

Chapter 2

Comparison of Dual-Source Evapotranspiration Models in Estimating Potential Evaporation and Transpiration

2.1 Introduction

Potential evapotranspiration (PET) is defined as the amount of ET that could occur if a sufficient water source were available, the value of which is a function of atmospheric conditions and surface vegetation distribution characteristics. However, traditional empirical PET models, such as the Hargreaves model and Priestley-Taylor model, only account for the effect of atmospheric demand on PET, whereas the impact of vegetation on PET is simply ignored. On the other hand, physical-based PET models, such as the Penman-Monteith model (refer to as the P-M model hereafter), take vegetation effect on PET into consideration. Nevertheless, the P-M model treats the land surface as a uniform layer, where the vegetation covers the land surface fully and uniformly as a “big leaf”. This simplification of vegetation treatment makes the P-M model unable to distinguish evaporation from soil (E) and transpiration from canopy (T), and therefore may not be appropriate for use in partially vegetated areas.

Considering contributions of energy fluxes from different components (soil vs. vegetation), dual-source ET models have been proposed to more precisely depict water and heat transfers from sparse or heterogeneous canopies. In particular, Shuttleworth and Wallace (1985) developed a two layer ET model, in which each source of water and heat flux is superimposed and coupled. This model is also referred to as the coupled model. In contrast, Lhomme et al. (1994) suggested that for surface with low vegetation cover or patchy vegetation, the interaction between components is generally very weak so that fluxes from each source interact independently with each other and directly with the above atmosphere. This type model is known as the patch model or uncoupled model. By combining the layer model and the patch model, Guan and Wilson (2009) proposed a hybrid dual source, which claims to be applicable for a range of vegetated surface.

Besides a general better performance of ET estimation, dual source models are also capable of distinguishing different processes of E and T. To that end, dual

source models contains a greater application potential for ET estimation and partitioning, in comparison to empirical ET models and single source ET models (e.g., P-M model). However, consensus on the applicability of different dual source ET models has not been achieved yet. The objective of this chapter is to compare the performance of the three above-mentioned dual source models in estimating PET and the partitioning between PE and PT. The comprehensive comparison could provide important implications for developing model for actual ET estimation at various spatial scales (see Chaps. 3–5).

2.2 Evapotranspiration Models

2.2.1 Penman-Monteith Model

The description of the Penman-Monteith (P-M) model is given in Eq. (2.1), and the model structure is shown in Fig. 2.1a.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho C_p D / r_a}{\Delta + \gamma[1 + (r_c / r_a)]} \quad (2.1)$$

where λ is the latent heat of vaporization; R_n and G are net radiation and soil heat flux, respectively (W/m^2); Δ is the slope of saturation vapor pressure—temperature curve (kPa/K), ρ is the air density (kg/m^3), C_p is the specific heat of air at constant pressure (J/(kg K)), D is the vapor pressure deficit (kPa), γ is the psychrometric constant (kPa/K), r_a is aerodynamic resistance (s/m), and r_c is bulk surface resistance (s/m).

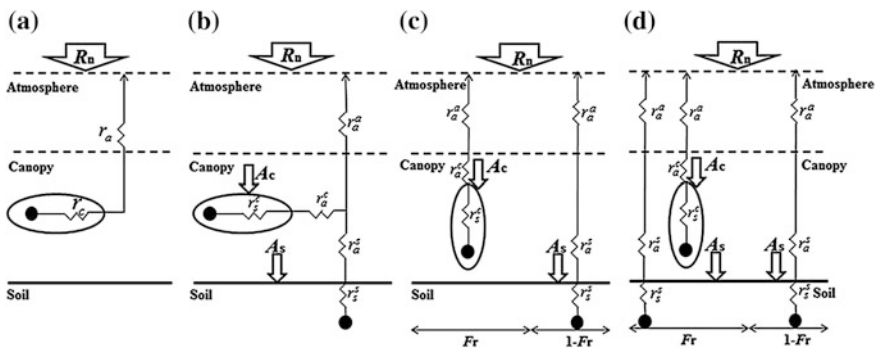


Fig. 2.1 Structure of the Penman-Monteith model (a); Shuttleworth-Wallace model (b); Two-Patch model (c); and TVET model (d). The nomenclature used is given in Sect. 2.2 (Yu et al. 2014)

