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Modelling soil suction changes due to mixed species planting

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ABSTRACT

Vegetation-induced changes of soil hydrology (i.e., infiltration rate and soil matric suction) has important implication to the stability of earthen infrastructure. Predicting the plant hydrological effects is challenging when multiple species are present. Most existing models consider only single-species due to lack of reliable and relevant experimental data and difficulty to partition solar radiant energy into individual species in a mixed-species condition. This paper aims to develop an improved hydrological model that can determine the water infiltration rate and suction responses under both single- and mixed-species (one tree and one grass species) condition. The model is verified by double-ring infiltration tests and field monitoring conducted in bare, grass-only, tree-only and mixed tree-grass plots. The model was subsequently used for parametric analyses. The mixed species plot had the lowest infiltration rate and preserved the greatest suctions because the tree-grass competition for water created high soil moisture deficit. Parametric study identifies a threshold ratio of tree and grass leaf area index of 2.0, beyond which the effects of grass root-water uptake on water competition with the adjacent tree were negligible. Induced suction in the mixed tree-grass plot was close to that in a tree-only plot. Contribution of tree root-water uptake to induced suction in a mixed species plot did not increase further when the leaf area index ratio exceeds 5.0.

1. Introduction

Soil hydrology changes by evapotranspiration (ET), a combined process that removes soil moisture from a given area, and during a specified period of time, by evaporation from the bare soil surface and transpiration from plants (Soil Science Society of America, 2008). This natural process reduces soil moisture or increases matric suction (Rahardjo et al., 2014; Garg et al., 2015; Smethurst et al., 2015; Leung et al., 2015a; Ng et al., 2016a). It is well-known that an increase in matric suction would not only increase soil shear strength but also reduce soil hydraulic conductivity (Alonso et al., 2010; Springman et al., 2013: Gadi et al., 2017). The ET-induced changes in soil suction and consequently the soil behaviour have important implication to the water balance and soil stability of some earthen infrastructure such as cuttings and embankments (Briggs et al., 2013; Smethurst et al., 2015; Das et al., 2017; Garg et al., 2017) as well as landfill covers (Feng et al., 2017), where vegetation is normally found.

Indeed, field studies reported by Rahardjo et al. (2014), Simon and Collison (2002) and Ni et al. (2017) showed that suction could be preserved after rainfall, providing substantial stabilisation to soil (Boldrin et al., 2017a). Recent centrifuge model tests have quantified extra slope stability that can be gained through transpiration-induced hydrological reinforcement (Ng et al., 2016b; Leung et al., 2017), in addition to mechanical root reinforcement (Fan and Su, 2008; Boldrin et al., in press; Liang et al., in press). Rock et al. (2012) also showed the importance of taking ET into account in water balance calculation to more correctly assess the amount of water percolation in landfill covers.

Mixed plant species of different functional groups (e.g., tree and grass) are often found in the field, instead of one. Ecological engineers who adopt soil bioengineering technique would want to, on one hand, enhance the stability of the infrastructure and on the other hand to grow multiple species for maximising ecological restoration effects and biodiversity to the surrounding built environment (Lamb, 1998; Hooper et al., 2005). In a mixed tree-grass condition, for examples, trees could facilitate grass growth due to increased nutrient availability (Ludwig et al., 2004). From engineering perspective, grass has shallow root system that can reduce soil erosion effectively, while tree has stronger and deeper root system that can provide tensile strength as mechanical reinforcement.

Most existing studies measured suction induced by grass-only soil (e.g., Ng et al., 2013; Rahardjo et al., 2014) or tree-only soil (e.g., Smethurst et al., 2015; Ng et al., 2016a). There were a few exceptions

