Journal of Hydrology 519 (2014) 1908–1913

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Influence of gravel mulch stratum thickness and gravel grain size on evaporation resistance

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ARTICLE INFO

Article history:
Received 7 February 2014
Received in revised form 26 September 2014
Accepted 30 September 2014
Available online 17 October 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Gokmen Tayfur, Associate Editor

Keywords:
Evaporation
Gravel mulch
Loess Plateau
Resistance
Water vapor transfer

SUMMARY

In the Loess Plateau of northwestern China, a system for dry farming has evolved based on the employ of gravel mulch. A couple of lab experiments were conducted to study the influences of mulch stratum thickness and gravel grain size on water vapor flow, with a focus on resistance to evaporation in gravel mulch stratum. In Experiment 1, six treatments included mulching with gravel of different thickness (2 cm, 4 cm, 6 cm, 8 cm and 10 cm) plus no mulching (control) were studied. In Experiment 2, the 10 cm thick mulch layer consisted of different grain size gravel [2–5 (A), 5–20 (B), 20–40 (C), 40–60 (D) and 60–80 (E) mm], plus three mixture treatments. Compared to bare soil, mulched soils had significantly lower accumulated evaporation, and gravel mulch significantly increased resistance to evaporation. The aerodynamic resistance to evaporation in bare soil is higher than that in mulched treatments and the relationship between equivalent grain size and aerodynamic resistance in mulched surface can be described by a line function. The relationships between mulch resistance and mulch stratum thickness or grain size of gravel, were represented by logistic curves. The findings showed that equivalent grain size and specific surface area of gravel were sensitive indicators of mulch resistance. Based on the results of laboratory experiments, we put forward a new calculated model of mulch resistance, but further research is needed for verification and exact parameterization of this model under field conditions.

1. Introduction

In the northwestern Loess Plateau, the mean annual precipitation ranges between 250 and 350 mm, and over 70% of the precipitation occurs between June and September (Li et al., 2001). The rainy seasons usually do not coincide with growth stages for most crops and the mean annual pan evaporation ranges from 1500 to 2000 mm. Farm fields mulched with gravel has been used for more than three hundred years in this region due to its effectiveness in reducing evaporation, improving infiltration and increasing soil temperature (Nachtergaele et al., 1998; Xie et al., 2006, 2010). A porous layer of gravel about 10 cm thick that lies on the soil surface lessens the risk of crop failure, which frequently occurs due to a combination of low precipitation and high evaporation that creates severe soil moisture deficits. This technique has been promoted and widely adopted due to the lack of sufficient water or high irrigation costs. The gravel mulched fields are mainly distributed in the west of the Loess Plateau, which first developed in the middle part of Gansu Province and gradually introduced into neighboring provinces such as Ningxia Hui Autonomous Region and Qinghai Province. By the late 1990s, 118,000 ha of fields with gravel mulch were distributed in Gansu Province and 66,000 ha of such fields were distributed in Ningxia Hui Autonomous Region. The effect on the resistance to evaporation is the most important function of gravel mulch. Although previous studies (Mellouli et al., 2000; Rasiah et al., 2001; Ma and Li, 2011) have reported a lot of determinations or comparisons about evaporation and pointed out that gravel mulch can reduce evaporation markedly compared to un-mulched soil, they did not find suitable parameters and a reliable model to calculate or simulate the evaporation in gravel mulch fields. Yamanaka et al. (2004) defined r_t as the gross resistance to evaporation from evaporating surface to an arbitrary level in the air, and evaporation rate is computed by an analogy of Ohm's law. They confirmed the gross resistance over soil surface to evaporation did not rely on gradient of temperature (i.e. atmospheric stability condition) and increased exponentially with the effective mulch thickness (i.e. the depth from the soil surface). However, previous results were difficult to be applied in practice due to a lack of attention about other parameters and studies about resistance to evaporation in the mulch stratum received little attention. To understand the mechanisms of the

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http://dx.doi.org/10.1016/j.jhydrol.2014.09.085
0022-1694/

evaporation reduction by using gravel mulch is of practical significance in optimization of gravel mulch stratum and properly evaluation the effectiveness of gravel mulch. The major objectives of this study were: (1) quantify resistance to evaporation in mulch stratum through parameterization of gravel mulch layer structure; and (2) to put forward a model of mulch resistance using the parameters obtained, thereby make the simulation and estimation of the evaporation in gravel mulch fields possible.

2. Analytical approach

Evaporation rate is computed by Eq. (1) (Yamanaka et al., 2004).

$$E = \frac{\rho_\alpha[q_{sat}(T_e) - q_{sat}(T_a)h_a]}{r_t} \tag{1}$$

where ρ_a is the air density (kg/m^3), T_e and T_a are the temperature of evaporating surface (°C) and the air temperature (°C) respectively, h_a is the relative humidity, $q_{sat}(T)$ is the saturation specific humidity (kg/kg), r_t is the gross resistance to evaporation from evaporating surface to an arbitrary level in the air (s m^{-1}).