The aerodynamic resistance determines the transfer of heat and water vapor from evaporation surface into the air above the canopy, which is calculated from Allen et al. (1998),

$$r_a = \frac{\ln\left(\frac{z_m - d}{z_{om}} + \varphi_M\right) \ln\left(\frac{z_h - d}{z_{oh}} + \varphi_H\right)}{k^2 u(z_m)} \quad (2.2)$$

where k is von Karman's constant ($=0.41$), d is zero plane displacement height (m), z_m and z_h are height of wind measurement and humidity measurement, respectively (m). $u(z_m)$ is wind speed at height z_m (m/s), z_{om} is the roughness length governing momentum transfer, and z_{oh} is the roughness length governing heat and vapor transfer. Both roughness lengths (z_{om} , z_{oh}) and zero plane displacement height (d) are defined as functions of vegetation height (h), given in Campbell and Norman (1998). φ_M and φ_H represent atmospheric diabatic correction factors for momentum and heat (or vapor) respectively and can be found in Brutsaert (1982).

The bulk surface resistance is estimated from Jarvis (1976),

$$r_c = \frac{1}{2LAI} \frac{r_{ST_min}}{f_1 f_2 f_3 f_4} \quad (2.3)$$

where r_{ST_min} is the minimum stomatal resistance (s/m). f_1 , f_2 and f_3 are factors accounting for the influence of shortwave radiation, air vapor deficit, and air temperature on stomatal resistance, respectively, and are estimated following Noilhan and Planton (1989). Parameter f_4 accounts for the influence of root zone soil moisture on stomatal resistance, which is calculated from

$$f_4(\theta) = \begin{cases} 0 & \theta \leq \theta_W \\ \frac{\theta - \theta_W}{\theta_F - \theta_W} & \theta_W < \theta < \theta_F \\ 1 & \theta_F \leq \theta \end{cases} \quad (2.4)$$

where θ is the soil water content within the root-zone (cm^3/cm^3), θ_F and θ_W are the soil water content at the field capacity and wilting point, respectively.

2.2.2 Shuttleworth-Wallace Model

The Shuttleworth-Wallace (S-W) model is a typical two-layer model, which is also the basis of other multi-layer models. The model structure is shown in Fig. 2.1b. In the S-W model, ET is calculated from,

$$\lambda ET_a = \lambda E + \lambda T = C_s PM_s + C_c PM_c \quad (2.5)$$

where λE is the latent heat from soil and λT is the latent heat from canopy (W/m^2). Subscript s and c represent soil and canopy component, respectively. The expressions of PM and C are given by

$$PM_s = \frac{\Delta A + [\rho C_p D - \Delta r_a^s (A - A_s)] / (r_a^a + r_a^s)}{\Delta + \gamma [1 + (r_s^s / (r_a^a + r_a^s))]} \quad (2.6)$$

$$PM_c = \frac{\Delta A + [\rho C_p D - \Delta r_a^c A_s] / (r_a^a + r_a^c)}{\Delta + \gamma [1 + r_s^c / (r_a^a + r_a^c)]} \quad (2.7)$$

$$C_c = 1 / (1 + R_c R_a / R_s (R_c + R_a)) \quad (2.8)$$

$$C_s = 1 / (1 + R_s R_a / R_c (R_s + R_a)) \quad (2.9)$$

$$R_a = (\Delta + \gamma) r_a^a \quad (2.10)$$

$$R_s = (\Delta + \gamma) r_a^s + \gamma r_s^s \quad (2.11)$$

$$R_c = (\Delta + \gamma) r_a^c + \gamma r_s^c \quad (2.12)$$

where r_a^a is the aerodynamic resistance between mean canopy surface and the reference height (s/m); r_a^s is the aerodynamic resistance between soil surface and mean canopy surface (s/m); r_a^c is the aerodynamic resistance between mean leaf surface and mean canopy surface (s/m); r_s^c is the canopy surface resistance, and r_s^s is the soil surface resistance (s/m). A and A_s are the total available energy and the available energy for the soil component (W/m^2), respectively, which can be estimated from

$$A = R_n - G \quad (2.13)$$

$$A_s = R_n \exp(-k_c LAI) - G \quad (2.14)$$

where k_c is the extinction coefficient of radiation attenuation, and is set to be 0.7 for deciduous broadleaf forests, 0.5 for evergreen needle-leaf forests, and 0.4 for herbs (Lhomme and Chehbouni 1999; Monsi and Saeki 1953).

