國立臺灣大學生物環境資源暨農學院

生物環境系統工程學研究所

碩士論文

Department of Bioenvironmental Systems Engineering

College of Bioresources and Agriculture

National Taiwan University

Master Thesis

濕草地上的植披阻抗

The Canopy Resistance of a Humid Grassland

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中華民國 106 年 6 月

June 2017

doi:10.6342/NTU201703681

國立臺灣大學（碩）博士學位論文
口試委員會審定書

中文題目：濕草地上的植披阻抗

英文題目：The Canopy Resistance of a Humid Grassland

本論文係 呂俊德 君（學號 R04622011）在國立臺灣大學生物環境系統工程研究所完成之碩士學位論文，於民國 106 年 6 月 1 日承下列考試委員審查通過及口試及格，特此證明

口試委員：

（簽名）

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Acknowledgement

首先要謝謝我的指導教授謝正義老師在大學和研究所期間對我的指導和照顧，在這六年的時間裡學到很多東西。也謝謝陳奕穎老師和朱佳仁老師在口試時提出諸多意見和建議，讓人發現原來自己可以更進一步的空間還有很多。

再來是謝謝碩士班期間在同一個研究室裡一起互相幫助和成長的丞駿學長、政崴和映辰。實在是無法想像沒有你們幫忙的話，這兩年的時間會過得多麼艱難。還要謝謝碩士班的朋友們，謝謝你們幫我在碩士班期間留下除了寫論文之外還有其他無可取代的回憶。

最後是感謝我的家人們。謝謝你們在我背後的支持。因為有你們，才有我現在的成就。非常感謝。

doi:10.6342/NTU201703681

摘要

植披阻抗(canopy resistance)為在使用 Penman-Monteith 法預測蒸發散量時的重要參數。因此為了預估蒸發散量，必須了解植披阻抗的特性。Pauwels 和 Samson 在 2006 年時，在一斜坡上的濕草地比較不同預測植披阻抗的方法。結果顯示 Katerji and Perrier method (Katerji and Perrier, 1983)有較佳的預估能力。在本研究中，我們嘗試利用相同的概念並比較六個預估植披阻抗的方法，包含：Jarvis type equation (Jarvis, 1976; Stewart, 1988)，Jarvis-Blanken and Black method (Blanken and Black, 2004)，Todorovic method (Todorovic, 1999)，Katerji and Perrier method，新方法和固定的植披阻抗值。研究地位於愛爾蘭的西南方科克縣 (Ireland, County Cork(51°59″N 8°46″W))，主要物種為多年生黑麥(*Lolium perenne* L.)。本研究利用渦流相關法(eddy covariance)量測濕草地上的潛熱通量。觀測的植披阻抗由 Penman-Monteith 法以及量測的熱及潛熱通量回推而得。研究結果顯示，潛熱通量的預估值好壞與植披阻抗的預估值好壞相關性不大。此外，Katerji and Perrier method 和新方法在本研究中相對其他方法皆可較佳的預測植披阻抗以及潛熱通量。

關鍵詞：蒸發散；植披阻抗；濕草地；Penman-Monteith 法；新方法

doi:10.6342/NTU201703681

Abstract

Canopy resistance is a key parameter for implementing the Penman-Monteith equation, which is a well-known method of estimating evapotranspiration. In order to estimate evapotranspiration, it is essential to know the knowledge concerning canopy resistance. Recent research (Pauwels and Samson, 2006) compared different methods of estimating the canopy resistance above a wet sloping grassland and showed that Katerji and Perrier method (Katerji and Perrier, 1983) had better performance on estimating canopy resistance. In this study, we tried to use the same idea and compared six methods to estimate canopy resistance, which are the Jarvis type equation (Jarvis, 1976; Stewart, 1988), the Jarvis-Blanken and Black method (Blanken and Black, 2004), the Todorovic method (Todorovic, 1999), the Katerji and Perrier method, a new approach and constant canopy resistance. The study site was located in County Cork, southwest Ireland (51°59″N 8°46″W), and perennial ryegrass (*Lolium perenne* L.) was the dominant grass species in this area. An eddy covariance system was used to measure the latent heat flux above this humid grassland. The observed canopy resistance was calculated by rearranging the Penman-Monteith equation combined with the observed latent and sensible heat flux. Our results showed latent heat flux estimation as being less sensitive to the accuracy of canopy resistance predictions. We also found that the Katerji

doi:10.6342/NTU201703681

and Perrier method and the new approach have better performance than other methods in estimating the canopy resistance and latent heat flux.