In our experiments, the total resistance r_t from soil surface is the totality of resistance in the air r_a (called as "aerodynamic resistance"), resistance of soil r_s (called as "soil surface resistance") and resistance within the mulch stratum r_m (called as "mulch resistance"), that is,

$$r_t = r_a + r_m + r_s \tag{2}$$

In our experiments, the soil in Box-B are saturated by water, r_t equals to r_a plus r_m because of $r_s = 0$. If E, T_a, h_a, and T_e are all known, r_m can be computed by rearranging Eq. (1) for r_m.

$$r_m = \frac{\rho_\alpha[q_{sat}(T_e) - q_{sat}(T_a)h_a]}{E} - r_a \tag{3}$$

Water vapor transfer between the soil surface and an arbitrary level in the air are controlled by the r_a (s m^{-1}), and r_a is computed by Eq. (4) (Choudhury and Monteith, 1988)

$$r_a = \frac{\{\ln[(z_u - d)/z_0]\}^2}{k_v^2 u}(1+\delta)^\varepsilon \tag{4}$$

$$\text{where} \quad \delta = 5g(z_u - d)(T_s - T_a)/(T_a u^2) \tag{5}$$

$$\varepsilon = -2 \quad \delta < 0$$

$$\varepsilon = -0.75 \quad \delta > 0$$

where z_u is the height at which wind speed is recorded (m), d is zero plane displacement (effectively zero for bare soil) (m), z_0 is roughness length, k_v is von Karman's constant (0.41), u is wind speed at height z_u (m s^{-1}), T_a is air temperature at height z_u and T_s is soil surface temperature. The accuracy of Eq. (5) when compared with a more detailed derivation of r_a is discussed by Choudhury et al. (1986).

3. Materials and methods

3.1. Experimental instrumentation

A series of experiments were carried out in a wind tunnel. The wind tunnel is of non-circulating blow-type, with a gross length of 37 m and mainly consisting of a power portion, an expansion portion, a working portion and a diffusion portion, wind speed can be controlled from 2 to 30 m s^{-1} (Dong et al., 2002).In the present study, three iron sample boxes were employed: one is Box-A (30 cm × 30 cm × 10 cm, with uniform holes in the bottom), in which soil sample was saturated by capillary rise and excess water was drained off from the small holes. Box-B was a bigger one (30 cm × 30 cm × 20 cm), so that we can put Box-A into Box-B and then mulched it with different types of gravel (above the Box-A). And another one was Box-C (100 cm × 30 cm × 20 cm), which was used to determine roughness by the wind speed profile method (Dong et al., 2002). The wind profiles (wind speed distribution at different height) were determined by employing a wind profiler: 10 Pitot static probes placed at 10 different heights (0.3, 0.6, 1, 1.5, 3, 6, 12, 20, 35 and 50 cm above the surface) and roughness z_0 can be calculated by Eq. (6) using measured wind speeds at different heights in the turbulent boundary layer.

$$\ln z_0 = \frac{u_2 \ln z_1 - u_1 \ln z_2}{u_2 - u_1} \tag{6}$$

where u_1 is wind speed at height z_1 (m s^{-1}), u_2 is wind speed at height z_2 (m s^{-1}), z_0 is roughness length.

The roof of Box-B or Box-C in the experiments was placed on the bottom of the wind tunnel. Wind speed was measured upwind of the floor at a height of 100 cm, and room temperature was kept at about 20 °C. The soil used in the study (28% clay, 40% silt and 32% sand, with a bulk density of 1.2 g/cm^3) were taken from the Gaolan Research Station and the gravel used in the study were sampled from fluvial materials of the Yellow River. Only relative spherical gravels with nearly equal L, I and S diameters were manually selected (L represents the longest pebble axis, I represents the intermediate axis and S represents the shortest axis), and we used the equivalent grain size (d_i) to differentiate the different types of gravel. Assuming the gravel are all spheroid, and the d_i is the diameter of corresponding equivalent sphere. So the volume of the pebbles can be computed by Eq. (7).

$$V = \frac{4}{3}\pi\left(\frac{L}{2}\right)\left(\frac{I}{2}\right)\left(\frac{S}{2}\right) = \frac{4}{3}\pi\left(\frac{d_i}{2}\right)^3 \tag{7}$$

Thus the equivalent grain size (d_i) of the gravel can be computed by Eq. (8).

$$d_i = \sqrt[3]{LIS} \tag{8}$$

T_e, T_a and h_a were measured by high precision temperature and humidity sensor (Testo 6600, Testo Instrument Company, Germany) at the soil surface and at a height of 15 cm. The weight of boxes was measured by a high-resolution balance with a readability of 0.1 g and a weighing max range of 34 kg (IBK34000D, Precisa Instrument Company, Switzerland). The heat source used for evaporation was natural solar radiation that passed through the glass windows.

3.2. Laboratory experiments

3.2.1. Experiment 1

In order to assess the relationship between the mulch resistance r_m and the thickness of gravel mulch layer, we used gravel (d_i = 11.01 mm) mulch layer with thickness of 0 cm (saturated bare soil) and 2, 4, 6, 8 and 10 cm. The wind speed of the experiment was kept at 2.0 m/s, and the soil in Box-A was full saturation. The weight of Box-B (included Box-A and gravel mulch layer) was recorded once half an hour. There were three replications for each treatment. We used Eq. (1) to calculate r_t, used Eq. (4) to calculate r_a, and then got r_m by Eq. (3).

3.2.2. Experiment 2

To study the relationship between the resistance of mulch stratum r_m and particle size, we used five types of gravel mulch with different equivalent grain size (d_i): (A) 3.43 mm, (B) 11.01 mm, (C) 19.31 mm, (D) 32.89 mm and (E) 43.73 mm (Table 1). In addition, three mixed treatments were included: mixture of A and C 1:1 by volume (M1), mixture of A and D 1:1 by volume (M2) and