The aerodynamic resistance r_a^a and r_a^s in the S-W model were assumed to change linearly between those for the surface with full vegetation cover (assumed equal to $LAI = 4$) and for bare soil, weighted by leaf area index (Shuttleworth and Wallace 1985),

when $0 < LAI < 4$

$$r_a^a = \frac{1}{4} LAI \times r_a^a(\alpha) + \frac{1}{4} (4 - LAI) \times r_a^a(0) \quad (2.15)$$

$$r_a^s = \frac{1}{4}LAI \times r_a^s(\alpha) + \frac{1}{4}(4 - LAI) \times r_a^s(0) \quad (2.16)$$

when $LAI \geq 4$

$$r_a^a = r_a^a(\alpha) \quad (2.17)$$

$$r_a^s = r_a^s(\alpha) \quad (2.18)$$

where α and 0 in the bracket indicate full vegetation cover and bare soil, respectively.

Above the fully developed canopy, where the wind speed profile is logarithmic, the aerodynamic resistance $r_a^a(\alpha)$ is calculated using Eq. (2.2). For aerodynamic resistance within the canopy, $r_a^s(\alpha)$ is obtained by performing an integration of eddy diffusion coefficient (K) over the height from 0 to $d + Z_{om}$, i.e.,

$$r_a^s(\alpha) = \int_0^{d+Z_{om}} \frac{dz}{K(z)} = \frac{\ln \frac{z-d}{Z_{om}} + \varphi_M}{k^2 u(z)} \frac{h}{n(h-d)} \{ \exp n - \exp[n(1 - \frac{d+Z_m}{h})] \} \quad (2.19)$$

where n is the extinction coefficient of the eddy diffusion, which is estimated by linear interpolation between the value for $h < 1$ m ($=2.5$) and $h > 10$ m ($=4.25$); $u(z)$ is the wind speed at height z . The eddy diffusion coefficient $K(z)$ is determined by

$$K(z) = \frac{k^2(h-d)u(z)}{[\ln(z-d)/Z_{om}]} \exp[-n(1-z/h)] \quad (2.20)$$

For surface without canopy, $r_a^a(0)$ and $r_a^s(0)$ are estimated from the following equations without the consideration of the zero plane displacement height,

$$r_a^s(0) = \frac{(\ln \frac{h}{Z_{om}'} + \varphi_M)(\ln \frac{h}{Z_{oh}} + \varphi_H)}{k^2 u(h)} \quad (2.21)$$

$$r_a^a(0) = \frac{(\ln \frac{Z_m}{Z_{om}} + \varphi_M)(\ln \frac{Z_h}{Z_{oh}} + \varphi_H)}{k^2 u(Z_m)} - r_a^s(0) \quad (2.22)$$

where Z_{om}' and Z_{oh}' are the roughness length of bare surface governing momentum transfer and heat and vapor transfer ($=0.01$ m), respectively; $u(h)$ is the wind speed at canopy height h

$$u(h) = \frac{\ln[(h-d)Z_{om}]}{[\ln(Z_m-d)/Z_{om}]} u(Z_m) \quad (2.23)$$

The intra-canopy aerodynamic resistance r_a^c is calculated from Choudhury and Monteith (1988),

Table 2.1 Different vegetation cover conditions considered in this study (Yang and Shang 2012)

Cases	Description
A (full vegetation)	Assuming a full vegetation cover with $F_r = 100\%$, surface leaf area index (LAI) ^a varies between 0.5 and 5, vegetation height of 5 m and minimum canopy resistance (r_{sc_min}) ^b of 170 s m^{-1}
B (partial, uniform vegetation)	Assuming a leaf area index for simple plant (L_c) ^c of 2, F_r varies from 10 to 100 %. Other vegetation parameters are the same as case A
C (partial, non-uniform vegetation)	Assuming a constant surface leaf area index, the degree of vegetation non-uniformity is reflected through varying vegetation cover ($LAI = L_c \times F_r$). The lower the F_c is, the higher the vegetation non-uniformity is. Other vegetation parameters are the same as case A

^aLAI of 0.5–5 represents LAI values over most fully vegetated surfaces

^b $r_{ST_min} = 170 \text{ s m}^{-1}$ represents an average r_{ST_min} of typical ecosystems [Grassland, $r_{ST_min} = 130 \text{ s m}^{-1}$; forest, $r_{ST_min} = 180 \text{ s m}^{-1}$; shrubland, $r_{ST_min} = 210 \text{ s m}^{-1}$ (Körner 1994)]

^cSingle plant leaf area index (L_c) ranges typically from 0.5 to 5 for most species. In this study, a midway of 2 was chosen

$$r_a^c = \frac{n}{0.02} \sqrt{\frac{l_w}{u(h)} \frac{1}{1 - e^{-n/2}}} \quad (2.24)$$

where l_w is the characteristic length of leaf width (m) (Table 2.1).