Keywords: Evapotranspiration; canopy resistance; humid grassland; Penman-Monteith equation; new approach

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1 Introduction

Canopy resistance is a required parameter in the Penman-Monteith equation for estimating evapotranspiration. The level of accuracy in evapotranspiration estimation may have an impact on management of water resources because evapotranspiration can account for 60% for terrestrial precipitation in the hydrological cycle (Shiklomanov, 1998). To a better estimation of evapotranspiration, it is necessary to understand canopy resistance estimation to apply Penman-Monteith equation for such estimation.

In estimating evapotranspiration, Penman (1948) was the first to combine the concept of using available energy and mass transfer to compute evaporation from an open water surface. Monteith (1965) modified Penman's equation by integrating plant physiological and micrometerological parameters, leading to the well known Penman-Monteith equation. Canopy resistance is one of the parameters in the equation that characterizes the stomatal control on transpiration and the effect of the canopy structure on evaporation. However, it is hard to estimate the stomatal resistance, as it depends on multiple factors such as temperature, solar radiation, vapor pressure deficit, carbon dioxide concentration, soil water content, and the position of leaves in the canopy. Moreover, mechanisms between environmental conditions and plant physiology have not been elucidated thoroughly yet (Berry et al., 2010; Damour et al., 2010).

doi:10.6342/NTU201703681

Therefore, the challenges that exist for using the Penman-Monteith equation owe to unknown parts of canopy resistance knowledge.

Several canopy resistance estimation approaches, which need calibrations for different vegetation types and climatic conditions, have been proposed. When estimating the canopy resistance, one would doubt the usefulness of these approaches due to unknown partions concerning canopy resistance. However, when the specific vegetation type and climatic conditions are given, reasonable estimations can be obtained by corresponding typical values of the coefficients. One of the approaches is the Jarvis multiplicative model (Jarvis, 1976; Stewart, 1988) based on plant physiological studies. Jarvis multiplicative model showed that canopy resistance was related to leaf area index and several climatic variables such as solar radiation, vapor pressure deficit, air temperature and soil moisture content. Another approach is the Katerji and Perrier method. Katerji and Perrier (1983) developed a linear model to estimate canopy resistance which depended on climatic variables and aerodynamic resistance.

Todorovic (1999) proposed a mechanistic approach to compute canopy resistance that was also a function of climatic variables and aerodynamic resistance, but does not need to be calibrated. Instead of assigning variable canopy resistance to the

doi:10.6342/NTU201703681

Penman-Monteith equation, a monthly averaged canopy resistance was suggested by Pauwels and Samson (2006).

Thus far, researchers have compared different approaches that estimate canopy resistance for different vegetation types under varying weather conditions. Lecina et al. (2003) concluded that a constant canopy resistance (70 s/m), which was recommended by Allen et al. (1998), could be used to estimate daily reference evapotranspiration under a semiarid condition in a river valley with uniform grasses. However, if daily reference evapotranspiration values were computed by hourly meteorological averages, the Todorovic model was recommended instead. Blanken and Black (2004) constructed a series relationship between canopy conductance and climatic variables using the Jarvis type equation, and showed that canopy conductance could be well parameterized in a boreal aspen forest. Perez et al. (2006) compared different methods such as the constant canopy resistance, the Katerji and Perrier method, and the Todorovic method under semi-arid conditions in a river valley with uniform grasses. The results suggested that through constant canopy resistance, there may be an underestimate of evapotranspiration values in the summer and an overestimate in the winter. Furthermore, the Todorovic method was shown to have performed better than other methods. Pauwels and Samson (2006) also compared different methods but in their case for a wet sloping

