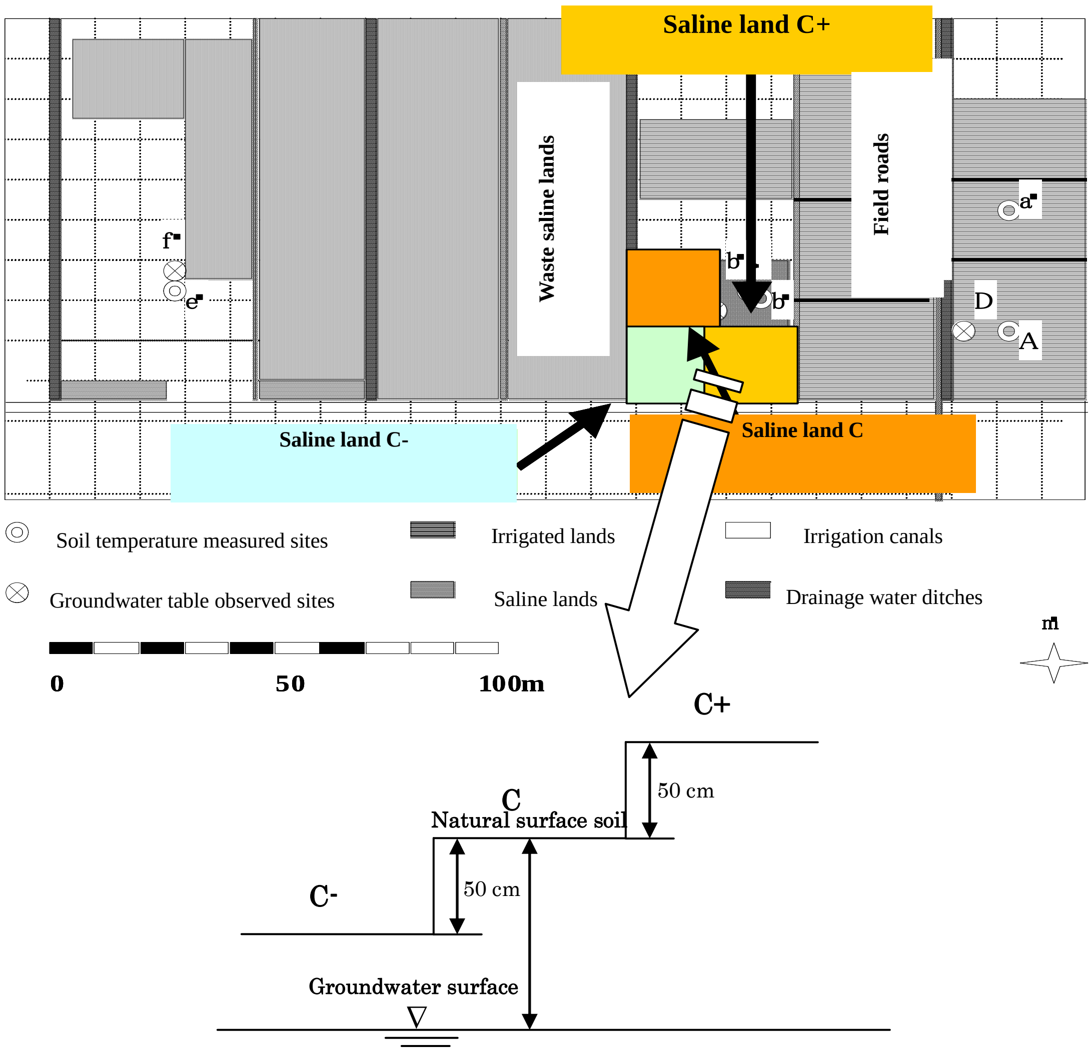

Figure 2 Schematic layouts of the entire studied field and the groundwater table on C site on May 4, 2005

3. Results and Discussion

3.1 The distribution of water and salt in soil profiles

Lacking in the continuous measured soil moisture content and electrical conductivity ($EC_{1:5}$) data, we choose soil moisture content and $EC_{1:5}$ of soil in spring (salinity return period), 2005 to reveal the soil water-salt distribution at the three sites. The variation of measured soil moisture content and $EC_{1:5}$ of soil with soil depths are shown in Figure 3 and 4.

