Catena 151 (2017) 34–48

Contents lists available at ScienceDirect

Catena

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

Coupled heat and moisture transfer and evaporation in mulched soils

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ARTICLE INFO

Article history:
Received 5 August 2016
Received in revised form 5 October 2016
Accepted 11 December 2016
Available online 18 December 2016

Keywords:
Heat transfer
Semi-arid region
Vapour flux
Weighing lysimeter
Mulch effect

ABSTRACT

Improving water efficiency in arid and semi-arid regions is an ongoing goal in agricultural production. Straw mulching is one cultural practice which can be used to this point. Mulch layers associated with the atmospheric condition can create a variety of water and heat flux conditions at the soil surface. This study was conducted to (a) analyses the effect of a straw mulch layer on coupled heat and moisture transfer in shallow depths compared to bare soil, and (b) to develop and evaluate a method to estimate soil evaporation. Experiments were conducted in a field with grass clipping mulch and sandy soil that was moistened with natural shower and included a weighing lysimeter to measure actual evaporation. Average albedo over the mulching plot was defined as 0.49 by using lysimeter data during experiment. Near 93% and 97% of vapour flux in mulching plot and bare soil plot was under effect of temperature gradient, respectively. On average, the contribution of water vapour flux to the total moisture flux was 2% for mulching plot and 7% for bare soil plot. The heat transported by latent heat flux was 15% for mulching plot and up to 22% for bare soil plot. Observed differences between cumulative evaporation estimations and lysimeter data was about 8%. The simplicity of proposed method reduced required incoming solar radiation information, R_s, to estimate evaporation. Mulch layer could reduce significantly evaporation amount 40%.
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1. Introduction

Improving efficiency in water use is an ongoing goal in agricultural production, especially in arid and semi-arid regions, where water resources are limited and strictly regulated. The water demands of urban populations are essentially fixed and growing, so water availability for agricultural producers is constantly reduced, and the associated costs are rising. Mulching is a cultural practice which can be used to address this problem. Covering the ground with mulch saves water by preventing surface evaporation (Demir et al., 2009; Yuan et al., 2009; Gilman et al., 2012). This layer increases water retention and prevents soil evaporation as well as can also greatly reduce or eliminate weed propagation, which will also result in higher water use efficiency (Hu et al., 1995; Liu et al., 2002; Baumhardt and Jones, 2002; Kar and Singh, 2004; McMillen, 2013). Moreover, mulches can benefit landscapes by reducing soil erosion, cooling the soil and possibly providing nutrients for plant growth (Shaw and McMaster, 2005). Straw mulch improved physical and chemical properties and reduced runoff generation and soil losses after 3-years experiment in a no tilled Fluvisol area (Jordán et al., 2010). Mulch layer with reducing in runoff amount and rate can decrease soil loess amount (Jordán et al., 2011; Prosdocimi et al., 2016a, b) Robichaud et al. (2013) reported that wood strand mulch significantly reduced sediment load for the first four post-fire years. Mulch material contributes to increase humus formation and, in turn, water holding capacity (Unger, 1974). Nishigaki et al. (2016) reported that surface mulching decreased soil loss amount up to 49% in a cropland. Since mulch layer reduces evaporation and short wave radiation to the soil surface, it plays a critical role in determining the mass and energy fluxes between the soil surface and the atmosphere. A one-dimensional physical model was developed to simulate of the temperature and moisture content in mulched soil during solarization treatment in a closed greenhouse that showed good agreement with measured data (D'Emilo, 2014). Sadeghi et al. (2015) showed that straw mulch decreased soil erosion at rate of 45% in sandy loam soil. Li et al. (2016) reported that using straw mulch in hill slope jujube orchard could increase water storage. Adding 60% of straw mulch on soil surface reduced water loess from 60% to 13% and decreased erosion amount from 5.1 to 0.2 Mg ha^{-1} h^{-1} (Cerdà et al., 2016). Median value of 59% straw mulch cover reduced sediment concentration in runoff from 9.8 to 3.0 g L^{-1} and the median total sediment detached from 70.34 to 15.62 g (Prosdocimi et al., 2016a, b).Mulch, associated with the atmospheric condition, can create a variety of water and heat flux conditions at the soil surface. It has been recognized that the movements of moisture and heat in the soil are coupled (Philip and de Vries,

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http://dx.doi.org/10.1016/j.catena.2016.12.010
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Table 1
Values of empirical coefficients used in Eqs.(25), (26), (27) and (28).