doi:10.6342/NTU201703681

grassland. The results showed that the Katerji and Perrier method provided better performance than Todorovic method. In addition, it was shown that using a monthly averaged surface resistance instead of a constant value would lead to a better estimation of evapotranspiration at seasonal time scale. Li et al. (2015) compared the Jarvis multiplicative model, Katerji and Perrier method, Todorovic method, and other surface resistance models under arid conditions with a dense canopy (maize field) and a partial canopy (vineyard). Their results showed that both the Jarvis multiplicative model and the Katerji and Perrier method performed better on dense canopy than partial canopy, whereas the Todorovic method performed poorly on both cases. Table 1 summarizes the performance comparison between different canopy resistance estimation methods above.

Though the best parameterization in Blanken and Black (2004) is much simpler than the Jarvis multiplicative model, it still requires certain parameters not measured in typical climate stations (e.g., CO_2 mixing raito). Moreover, Blanken and Black (2004) showed that the Jarvis type equation, which is simpler than the original Jarvis multiplicative model, can also provide good performance. In accordance with previous studies, canopy resistance estimation methods may have different specific responses to different climatic conditions and vegetated surfaces. Therefore, in this study, our objectives were to develop a relative simple method for estimating canopy resistance

doi:10.6342/NTU201703681

whose parameters can be measured in typical climate stations and to compare the developed method with other methods of estimating the canopy resistance of a humid grassland.

2 Experiment

2.1 Site description

The study site (Latitude 51°59'N; longitude 8°46'W) is located in 25 km northwest of County Cork, southwest Ireland. The climate is temperate and humid. The regional 30-year average air temperature is 9.6°C, and average annual precipitation is 1222.7 mm (Met Eireann, 1970-2000 Cork Airport Meterological Station). Data collection commenced January 1, 2013 and continued to December 31, 2013. In the study period, the daily mean temperature was 17.67°C in July and 5.04°C in January; the hourly maximum net radiation was 747.8 W/m^2 in July and 217.8 W/m^2 in January. Annual rainfall was 1161 mm. The average elevation of the study area is 200 m above sea level. The dominant plant species is perennial ryegrass (*Lolium perenne* L.), and the grass height is varies between 0.2 and 0.45 m during summer. The leaf area index during summer and winter are about 2.0-2.5 m^2/m^2 and 0.5-1.0 m^2/m^2, respectively. The grassland consists of individual paddocks which are all intensively managed. Grazing

doi:10.6342/NTU201703681

occurs during from late March to early October, and fertilizer is applied throughout the year (Peichl et al., 2011).

2.2 Instrumentation for micrometeorological measurements

Precipitation was measured with a tipping bucket rain gauge (ARG100, Environmental Measurements Ltd., UK). Net radiation and solar irradiance were measured with a net radiometer (CRN1, Kipp and Zonen, Netherlands). Air temperature and humidity were measured with a temperature and humidity probe (HMP45C, Campbell Scientific, UK). Ground heat flux was measured with a heat flux plate (HFP01, Hukseflux, Delft, Netherlands). These instruments were mounted at 0 m, 4 m, and 2.5 m above the ground, and also at 0.1 m below the ground. A 1 minute sample frequency was used for all meteorological measurements, and all data was averaged every 30 minutes. All average data was logged by a CR23X datalogger (Campbell Scientific, USA).

In this study, observed surface fluxes, latent heat, and sensible heat flux were measured using the eddy covariance method. The 3D wind velocity was measured with a 3D sonic anemometer (CSAT3, CS, Logan, Utah, USA). Water and carbon dioxide concentration were measured with an open path infrared gas analyzer (LI-7500, Licor, USA). Both instruments were mounted at 5 m above the ground, and all data was logged

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at 10Hz and averaged in 30 minute intervals. Table 2 shows a summary of the instrumentation.

2.3 Data processing

In order to obtain corrected flux data, data processing followed standard process. Outliers (±3 σ) in raw data were removed. Wind speed and wind direction were double rotated to align the coordinate system (Wilczak et al., 2001). Webb correction was applied to rectify data variations in air density (Webb et al., 1980). Energy closure correction was applied to the sensible and latent heat flux data by considering the Bowen ratio measured by eddy covariance (Twine et al., 2000; Wilson et al., 2002; Sumner and Jacob, 2005; Anderson et al., 2007; Tsai et al., 2007; Wang and Dickinson, 2012).