Figure 3 indicates the return salt period, the movement of soil water almost was upward until next irrigation event, it is also shown that the soil moisture content increases with increasing soil depth, but increasing ratio between layers is not so large, the minimum of soil moisture content is 19.9% in surface layer in C+ site; the maximum is 33.2% in 150cm of depth in C site. The coefficient of variation (Cv) of soil profile water content in the C+, C, and C− sites is 0.09, 0.31, and 0.18, respectively. However, there was a significant difference on the three sites, except for the 20cm, and 80cm of soil depth, the total tendency of soil profile water content is in the order of C−>C>C+ due to the influence of undulate surface soil.

In spring, generally, the groundwater table (GWT) is deeper in the district. The measured GWT was 217 cm in C site on May 4, 2005. At that period the groundwater supply was relatively low, the most of soil water almost come from the fall irrigation in the previous year. Because of the waste saline land is neighboring to the irrigated lands, the lateral infiltration carries water and salt at every events of irrigation, surface water collected to store more in C− than in C, and C+ sites due to the effect of undulate surface. During that period the soil water almost moved upward for evaporation from surface soil and then the salts and heat also moved with soil water movement.

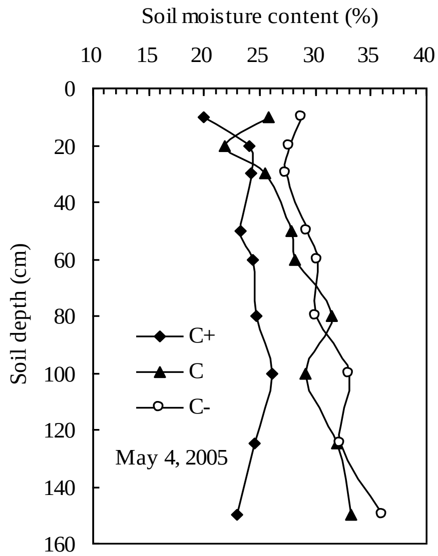

Figure 3 Variations of soil moisture content in different depths at C+, C and C−site

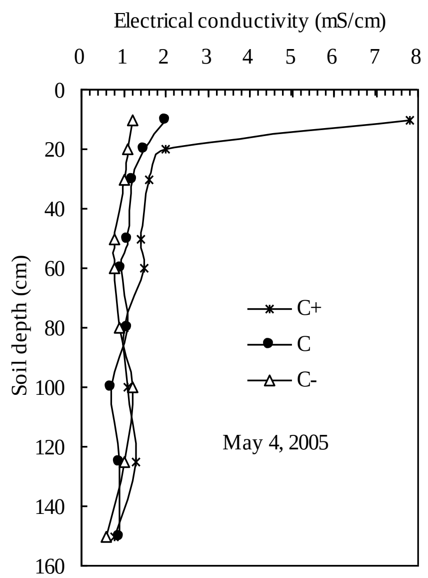

Figure 4 Variations of $EC_{1:5}$ in different depths at C+, C and C−site

The curves in the Figure 4 show the resulting change in $EC_{1:5}$ values with soil depth. The $EC_{1:5}$ values in surface layers were significantly higher than deeper depth and decreased with increasing soil depths, which shows that the accumulation of salt occurred at the surface and sub-layer soil, especially, in soil surface layer had highly significant. The Cv of $EC_{1:5}$ in soil layers at C+, C, and C− sites were 0.58, 0.62, and 0.37 respectively. Because this soil had been idle and not irrigated losing chances for leaching for many years, the lateral infiltration of salt was occurred and accumulated on the top of soil due to intensive evaporation. The result is similar with Akae et al. (2004) who found that, especially, for surface layer from 7.5 cm to 2.5 cm depth the salt concentration had rapidly increasing in saline soil.

