The annual evaporative demand of arid and semiarid regions near Xinjiang in northwest China exceeds 2000 mm whereas annual precipitation is less than 200 mm (Yearbook of water conservation for Xinjiang, China, 2001). Thus, a great need exists in the area to make efficient use of all agricultural water.

Plastic mulch cultivation, a management practice, is a cropping system feature for water saving that is used extensively in arid and semiarid areas of northwest China. When evaporative demand is fairly strong, film mulching can greatly reduce soil water evaporation. However, research on water flow beneath and through various open hole ratios of the perforated film mulches is limited, and questions concerning soil water flow and soil heat transfer for this type of water-saving system remain unanswered. It is, therefore, very important to perform research on soil water evaporation and soil temperature distribution with various open hole ratios of the perforated plastic mulches. A series of soil water evaporation experiments using different open hole ratios of perforated plastic mulches was conducted. The columns received mulches with various open hole ratios: 0% (covered with a solid plastic mulch), 1.39%, 2.84%, 7.24%, 30.5%, and 100% (nonmulched bare surface). In conjunction with the water movement of evaporation from film hole studies, soil temperature distributions were also analyzed. Our measurements indicated that film hole mulch had a restraining effect on evaporation and that the restraining effect decreased with the increase in open hole ratios. Compared with bare soil evaporation, the percentage of evaporation reduction rates for open hole ratios of 0%, 1.39%, 2.84%, 7.24%, and 30.5% were 69.26%, 33.09%, 22.80%, 20.05%, and 11.82%, respectively. The results showed a linear relationship between cumulative water evaporation and square root of time for the different open hole ratios of the perforated plastic mulches, and the coefficients of the linear function, i.e., the C parameters, were fitted well with the open hole ratios—u(C = 0.0101u0.1019 + 0.0075). On this basis, mathematical relations of relative evaporation rate and evaporation based on hole areas of perforated plastic mulches were analyzed and discussed. These results extend the Gardner evaporation equation to bare soils to include water evaporation from soils covered by various perforated plastic mulches. The resulting equations presented in this paper provide an approach for describing evaporation from plastic mulch-covered soil. (Soil Science 2003;Volume 168:000–000)

Key words: Evaporation, irrigation, mulching, water conservation.
technique used in recent years, has been applied extensively in arid and semiarid regions in China. The use of plastic mulch cultivation to reduce soil water evaporation and increase early spring soil temperature has demonstrated great potential in arid and semiarid regions. At the same time, irrigation methods corresponding to the plastic mulch practices have also been developed. These methods include plastic mulch irrigation through open holes in the perforated plastic films, trickle irrigation under the plastic films, and lateral film irrigation. According to the 2001 statistical data of Xinjiang, the plastic mulch cultivation area has been extended to 1.4 million ha, of which, the total plastic mulch irrigation area is 670,000 ha (Yearbook of water conservation for Xinjiang, China, 2001). To support plant emergence and irrigation water distribution, the plastic mulch must be perforated. A critical parameter for effective use of perforated plastic mulches is the open hole ratio of each plastic mulch, i.e., the area of opened holes over the total area of the plastic mulch. Topics that require further research are (i) the measurement and (ii) the estimation of perforated plastic mulch open hole ratios on soil water evaporation. Plastic mulches can also increase soil temperature, and the increase in soil temperature can cause changes in soil water distribution (Meng and Jian, 1993). Thus the coupled transport of water and heat in soils should be researched in order to understand the fundamental features of soil water evaporation with different open hole ratios of plastic mulch.