The canopy surface resistance in the S-W model (r_s^c) is similar with the bulk surface resistance in P-M model (r_c). Thus, r_s^c can be computed from Eqs. (2.3) and (2.4). The soil surface resistance is computed using an empirical equation given by Lin and Sun (1983),

$$r_s^s = 3.5(\theta_s/\theta_1)^{2.3} + 33.5 \quad (2.25)$$

where θ_1 is the soil water content within the surface soil layer.

2.2.3 Two-Patch Model

In the two-patch (T-P) model (Fig. 2.1c), both soil and vegetation components are assumed to receive full radiation loading, and the total flux of latent heat per unit area is calculated as the mean of fluxes from each component (canopy or soil) weighted by their relative areas (Lhomme and Chehbouni 1999),

$$\lambda ET_a = Fr \times \lambda T + (1 - Fr) \times \lambda E \quad (2.26)$$

$$\lambda T = \frac{\Delta A + \rho C_p D / (r_a^a + r_a^c)}{\Delta + \gamma [1 + r_s^c / (r_a^a + r_a^c)]} \quad (2.27)$$

$$\lambda E = \frac{\Delta A + \rho C_p D / (r_a^a + r_a^s)}{\Delta + \gamma [1 + r_s^s / (r_a^a + r_a^s)]} \quad (2.28)$$

where Fr is the fractional vegetation coverage. The value of Fr can be either determined by in situ measurements or estimated from remote sensing images (Table 2.1), in which Fr is calculated from Mu et al. (2011),

$$Fr = (EVI - EVI_{\min}) / (EVI_{\max} - EVI_{\min}) \quad (2.29)$$

where EVI is the enhanced vegetation index (Huete et al. 2002); $EVI_{\max}$ and $EVI_{\min}$ are the maximum and minimum EVI values, respectively (Mu et al. 2007).

Aerodynamic resistances in the T-P model are similar with those in the S-W model. However, when calculating λE and λT , the T-P model assumes that transpiration occurs from a closed canopy surface while evaporation happens over bare soil. As a result, aerodynamic resistances r_a^a and r_a^c in Eq. (2.27) are estimated by Eqs. (2.2) and (2.23), while those in Eq. (2.28) are computed from Eqs. (2.21) and (2.22), respectively.

Lhomme and Chehbouni (1999) suggested that for patchy or clumped vegetation, it is better to use the clumped leaf area index (L_c), which is defined as the LAI per unit vegetated area ($L_c = LAI/F_r$). Therefore, the bulk canopy surface resistance r_s^c is estimated from

$$r_s^c = \frac{1}{2L_c} \frac{r_{ST_min}}{f_1 f_2 f_3 f_4} \quad (2.30)$$

where r_{ST_min} , f_1 , f_2 , f_3 , and f_4 keep the same meanings as those in P-M and S-W model.

Soil surface resistance of the T-P model is calculated from Eq. (2.25).

2.2.4 TVET Model

By coupling the layer and patch models, Guan and Wilson (2009) developed a hybrid dual source model for estimating potential evaporation (PE) and potential transpiration (PT) partitioning (i.e., the TVET model). The TVET model adopts the layer approach to allocate available energy between canopy and soil (Eq. 2.14) and to calculate aerodynamic resistances, and uses the patch approach to partition energy into latent heat (E or T), sensible heat (H), and ground heat flux (G). The model structure is given in Fig. 2.1d, and the equations is given below,

$$\lambda PE = \frac{\Delta A_s + (1 - F_r) \frac{\rho_a C_p D}{r_a^a + r_a^s}}{\Delta + \gamma} \quad (2.31)$$

$$\lambda PT = \frac{\Delta A_c + F_r \frac{\rho_a C_p D}{r_a^s + r_a^c}}{\Delta + \gamma \left(1 + \frac{r_a^c}{r_a^s + r_a^c}\right)} \quad (2.32)$$

where A_s and A_c are available energy for soil and canopy, which can be estimated from Eqs. (2.16) and (2.17), respectively.

The TVET model estimates aerodynamic resistances following the same way as the S-W model, and calculates surface resistances as that of the T-P model.