Variable	Value
s	0.736
θ_s	0.429
θ_r	0
n_1	4.87
α_1 (1/cm)	0.0469
n_2	1.33
α_2 (1/cm)	0.141
Ks (cm/min)	2.816655
a	21.3
b	1.38
c	6.8
a_h	0.0061
b_h	0.0032
d_h	22.6
c_h	0.00152
w	1.46
a_e	5
b_e	19
d_e	1
c_e	96
f	1.8

1957; Bittelli et al., 2008; Novak, 2010). In arid and semiarid regions, temperature gradients in the shallow subsurface can be very large and the liquid water flow and water vapour transport due to temperature fluctuations may have a significant effect on temporal soil water distributions. Various authors have examined coupled moisture and heat flux under bare soil or cultivated fields (Cahill and Parlange, 1998; Antonopoulos, 2006; Ao et al., 2007; Smits et al., 2010); however, little information about the mulch impact on coupled heat and mass transfer in subsurface soil layers is available on experimental designs.

The major objectives of this investigation were: 1) to investigate effect of straw mulch layer on coupled heat and moisture movement in subsurface unsaturated soil as compared to the bare soil. 2) to estimate the effects of the straw grass mulch on the evaporation processes by developed method.

2. Theoretical consideration:

2.1. Energy equation

The vertical transport of heat in soils based on Fourier's law is described as

$$C\frac{\partial T}{\partial t} = -\frac{\partial q_h}{\partial z} = -\frac{\partial G}{\partial z} - L\ S_e = -\frac{\partial}{\partial z}\left(k_h\frac{\partial T}{\partial t}\right) - L\frac{\partial q_v}{\partial z} \tag{1}$$

where C is heat capacity of the soil (W/cm^3 K), T is the temperature (K), t is time (s), q_h heat flux density (W/cm^2), z is the depth below the soil surface (cm), G is the convective heat flux density (W/cm^2), L is the latent heat of vaporization (2.45×10^3 J/g), S_e is the vapour flux per unit of soil depth, k_h is the thermal conductivity (W/cm·K), q_v is the water vapour flux (g/cm^2·s).

2.2. Mass equation

The one-dimensional conservation for liquid andvapour water within the soil is described as

$$\frac{\partial\theta}{\partial t} = -\frac{\partial q_m}{\partial z} = -\frac{\partial q_1}{\partial z} - \frac{1}{\rho_w}\frac{\partial q_v}{\partial z} \tag{2}$$

where ρ_w is the water density (gr/cm^3), θ is the volumetric water content (cm^3/cm^3), q_m is the total moisture flux, which is simply equal to the sum of the liquid and vapour flux (de Vries, 1986), q_l is the liquid water flux (cm/s).

The liquid water flux is defined as

$$q_1 = -D\theta_1\nabla\theta - D_{T1}\nabla T - K \tag{3}$$

where $D\theta_l$is the isothermal liquid diffusivity (cm^2/s), D_{Tl} is the thermal liquid diffusivity (cm^2/s·K) and K is the hydraulic conductivity (cm/s) (Philip and de Vries, 1957). The isothermal liquid diffusivity is

$$D_\theta = K\frac{\partial\psi_m}{\partial\theta} \tag{4}$$

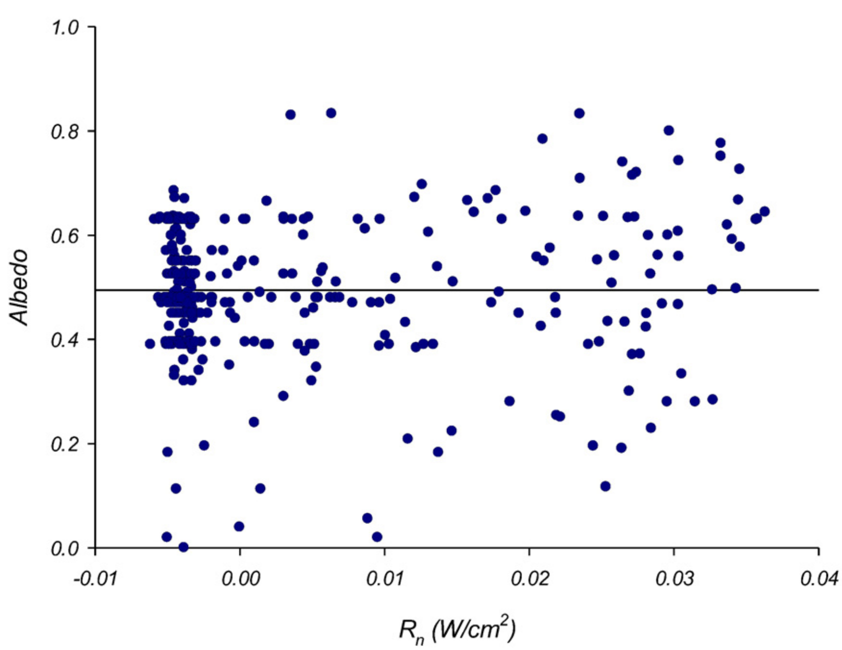

Fig. 1. Calculated albedo (dark gray filled circles) in function of net radiation (R_n) in the mulched plot; the average line is fixed in 0.49.

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