Research regarding bare soil water evaporation has been conducted by experimental methods, theoretical analysis, and numerical calculation (Bachmann et al., 2001; Black et al., 1969; Brisson and Perrier, 1991; Fritton et al., 1970; Gardner, 1959; Gardner and Gardner, 1969; Reynolds and Walker, 1984; Lascano and van Bavel, 1986; Milly, 1984; Munley and Hipps, 1991; Philip, 1957; Suleiman and Ritchie, 2003). The evaporation equation for bare soils developed by Gardner (1959) is one of the most popular equations for calculation of soil water evaporation. Gardner (1959) solved the Richards equation based on an exponential relationship between soil water diffusivity and soil water content. He found that cumulative evaporation was a linear function of the square root of time. The relationship can be expressed as follows (Black et al., 1969; Gardner, 1959; Reynolds and Walker, 1984):

$$E = Ct^{1/2}$$

Where $E$ is cumulative water evaporation from the soil surface, cm; $C$ is a coefficient related to characteristics of soil; and $t$ is time in minutes.

Water evaporation from mulched soil has been reported in some papers. Chung and Horton (1987) developed a numerical model using the alternating direction implicit (ADI) finite difference method to study two-dimensional coupled soil heat and water flow with partial surface mulching. Mahrer et al. (1984) studied one-dimensional heat and water flow when a transparent polyethylene mulch covered the entire soil surface. However, the influence of open hole ratios of perforated mulches on soil water evaporation has not been evaluated.

The objective of this research was to perform a series of soil water evaporation experiments using different open hole ratios of perforated plastic mulches. The influence of open hole ratios of plastic mulch on soil temperature, soil water content distribution, and cumulative evaporation were analyzed, and an equation extending the Gardner evaporation equation was developed.

**MATERIALS AND METHODS**

To analyze the effects of open hole ratios of the perforated film mulches on soil water evaporation, a series of experiments was performed in 2001. There were three replicates for each treatment. A one-dimensional vertical evaporation experiment system was set up, as illustrated in Fig. 1. Each column consisted of vacuum-insulated Plexiglas. The soil columns were packed with silt loam soil (classified in China as Grey Desert Soil) collected from a 10-cm-thick surface layer of a field in Xinjiang, China. The particle-size distribution of the test soil was determined using the pipette method (Gee and Bauder, 1986). The results showed that the contents of clay, silt, and sand in the soil were 113, 543, and 344 g kg$^{-1}$, and the soil texture was classified as silt loam (China system). After air drying and sieving through a 2-mm screen, the soil was wetted to a volumetric soil water content of 0.23 m$^3$ m$^{-3}$. The columns were packed with the moistened soil, layer-by-layer, to a designed bulk density of 1.45 g cm$^{-3}$. Various transparent 0.05-mm-thick plastic films were placed as mulch on the soil column surface. Different columns received mulches with different open hole ratios, e.g., 0% (covered with a solid plastic mulch), 1.39%, 2.84%, 7.24%, 30.5%, and 100% (nonmulched bare surface). On the perforated plastic mulches, the holes were distributed uniformly and hole sizes ranged from 1
to 5 mm in diameter. A heating system consisting of an incandescent light source was fixed at a height of 22 cm above soil column surfaces in order to provide a steady heating source to drive soil water evaporation. Each soil column was heated for 240 h. During the heating period, a \(^{137}\text{Cs}\) gamma ray apparatus (Shen et al., 1991) and \(\text{Cu}_{50}\) temperature transducers (made in China) were used to measure soil water content and temperature, respectively. The measurement interval for soil water content was 60 min, and the measurement interval for soil temperature was every 5 min at the beginning of heating and every 120 min near the end of the heating period. Compared with the oven drying method, the gamma ray equipment is about 99% accurate (the relative error is 1%). The measurement range of the temperature transducers is 0 to 100 °C, with an accuracy of ±0.1 °C. The cumulative soil water evaporation from each column was determined as the difference in soil column water content as a function of time. In order to prevent unwanted ambient temperature fluctuations, all of the soil columns were placed in a constant temperature room (26 °C) during the evaporation experiments.