Figure 4 also indicates that there are two different parts distinguished in salt profiles at the three sites. The $EC_{1:5}$ values from 0 cm to 80 cm depth are in order of C+>C>C− and then from 80 cm to 150 cm layers the $EC_{1:5}$ values are not significantly different at spring season. The maximum value of $EC_{1:5}$ was 7.8 mS/cm occurred the surface soil at C+ site higher than other two sites on elevation, indicates that the trend of salt moved to the surface layer of C+ site starting from the 80 cm layer at spring return salt season.

Figure 3 and 4 show the water-salt distribution at three sites. At spring salinity return season, the soil water distribution in each soil profile at C+, C, and C− sites showed not significant difference. However, the distribution of $EC_{1:5}$ for each soil depth showed significant difference from 0 cm to 80 cm depth in spring.

3.2 Soil temperature and heat flux

3.2.1 Soil temperature variations with time and depth

Soil temperature and its variation with time and depth will be greatly influenced by surface cover and by the thermal properties of undulating ground, like soil water content and so on. The fluctuation of the temperature is affected mainly by variation in solar radiation, as well as the influences of geographic location.

The variation in solar net radiation and soil temperature with time at topsoil in C+, C, and C− sites respectively are shown in Figure 5. The fluctuation in soil temperature responding to solar net radiation is simulated by a sine wave.

Figure 5 shows that diurnal soil temperature at topsoil in the C+, C, and C− sites during the spring. In the morning before sunrise, the soil temperature of surface was lowest and increased with depth. Because of the time lag associated with heat flow when the surface and subsurface temperature are changing, the lower depths continue to cool for a period of time.

From figure 5 we can also see that the amplitude of wave decreases with depth and has a phase shift which increases with depth. The amplitude of variation in wave is significantly occurred at topsoil in C+ and C sites but is not significantly large at relatively low elevation C− site, which was mainly caused by the different soil water content at topsoil profiles. Because the different soil water content resulted to the different thermal properties in the three sites and then caused the different thermal conductivity. Consequently, the different heat flows were occurred in C+, C, and C− sites.