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List of notations

a_g	extinction coefficient for radiant energy intercepted by grass foliage
a_t	extinction coefficient for radiant energy intercepted by tree canopy
h_{fc}	water pressure head corresponding to the field capacity
h_{wp}	water pressure head corresponding to the permanent wilting point
R_g	radiant energy intercepted at the grass foliage
R_s	radiant energy intercepted at the bare soil surface
R_t	radiant energy intercepted at the tree canopy
R_v	root volume ratio
V_r	total volume of roots
V_s	soil volume
c_p	specific heat of moist air
e_a	actual vapor pressure
e_s	saturated vapor pressure
k_s	saturated hydraulic conductivity
m_1	fitting parameter for Eq. (11)
m_2	fitting parameter for Eq. (11)
m_3	fitting parameter for Eq. (11)
m_4	fitting parameter for Eq. (11)
r_a	aerodynamic resistance for water vapor transfer from canopy to air
r_s	stomatal resistance
γ_w	unit weight of water
ε_g	Albedo of grass foliage
ε_s	Albedo of ground surface
ε_t	Albedo of tree canopy
θ_r	residual volumetric water content
θ_s	saturated volumetric water content
ρ_a	air density at constant temperature
G	soil heat flux
h	water pressure head
Θ	degree of saturation
AE	actual evaporation
AEV	air entry value
ET	evapotranspiration
LAI	leaf area index
PE	potential evaporation
PET	potential evapotranspiration
PT	potential transpiration
R	incoming solar radiation energy
RH	relative humidity
S	sink term
$SWRC$	soil water retention curve
a	fitting parameter for Eq. (13)
b	fitting parameter for Eq. (13)
d	root depth
e	void ratio
g	distribution of root volume ratio along depth
k	soil hydraulic conductivity function as a function of pressure head
s	soil matric suction
t	time
u	wind speed
z	vertical co-ordinate
Δ	rate of change of saturated vapor pressure with time
α	transpiration reduction function
γ	psychrometric constant
θ	volumetric water content
λ	latent heat of water vaporization

such as February and Higgins (2010) and Ni et al. (2017) who focused on the hydrological responses of mixed tree-grass soil. In particular, Ni et al. (2017) found that tree spacing controls the amount of ET-induced suction. To-date, it is unclear from these limited field data that (i) how much each individual species contribute to the overall suction induced in a mixed-species soil, and (ii) in what circumstance(s) the contribution from one species might dominate the other. These are two important aspects that assist ecological engineers to apply the soil bioengineering technique in terms of the selection of plant species and long-term vegetation management.

Many models (e.g., Feddes et al., 1976, 2001; Lai and Katul, 2000; Fatahi et al., 2010; Moene and van Dam, 2014) have been developed to incorporate a sink term into a water balance equation (e.g., Darcy-Richards equation) to capture root-water uptake. Although these models appear to be quite successful in estimating the ET-induced changes in suction of a single plant species (Allen et al., 1998; Feddes et al., 2001), further examination is needed for mixed species case. In this more complicated case, intra- or inter-species competition for sunlight (or solar radiation) and soil water would occur.

Some studies have been conducted to model the partition of soil evaporation and plant transpiration for a given ET (Ritchie, 1972; Mahat and Tarboton, 2012; Kool et al., 2016). Among these, Ritchie (1972), which satisfies the Beer-Lambert's law, has been widely used. Beer-Lambert's law is a concept from the spectroscopy that is used to quantify the transmittance and attenuation of solar radiation in the atmosphere. Ritchie (1972) considered plant canopy/foliage as a "layer", through which the solar radiation could penetrate and attenuate. The degree of attenuation by a "layer" depends on the plant leaf area index (LAI; ratio of the total green leaf area of a plant species to the projected canopy area on plan). While the energy attenuated at the "layer" would be used for plant transpiration, the remaining energy fallen on the soil surface would be used for soil evaporation. However, this kind of model considers a relatively simple single-plant system, where the single-"layer" assumption (Massman, 1992) would not be applicable to multiple species cases.

This study aims to develop and verify a new soil hydrological model that can be used to investigate the effects of mixed tree-grass plantations on (i) the partition of solar radiation and (ii) inter-species competition for soil water and associated soil suction change.

2. Soil hydrological model for mixed plantation

The model was derived based on radiant energy partition, water balance and their coupling in a soil-plant system defined in Fig. 1(a). The proposed model structure is shown in Fig. 1(b). The system includes a bare ground (i.e., without vegetation) or a vegetated ground with single or multiple plant species.

2.1. Partition of solar radiant energy

A major source of energy for ET is the incoming solar radiant energy, R. The model applies the Beer–Lambert's law to capture the partition of R in the above-ground soil-plant system (Fig. 1). For a bare ground, the radiant energy that is not reflected (due to albedo) would be absorbed by the soil for evaporation mainly. For a grass- or tree-only ground, on the other hand, a portion of the energy would be intercepted by the tree canopy (or grass foliage), leaving the rest fallen on the ground surface. For mixed species ground with one tree and one grass species, energy partition would occur first at the tree canopy, followed by the grass foliage and finally the ground surface. Hence, the energy partition equations in a mixed tree-grass case can be expressed as:

$$R_t = R\cdot(1-\varepsilon_t)\cdot[1-exp(-a_t\cdot LAI_t)] \quad (1)$$