**RESULTS**

**Column Soil Temperature**

Soil temperature is an important factor influencing crop growth. One reason for using plastic mulch cultivation is to provide a favorable soil temperature. Our experimental set-up provided heat to the upper surfaces of soil columns, thus producing maximum temperatures at the surfaces and minimum temperatures at the bottom of the soil columns. In general, the differences between soil temperatures under the perforated mulches with different open hole ratios was not large. At the start of the experiment, the soil temperature beneath the plastic mulches increased more rapidly than did the bare soil. Figure 2 indicates that changes in the soil temperature distributions...
were larger during the first 4 days than for the last 6 days. Figure 3 shows the final (after 10 days of heating) soil temperature distributions for the soil columns covered by mulches with different open hole ratios. Maximum temperatures at the surface of the bare soil column and at the soil surface of the column with nonperforated plastic mulch cover were 57.8 °C and 63.3 °C, respectively. The soil temperature was closely related to the open hole ratio of the surface mulch. The smaller the open hole ratio the greater the soil temperature.

Exponential functions were fitted to the measured soil temperature distributions in each soil column. Equation (2) shows the relationship of the final temperature with soil depth for columns mulched at different open hole ratios after 10 days of heating. The function is written as follows:

\[ T = A e^{-Bz} \]  

(2)

The temperature gradients can be calculated from the derivatives of the exponential functions

\[ \frac{dT}{dz} = \text{Grad}(T) = -AB e^{-Bz} \]  

(3)

where \( T \) is soil temperature, °C, \( \frac{dT}{dz} = \text{Grad}(T) \) is temperature gradient, °C cm\(^{-1}\), and \( z \) is soil depth/cm. The \( A \)-parameters, \( B \)-parameters, and coefficient of determination values–\( R^2 \) from fits of Eq. (2) to the measured data for different open hole ratios are listed in Table 1. In Table 1, the large coefficients of determination show that the exponential function describes the final (10 day) soil temperature distribution accurately. Both \( A \)-parameter and \( B \)-parameter decrease as the open hole ratio increases, but differences among the soil columns are small.

**Soil Moisture**

Soil water content in the upper portion of the soil columns decreased as heating time increased, and the largest decrease of soil water content occurred at the surfaces of the soil columns. Measured soil water content distributions with time for the nonmulched, open hole ratio of 100% soil column are shown in Fig. 4.

During heating, the rate of soil water evaporation decreased as the time of heating increased. Soil water evaporation rates also decreased as the perforated mulch open hole ratios decreased.
Compared with bare soil evaporation, the percentage of evaporation reduction rates for open hole ratios of 0%, 1.39%, 2.84%, 7.24%, and 30.5% were 69.26%, 33.09%, 22.80%, 20.05%, and 11.82%, respectively. Figure 5 shows the final soil water content distributions for the different mulch open hole ratios at the end of the evaporation experiment. The smaller the open hole ratio, the larger the soil water content to the same depth, especially in the upper layer. The effect of open hole ratio was most pronounced near the soil surface.

As a result of surface water evaporation, the soil water content in all six surface mulch columns was less than the initial water content. A small amount of water was lost by evaporation even from the soil column that had its surface covered by nonperforated plastic mulch as a small amount of water vapor exited the soil column by moving around or through the nonperforated plastic mulch.

**Cumulative Evaporation**

The measured cumulative soil water evaporation values for the six open hole ratios of plastic mulch were analyzed, and Fig. 6 shows the cumulative evaporation versus square root of time. The results indicated that cumulative evaporation for different open hole ratios of plastic mulch

**TABLE 1**

The $A$-parameter, $B$-parameter, and coefficients of determination ($R^2$) for fitted exponential functions of soil temperature distributions as well as the slopes $C$ and coefficients of determination values ($R^2$) for linear fits of cumulative evaporation versus square root of time for soil columns covered by mulches of various open hole ratios.