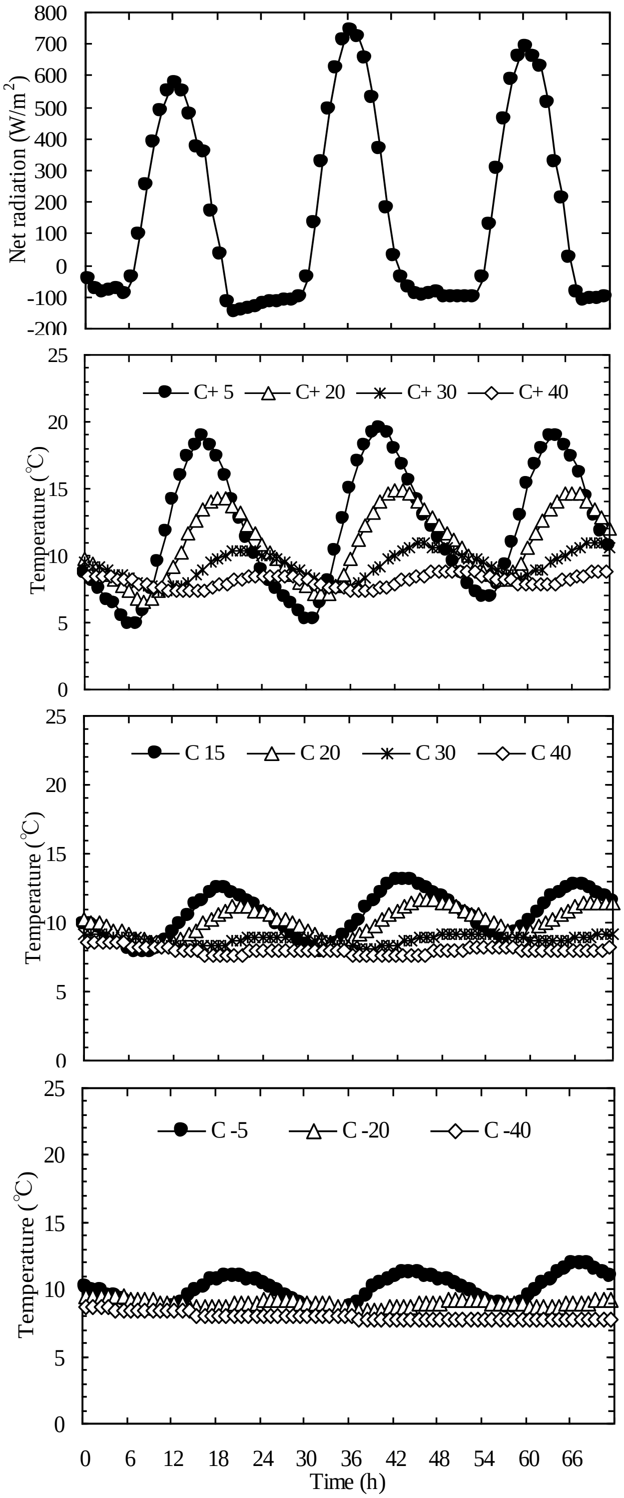

Figure 5 Changes in net radiation and soil temperature at topsoil in the three sites with times from 5 to 6 May, 2005

3.2.2 Soil temperature model description

When the heat is simply transferred by conduction, it is described by following partial differential equation (1) (Hillel, 1980).

$$\frac{\partial T}{\partial t} = D_T \frac{\partial^2 T}{\partial z^2} \tag{1}$$

where T is soil temperature, $D_T=\lambda/C_{soil}$ is the thermal diffusivity, t is time , and z is soil depth.

In equation (1), the boundary condition is z=0. For the sake of convenience, we assume that at infinite depth ($z\to\infty$) the temperature is constant and equal to $\overline{T}$. The temperature at the surface and infinite depth can be expressed respectively as equations (2) and (3).

$$T(0,t) = \overline{T} + A_0 \sin \omega t \tag{2}$$

$$T(\infty,t) = \overline{T} \tag{3}$$

We can estimate soil temperature by solving equation (1) with the boundary conditions (2) and (3), obtained following analytical solution shown by equation (4).

$$T(z,t) = \overline{T} + A_0\left[\sin(\omega t - z/d)\right]/e^{z/d} \tag{4}$$

where T(z, t) is the soil temperature at time t (h) and soil depth z (cm), is the average soil temperature (℃), A0 is the hourly amplitude of the surface soil temperature (℃), d is the damping depth (cm) of hourly fluctuation.

The damping depth is defined as equation (5).

$$d = (2D_T/\omega)^{1/2} \tag{5}$$

where D_T is the thermal diffusivity and $\omega=2\pi/24h^{-1}$ is the radial frequency, in the case of daily variation the period is 24 hours.

From equations (2) and (4) it can be seen that the A_0 is a constant regardless of how the change of depth takes place, so we can write the amplitude at arbitrary depth as following equation (6).

$$A(z) = A_0 \exp(-z/d) \tag{6}$$

By rearranging the equation (6) and taking logarithm on both sides, then lead to equation (7).

$$LnA(z) = Ln(A_0) - z/d \tag{7}$$

Basing on the model and above conditions, we implemented the regression line between the logarithm of amplitude and soil depth as shown Figure 6.