2.3 Comparison Setups

Single source model treats the land surface as uniform layer so that it cannot distinguish evaporation from transpiration. In addition, studies have shown that single source model does not suitable for ET estimation over partially vegetated surfaces, on which dual source model performs generally better. In this section, the three dual source ET models will be compared and evaluated in estimating potential ET and its partitioning over surfaces with different hypothesized vegetation cover conditions (Table 2.1).

When evaporating surface is not water-limited, the soil surface resistance is considered to be negligible (Shuttleworth and Wallace 1985) and the canopy surface resistance equals to the minimum canopy resistance. The meteorological data is taken from the Linhe Station in the Inner Mongolia during the main growing season of 2006 (April–October). The site is characterized with a dry and cold climate, with a mean annual temperature of 6.8 °C and mean annual precipitation of 139 mm.

2.4 Results and Discussion

2.4.1 Surfaces with Full Vegetation Cover (Case A)

Previous studies have shown that the P-M model performs well in estimating potential evapotranspiration (PET) over fully vegetated surface (e.g., Allen et al. 1998). Thus, PET estimates from the P-M model are considered as reference to evaluate the performance of the other three dual source models. Results show that the T-P model performed exactly the same as the P-M model (Fig. 2.2). This is because that the T-P model shares the same formulation of the P-M model when F_c equals 1. TVET model also gives similar results as the P-M model, except for a slightly overestimation of PET by TVET in low LAI end (Fig. 2.2). In comparison, the S-W model seriously overestimated PET and the difference increases with the decrease of LAI (Fig. 2.3). Taking LAI = 2 as an example, Fig. 2.3 compares PET

Fig. 2.2 Relationship between LAI and estimated PET by different model over fully vegetated surfaces (Yang and Shang 2012)

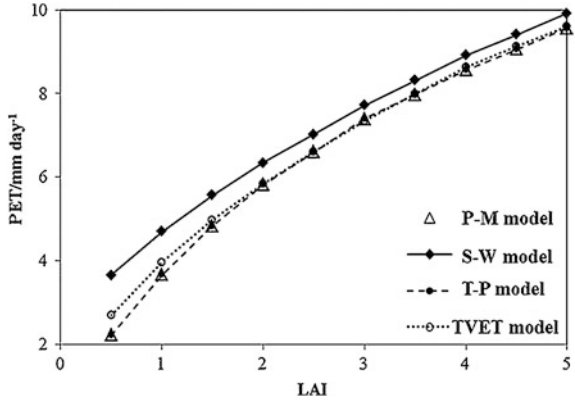
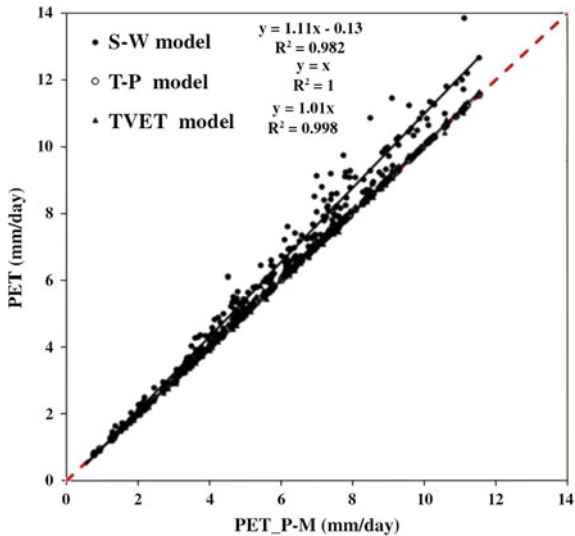


Fig. 2.3 Comparison between PET from P-M model and those from the three dual source models over fully vegetated surfaces with a fixed LAI = 2 (Yang and Shang 2012)



estimated from the P-M model with that from the three dual source models. It shows that PET from TVET agrees very well with that from P-M ($R^2 = 0.998$) whereas the difference between S-W PET and P-M PET appears to be relatively large ($R^2 = 0.982$).