<table>
<thead>
<tr>
<th>Open hole ratio (%)</th>
<th>0</th>
<th>1.39</th>
<th>2.84</th>
<th>7.24</th>
<th>30.5</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>29.0</td>
<td>26.8</td>
<td>25.0</td>
<td>23.6</td>
<td>23.0</td>
<td>22.7</td>
</tr>
<tr>
<td>$B$</td>
<td>0.0389</td>
<td>0.0382</td>
<td>0.0377</td>
<td>0.0370</td>
<td>0.0368</td>
<td>0.0366</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.95</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>$C$</td>
<td>0.0075</td>
<td>0.0182</td>
<td>0.0190</td>
<td>0.0192</td>
<td>0.0214</td>
<td>0.0243</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.98</td>
<td>0.99</td>
<td>0.99</td>
<td>0.98</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>$C$-0.0075</td>
<td>0.0</td>
<td>0.0107</td>
<td>0.0115</td>
<td>0.0117</td>
<td>0.0139</td>
<td>0.0168</td>
</tr>
</tbody>
</table>

Fig. 4. Soil water content distributions vs heating time in a soil column with a bare surface (open hole ratio of 100%).

Fig. 5. Soil water content distributions after 10 days of heating for soil columns covered with perforated plastic mulches with different open hole ratios (OR: open hole ratio).
were linear functions of square root of time. Equation (1) was used to fit the measurements, with the results shown in Table 1. Coefficients of determination, $R^2$, exceeded 0.96 for all six treatments. These results indicate that the Gardner (1959) equation can be used to describe not only bare soil water evaporation but that it can be extended to describe soil water evaporation in the presence of surface mulches.

Because there was a small amount of evaporation, the $C$-parameter from Eq.(1) did not have a value of zero for the soil column covered by nonperforated plastic mulch. For soil columns covered by perforated plastic mulches, we can assume that most of the evaporation occurred through the holes in the plastic, but, similar to the column with nonperforated plastic mulch, some of the evaporation from the columns covered with perforated plastic occurred via pathways around and through the plastic. To compare soil water evaporation among all of the mulch treatments the values of $C$ and the differences in values of $C$ for the open hole ratio of 0%($C-0.0075$) were calculated, and the results are listed in Table 1.

The analysis of cumulative evaporation with Eq. (1) indicates that the open hole ratio affects only a single parameter, $C$. In order to view the relation of the $C$-parameter to the open hole ratio, we present the following fitted function:

$$C = 0.0101u^{0.1019} + 0.0075 \quad R^2 = 0.951 \quad (4)$$

where $u$ is the open hole ratio, %. When $u$ is set equal to zero, the $C$-parameter equals the value from the soil column covered by a nonperforated plastic mulch, and when $u$ is set equal to 100, the $C$-parameter represents bare soil evaporation.

Combining Eq. (4) with Eq. (1) gives the following relationship:

$$E = (0.0101u^{0.1019} + 0.0075)t^{0.5} \quad (5)$$

Equation (5) indicates that cumulative soil water evaporation varies with open hole ratios and evaporation times.

By differentiating Eq. (5), soil water evaporation rates for different open hole ratios can be obtained as follows:

$$e = (0.0051u^{0.1019} + 0.0038)t^{-0.5} \quad (6)$$

where $e$ is soil water evaporation rate, cm min$^{-1}$. Figure 7 shows evaporation rates from soil
columns with various open hole ratios. Note that the column with an open hole ratio of zero (non-perforated plastic mulch) had noticeably smaller evaporation rates than did the other open hole ratios.

Relative Evaporation

The cumulative soil water evaporation for the column with an open hole ratio of 100% demonstrates the characteristics of evaporation without mulch. For any given soil, the evaporation without mulch is relatively easily determined by experiment. In order to discuss the influence of perforated plastic mulches on evaporation, the ratio of cumulative soil water evaporation with different open hole ratios to the cumulative soil water evaporation with 100% open hole ratio is defined as the relative evaporation, \( E_r \). \( E_r \) is a dimensionless value calculated by the ratio of the \( C \)-coefficient for each different open hole ratio to the \( C \)-coefficient for the 100% open hole ratio. Letting \( C \) and \( C_{100} \) represent the \( C \)-coefficients of different open hole ratios and of the 100% open hole ratio, respectively, then \( E_r = C/C_{100} \). \( E_r \) for different open hole ratios from 0 to 100% can be calculated based on experimental data, as shown in Table 2.