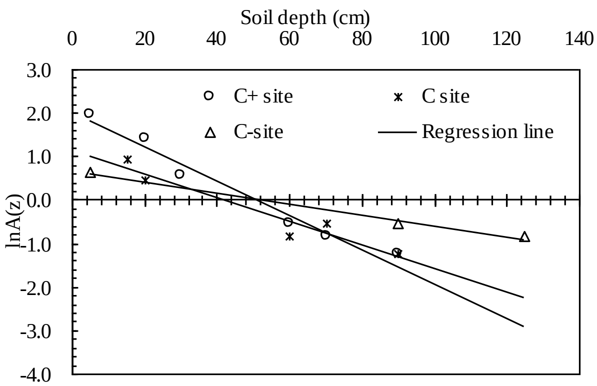

Figure 6 Regression line between the logarithm of amplitude and soil depth

As the Table 2 shows that the correlation coefficient (R) between the logarithm of amplitude and the soil depth is 0.98 in C+ site, 0.96 in C site, and 0.99 in C− site, respectively. These results indicate that the logarithms of amplitude values are mainly correlated with soil depth.

Table 2 Parameters of regression equation

Site	Correlation coefficient	Amplitude	Damping depth
	R	A_0(℃)	d (cm)
C+	0.98	2.02	25.51
C	0.96	1.14	37.04
C−	0.99	0.66	80.00

In addition, we obtained that the thermal parameters in studied sites as shown in Table 3.

Table 3 Thermal parameters in model

site	Amplitude in surface	Volumetric water content*	Volumetric heat capacity*
	A_0(℃)	θ(cm^3/cm^3)	C_s (cal/cm^3·℃)
C+	7.57	0.36	0.91
C	3.12	0.43	1.04
C−	1.94	0.43	1.07
site	Damping depth	Thermal diffusivity	Thermal conductivity*
	d (cm)	D_T(cm^2/s)	λ (cal/cm·s·℃)
C+	25.51	0.02	0.02
C	37.04	0.05	0.05
C−	80.00	0.23	0.25

*Average values given

Basing on these parameters above, this study presents the diurnal change in temperature measured and calculated values from May 5 to 7, 2005 at topsoil in C+, C, and C− sites, respectively as shown in Figure 7.

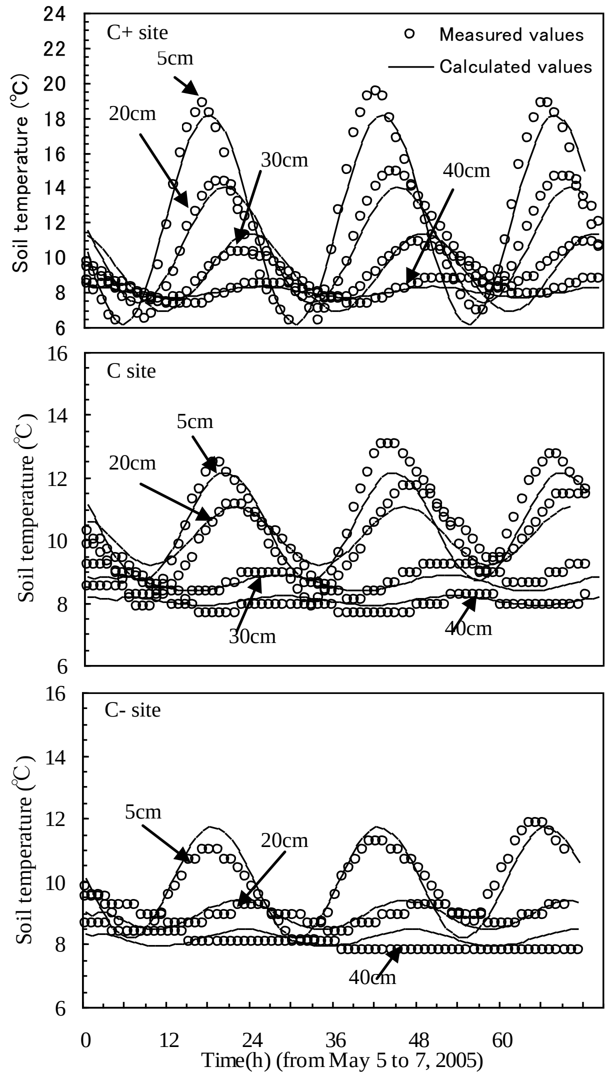

Figure 7 Diurnal variations in temperature at topsoil measured and calculated at C+, C, and C− site

Figure 7 compares the diurnal variations in temperature measured and calculated by analytical solution at topsoil in C+, C, and C− sites. From this figure it can be seen that the model has good agreement with the observed diurnal variations in temperature for the surface layer of C+, C sites, but not so good for C− site. The fitting of soil temperature calculated and measured decreases with depth. On the whole, the fitting occurred at surface soil and the fitness is in the order of C+>C>C−.