Further analysis on the results of PE and PT partitioning shows that PT from the S-W model agrees well with that from the TVET model, whereas the S-W PE is consistently higher than the TVET PE. This phenomenon suggests the overestimation of PET by the S-W model is very likely due to its overestimation in potential evaporation (Fig. 2.4). Shuttleworth and Wallace (1985) reported that when soil surface resistance is large enough, E and T can be considered as two separate processes such that the S-W model can be simplified to be the P-M model. However, such extreme large soil surface resistance rarely occurs in realities,

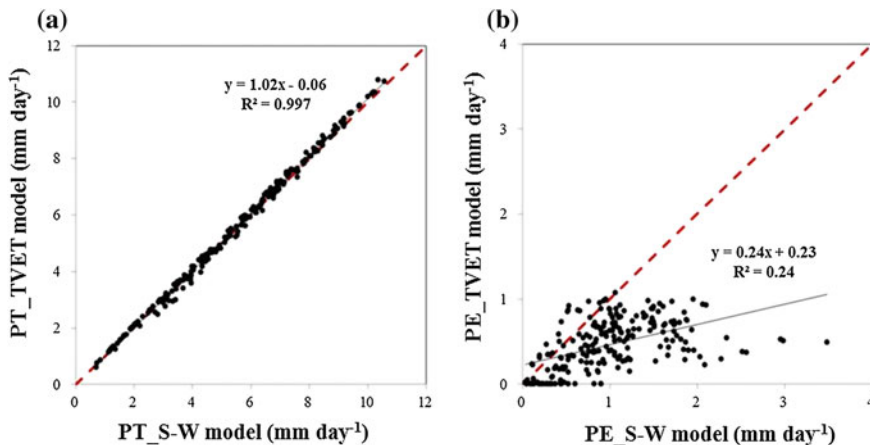


Fig. 2.4 Comparison of PT (a) and PE (b) estimated from the S-W and TVET model under full vegetation cover condition (LAI = 2) (Yang and Shang 2012)

particularly when the soil surface resistance is taken to be zero for potential ET estimation in this study. As a result, the S-W model appears to overestimate PE and therefore PET under low LAI condition. For the T-P model, soil evaporation is neglected under fully vegetated surfaces, which also obviously deviates from real conditions. Compared with the S-W and T-P model, the TVET model performed generally better in estimating PET and the partitioning of PE and PT under full vegetation cover conditions.

2.4.2 Surfaces with Uniform and Partial Vegetation Cover (Case B)

The relationship between F_c and PET estimated from the three dual source models is shown in Fig. 2.5. It shows that PET from the S-W model is obviously higher than that from the other two models, and the difference shows an increasing trend with the increase of F_r . Similar with Case A, the overestimation of PET by S-W model is due to its overestimation in PE (Fig. 2.6). The S-W model treats the soil surface equally over the whole area and does not distinguish soil evaporation under and between vegetation canopies, resulting in an increased error in PE estimates as F_r increased. Combining the fact that the overestimation of PET by S-W model increases with the decrease of LAI (higher PE/PET ratio) (Fig. 2.2), the results suggest that PE from the S-W model are more likely close to that from inter-canopy soil surfaces.

In contrast to the S-W model, the T-P model neglect evaporation from under-canopy surfaces, resulting in lower PE estimates as F_r increased (Fig. 2.6). In comparison, PE from the TVET model lies between that from the S-W model

Fig. 2.5 Relationship between F_r and PET estimated from the three dual source models (Yang and Shang 2012)

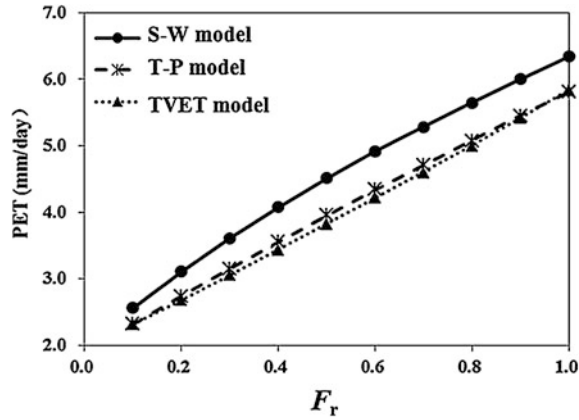
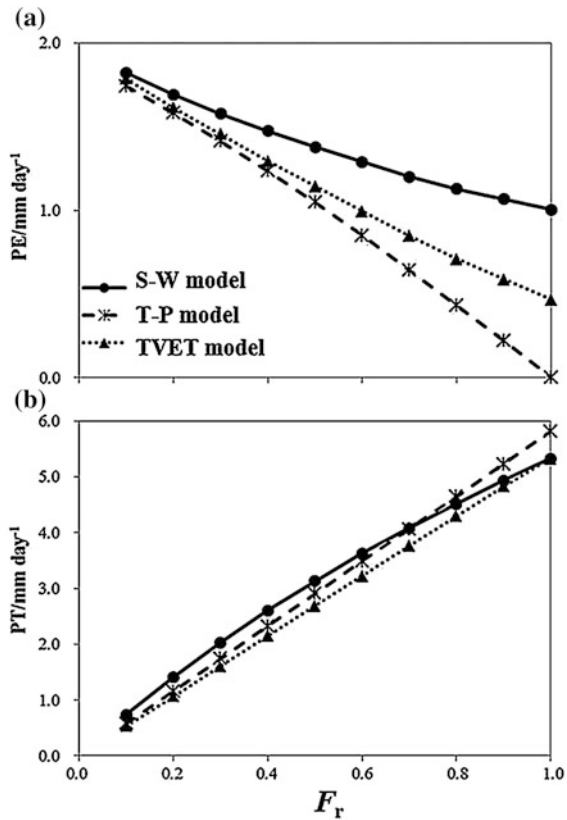