It is obvious that \( E_r \) is a function of open hole ratios. For the particular soil used in this study, \( E_r \) may be expressed as

\[
E_r = C/C_{100} = 0.416u^{0.1019} + 0.309 \quad R^2 = 0.951
\]

(7)

Where the constant 0.309 corresponds to \( E_r \) when the soil surface is covered entirely. From Eq. (7), the \( C \)-coefficient for any open hole ratio used on this soil is

\[
C = (0.416u^{0.101} + 0.309) C_{100}
\]

(8)

Correspondingly, the cumulative soil water evaporation for any open hole ratio is

\[
E = (0.416u^{0.1019} + 0.309) C_{100}^{0.5}
\]

(9)

Final (10 days) Cumulative Evaporation Based on the Area of Open Holes in the Perforated Plastic Mulches

The analysis has thus far been based on the concept that evaporation is the volumetric loss of soil water divided by the soil surface area. For the soil columns covered with perforated plastic mulches, the primary route of evaporation of the soil water was through the holes in the plastic. Another way we can analyze our evaporation data is to divide the cumulative evaporation by the area of open holes in the mulches. We can define final (10-day) cumulative evaporation per unit of open hole area, \( E_R \), as the ratio of cumulative evaporation of any perforated plastic mulched soil column to total area of opened holes. The \( E_R \)-values of the perforated plastic mulch treatments were calculated, and the results are presented in Fig. 8.

Figure 8 shows that \( E_R \) decreases as the open hole ratio increases. In other words, the average evaporation rate per unit of open hole area decreases as the open hole ratio increases. One main reason for this result is that upper boundary conditions of soil water evaporation differ, and the continuous properties between soil and atmosphere change correspondingly when the soil surface is covered with different perforated plas-

<table>
<thead>
<tr>
<th>Open hole ratio (%)</th>
<th>0</th>
<th>1.39</th>
<th>2.84</th>
<th>7.24</th>
<th>30.5</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_r )</td>
<td>0.309</td>
<td>0.749</td>
<td>0.782</td>
<td>0.790</td>
<td>0.881</td>
<td>1.00</td>
</tr>
</tbody>
</table>
tics. The open holes in the mulch provide direct pathways between soil and air, from which soil water exits during evaporation. When the area of holes is small, the water vapor can freely spread laterally as it exits the holes. Because of the lateral movement of the water vapor, the evaporative flux per open hole area is greatest from the plastic mulch with the smallest open hole ratio. In other applications, the effect of perimeter on mass flux has been called the “chimney effect”. Here we refer to the variations of $E_R$ as the “film hole effect”. The film hole effect has mechanics similar to those of the chimney effect. Mass flux can also be connected with the hole radius, i.e., the smaller the radius, the more the perimeter affects mass movement. When the hole radius is very small, the $E_R$ is very large.

A power function relationship describes $E_R$, as follows:

$$E_R = 201.84u^{-0.9246} \quad R^2 = 1.00$$

(10)

CONCLUSIONS

The results of soil temperature variations in evaporation showed that the soil temperature was closely connected to the open hole ratio of the surface mulch, and the smaller the open hole ratio, the larger the soil temperature. These studies on soil water evaporation with plastic mulch indicated that the cumulative soil water evaporation for different open hole ratios was related linearly to the square root of time, which corresponded to the theory of Gardner (1959) for bare soil evaporation. On this basis, mathematical relations of relative evaporation rate and evaporation based on hole areas of perforated plastic mulches were analyzed and discussed. Our measurements indicated that film hole mulch had a restraining effect on evaporation and that the restraining effect decreased with the increase of open hole ratios.

ACKNOWLEDGMENTS

This work was funded by the China National Natural Science Foundation (Project Nos. 40025106 and 90102012) and is the key project of ecological and environmental research resources of the Chinese Academy of Sciences (Project No. KZCX2—411). Support was also provided by the Iowa Agriculture and Home Economics Experiment Station, Ames, IA (Project No. 3287) and, in part, by Hatch Act and State of Iowa funds.

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