The amplitude parameters in the model were obtained from measured diurnal change in temperature as shown in Figure 8. It shows the amplitude of wave decreases with soil depth. The amplitude decreases rapidly from surface to 30 cm in C, C− sites and to 40 cm in C+ site and then the variations in amplitude is not significant with further increasing soil depth.

The figure 8 can also indicate that the distribution of soil temperature is different at soil profile in the three sites due to the lag of amplitude of temperature wave as shown Figure 5 and 7. These reasons maybe due to the lag of temperature wave transport in soil.

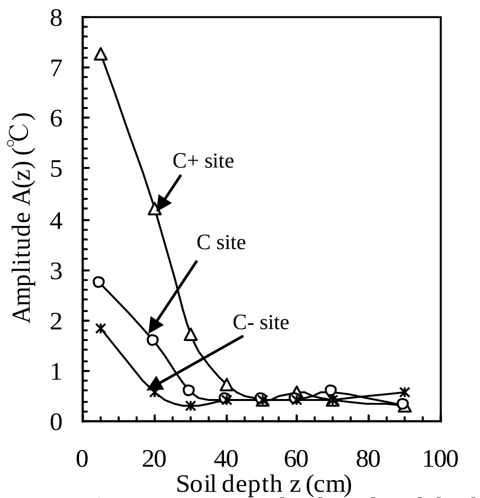

Figure 8 Variations in amplitude with soil depth in C+, C, and C- sites

3.2.3 Soil heat flux

In this study, we used the Fourier's law to calculate the soil heat flux in the vertical direction representing soil depth as following equation (8).

$$q_h = -\lambda \frac{dT}{dz} \tag{8}$$

where q_h is soil heat flux (cal/cm^2·s), $\lambda = D_T \cdot C_{soil}$ is thermal conductivity (cal/cm · s · ℃), T is soil temperature (℃) and z is soil depth (cm). The soil heat capacity (C_{soil}) is given (De Vries, 1963).

$$C_{soil} = 0.48 f_m + 0.60 f_o + f_w \tag{9}$$

where subscripts *m*, *o*, *w* refer to mineral matter, organic matter, and water volume fraction.

We calculated the soil heat flux in a day (May 5, 2005) basing on measured daily average soil temperature as shown in Figure 9, which shows that the variation in soil heat flux with depth in C+, C, and C− sites. The variation range of the soil heat flux is almost in the order of C+>C>C−. For example, the heat flux is from 0.04 to 0.13 cal/cm^2·s at 20 cm to 40 cm depth in C+ site; from 0.03 to 0.11 cal/cm^2·s at 20 cm to 40 cm depth in C site; from 0.03 to 0.04 cal/cm^2·s at 20 cm to 40 cm depth in C− site. From figure 8 it can be also seen that the variations in thermal conductivity is not significant in whole profile due to relatively high water content in C− site. The temperature gradients in the three sites is the order of C+>C>C−.