Fig. 2.6 Relationship between F_r and PE (a) and between F_r and PT (b) estimated from the three dual source models (Yang and Shang 2012)



(overestimated) and the T-P model (underestimated), implying that the results from the TVET model may be more reasonable.

2.4.3 Surfaces with Non-uniform and Partial Vegetation Cover (Case C)

When surface leaf area index (LAI) is fixed, the non-uniformity of vegetation distribution can be reflected by varying fractional vegetation cover (F_r). Our results show that S-W PT does not vary with the changes on F_r , demonstrating that the S-W model may not be applicable over surfaces with partial and patch vegetation. In addition, PE from the S-W model does not decrease with the increase of F_r . On the contrary, it shows a slightly increasing trend as F_r increased. This is because the increase in F_c would lead to a lower surface albedo and therefore higher available energy for evapotranspiration (surface albedo is a function of F_r).

For the TVET model, its PT/PE increases/decreases with the increase of F_r , suggesting that the TVET model is able to capture surface characteristics over a wide range of vegetation cover conditions. For higher F_r (close to 100 %), results in Case A have already shown a good performance of the TVET model; for lower F_r (e.g., 20 %), the TVET PE is very close to that of the S-W model, whereas the TVET PT is significantly lower than that of the S-W model, indicating that the TVET model may depict the reality better than the S-W model.

The relationship between F_r and PE/PT from the T-P model is very similar with that of the TVET model (Fig. 2.7). Lhomme and Chehbouni (1999) reported that the T-P model is more suitable for surfaces with low and patchy vegetation cover. Similar finding was also reported in Blyth and Harding (1995), who found a good performance of the T-P model over a surface with a ratio of vegetation height to patch size larger than 0.1. Our results in Fig. 2.7 show that the estimated PE from the T-P model agrees well with that from the TVET model under low LAI conditions. However, when LAI is high, the T-P PE decreases towards zero with the increase of F_r . Similar with Casa B, this is because the T-P model does not account for soil evaporation from under-canopy surfaces, which results in an increased underestimation of PE as F_r increased by the T-P model. Moreover, for fixed F_r , PE from the T-P model does not vary with changes in LAI. This is due to the ignorance of radiation interception by vegetation canopy in the T-P model. On the other hand, it assumes that each component (or patch) receives the same radiation load (i.e., full radiation). In such a case, the amount of radiation received by soil surface is only determined by fractional vegetation cover but not related with leaf size and density (as reflected through LAI).

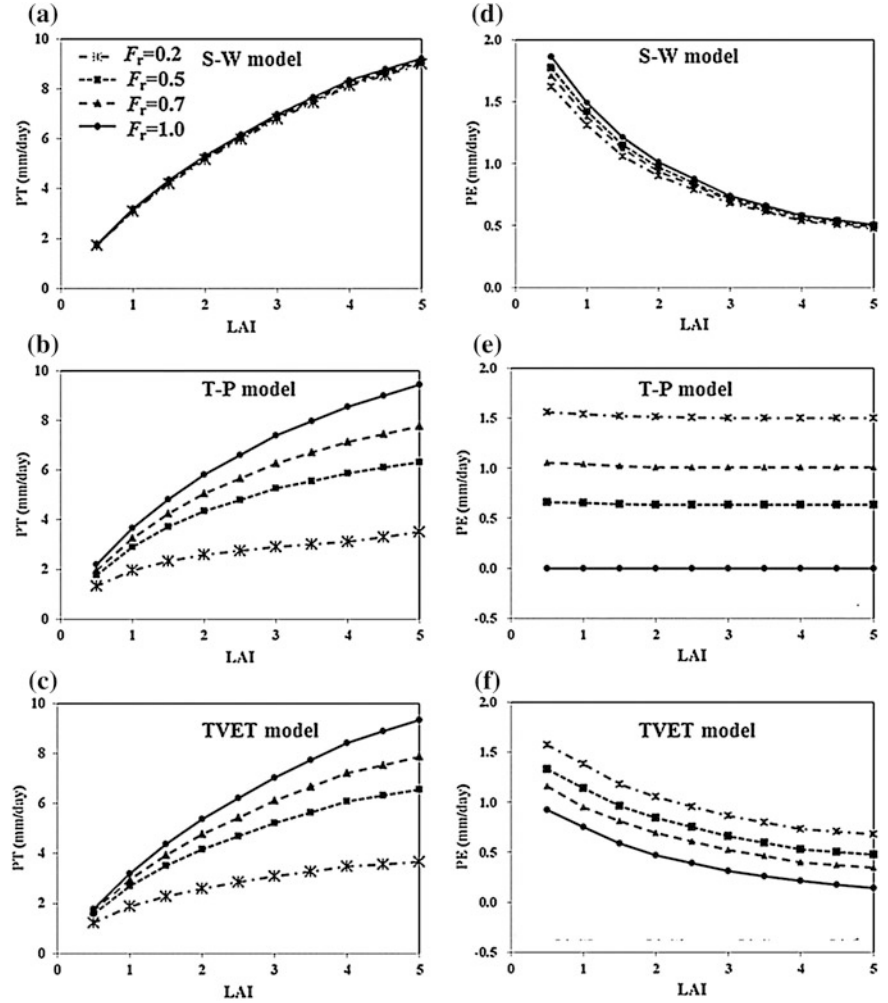


Fig. 2.7 Variations in PT and PE estimated from the three dual source models with those in LAI and F_r (Yang and Shang 2012)

2.5 Conclusion

Potential evapotranspiration depends greatly on local climate and vegetation distribution conditions, and is important in studying the cropland and basin hydrological circles. The chapter provides a detailed comparison of the performances among three dual-source evapotranspiration models, including the S-W model (layer approach), the T-P model (patch approach) and the TVET model (hybrid approach), in estimating and partitioning potential evaporation and potential

transpiration under different hypothetical vegetation distribution conditions. The S-W model ignores the difference of energy fluxes between under- and inter-canopy soil; while the T-P approach assumes a full radiation loading for both the canopy and inter-canopy soil and ignores the evaporation from under-canopy soil surfaces. The TVET model is a combination of the layer and patch models, and adopts the layer approach to partition available energy between canopy and soil and uses the patch approach to calculate energy fluxes. As a result, both under- and inter-canopy soil evaporation were estimated and distinguished in the TVET model. In simulation scenarios, the height of vegetation was assumed to be 5 m with canopy leaf area index of 2 and minimum stomatal resistance of 170 s/m. The bulk surface leaf area index (LAI) varied from 0.5 to 5, and fractional vegetation coverage (F_c) varied from 10 to 100 %. The vegetation clumpy patterns were quantified by fixing LAI while varying F_c . The climate data was obtained from the Linhe meteorological station located in an arid region in central Inner Mongolia of North China. The results indicated that both the patch and hybrid model performed reasonably well in estimating potential evapotranspiration under homogeneous vegetation distribution conditions. However, the S-W model tended to overestimate potential evapotranspiration, as it generally gave higher potential evaporation estimates. The overestimation in potential evapotranspiration by the S-W model was increased with the increase of F_r and the decrease of LAI. In contrast, the T-P model had a tendency to underestimate potential evaporation, especially with high F_c and low LAI. For heterogeneous vegetation distribution conditions, potential evapotranspiration estimated from the S-W model was generally higher than that given by the T-P and TVET model, particularly with low F_r . Potential evaporation (potential transpiration) from the S-W model increases (decreases) with the increase of LAI. However, both variables from the S-W model did not change with changes of F_r . In contrast, potential transpiration estimated from the T-P and TVET model was increased with the increase of both LAI and F_r . Potential evaporation from the T-P model was increased with the increase of F_r , but kept relative constant under various LAI conditions, while potential evaporation from the TVET model was increased with the decrease of both F_c and LAI. The above results suggest that the S-W model may give reasonable potential transpiration estimates over homogeneous vegetated surfaces, while the T-P model is more suitable for surfaces with lower fractional and clumped vegetation cover. By contrast, the TVET model performs better than both the S-W model and the T-P model, which can be used to estimate potential evaporation and potential transpiration partitioning for a wide range of surfaces with different vegetation distribution patterns.

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