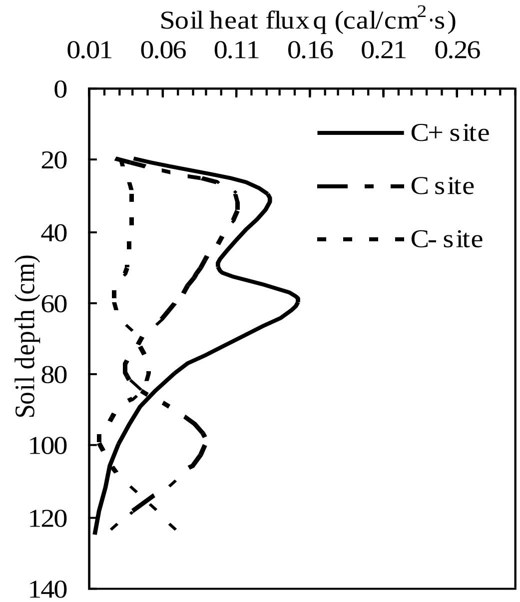

Figure 9 Variation in soil heat flux with depth in C+, C, and C- sites

However, the maximum heat flux is occurred at subsurface in C+ site, the minimum is at the subsurface in C− site. The reasons are that the different soil water content at subsurface results to the different evaporation from surface soil and the heat is easily diffused to atmosphere in relative high soil water content. Therefore, in relatively high water content condition, the heat transport is not significant, on the contrary in lower water content status, the heat transport is significant which also indicates the effect of temperature gradients on water movement is not so significant.

We can explain the above phenomenon basing on the movement of soil water and thermal energy in soil are interactive and coupled effect. The soil temperature gradients influence the soil water potential and then moisture gradients move water which carries heat and salt. The combined transport of heat and water can generally be ignored in the extreme cases of a relatively wet and a nearly dry soil. When soil is relatively wet the influence of temperature gradients on water flow is generally small in comparison with the influence of moisture gradient; when soil is relatively dry the heat flow can influence on significant movement of water. In C− site the soil water content was relatively higher the heat energy was quickly diffused to atmosphere from surface soil, which resulted to the relatively low temperature occurred in

C− soil profiles as shown in Figure 7. However, in C+ site the soil water content was relatively lower the movement of water almost was not influenced by temperature gradients, most of heat was stored in surface soil profile, which resulted to the relative high soil temperature occurred at subsurface in soil as shown in Figure 5 and 7. This can explain why in the soil profile of a dry soil exhibits relatively high temperature and in that moist soil exhibits low temperature.

Due to soil water content in topsoil profiles was different that made the different evaporation occurred in the three sites and then resulted to the different salt accumulation as shown in Figure 4. The C site is located between C+ and C− sites, belongs to general case that need to study and explain in more detail in the future.

4. Conclusion

By analysis of studied data about soil water-temperature-salt distribution at three sites, the results are revealed as following:

1) Basing on measured data in soil revealed the distribution in soil profiles water content was in order of C−>C>C+ and in soil temperature was in order of C+>C>C−,and then in salt was in order of C+>C>C− at spring season, respectively.

2) By using the soil temperature model to calculated the thermal parameters (Thermal diffusivity D_T in C+, C, and C−site is 0.024, 0.049, and 0.233 cm^2/s; the thermal conductivity is 0.022, 0.051, and 0.246 cal/cm·s·℃, respectively) and also indicated that has a very good agreement with measured values in the diurnal temperature for the low soil moisture content in C+, C site, but not so good for relatively higher soil moisture content in C− site due to the effect of undulate surface on the distribution of soil water content at the three soil profiles.

3) Basing on the movement of soil water and thermal energy in soil are interactive and coupled effect to further explain the variation in soil water and heat flux in the C+, C, and C− site. Only in lower water content status the heat transport in soil is significant. On the contrary in relatively high water content condition the heat transport is not significant which also indicates the effect of temperature gradients on water movement is not so significant.

These results suggest that in arid area like Hetao Irrigation District, China, water loss by evaporation should be reduced for preventing salt from accumulating on soil surface or rooting zone hazarded to seed germination and growth at the spring.

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Correspondence to:

Zhu Xue

Graduate School of Environmental Science, Okayama University, 1-1, Naka 3-chome, Tsushima, Kita-ku Okayama 700-8530, Japan

Telephone: 081-090-4100-7258

Emails: xuezhu_okayama@yahoo.com

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