Filters were used to remove unreasonable data. Foremost, as the eddy covariance system performed poorly during rainy days, observed values in rainy days were rejected. Secondly, in order to get accurate data, a canopy resistance filter was used to screen out unsatisfactory data. Thirdly, since the daytime canopy resistance was a concern, a net radiation threshold of 50 W/m^2 and a positive sensible heat flux were set for selecting daytime data.

doi:10.6342/NTU201703681

Since the main source of the evapotranspiration is from canopy transpiration under full canopy conditions, surface resistance can be treated as the canopy resistance through neglecting soil resistance. In concerning full canopy condition, the dataset during summer (June, July and August, 2013) were used for this study. The calibration dataset was determined by the top one third of the dataset, and the validation dataset was determined by the remaining.

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3 Methods

3.1 Penman-Monteith equation

The Penman-Monteith equation was used to estimate the actual evapotranspiration from a vegetated surface (Monteith, 1965; 1981). It is expressed as:

$$\mathrm{LE} = \frac{s(R_n - G) + C_p \rho_a \delta q / r_a}{s + \gamma(1 + r_c / r_a)} \tag{1}$$

where LE is the latent heat flux density (W/m^2), $\gamma = C_p/L$ is the psychrometric constant (1/K), L is the heat of evaporation (J/kg), s is the rate of the change of saturated specific humidity with temperature (1/K), R_n is the net radiation (W/m^2), G is the soil heat flux (W/m^2), C_p is the specific heat of moist air (J/kg/K), ρ_a is the air density (kg/m^3), δq is the specific humidity deficit (kg/kg), and r_c is the canopy resistance. The aerodynamic resistance (r_a) can be calculated as (Thom, 1972):

$$\mathrm{r_a} = \frac{\ln\left(\frac{z-d}{z_{0M}} + \psi_M\right) \ln\left(\frac{z-d}{z_{0H}} + \psi_H\right)}{k^2 u_z} \tag{2}$$

$$\mathrm{d} = \frac{2}{3} h \tag{3}$$

$$z_{0M} = 0.1h \tag{4}$$

$$z_{0H} = 0.1 z_{0M} \tag{5}$$

where z is the measurement height (m), d is the zero plane displacement height (m), h is the canopy height (m), z_{0M} is the roughness length for momentum transfer (m), z_{0H} is the roughness length for heat transfer (m), ψ_M is the stability correction

doi:10.6342/NTU201703681

function for momentum transfer, ψ_H is the stability correction function for heat transfer, k is the von Kármán constant (0.4), and u_z is the wind speed at the measurement height (m/s).

By rearranging equation (1), $\mathrm{r_c}$ can be computed with observed data as:

$$\mathrm{r_c} = \frac{\rho_a C_p}{\gamma}\frac{\delta q}{LE} + \left(\frac{s}{\gamma}\beta - 1\right) r_a \tag{6}$$

where β ($=$ H/LE) is the Bowen ratio and H is the sensible heat flux (W/m^2).

3.2 Jarvis multiplicative model

Based on the plant physiological studies, Jarvis (1976) proposed the multiplicative model for estimating the stomatal resistance/conductance. In 1988, Stewart simplified the parameterization, and the classical Jarvis multipliacative model can be expressed as:

$$\mathrm{r_c} = \frac{r_{st}}{LAI} = \frac{a_1}{LAI * f(R_{si}) * f(D_a) * f(T_a) * f(\theta)} \tag{7}$$

$$f(R_{si}) = \frac{R_{si}(1000 + a_2)}{1000(R_{si} + a_2)} \tag{8}$$

$$f(D_a) = \exp(-a_3 * D_a) \tag{9}$$

$$f(T_a) = \frac{(T_a - T_L) * (T_H - T_a)^t}{(a_4 - T_L) * (T_H - a_4)^t}, t = \frac{T_H - a_4}{a_4 - T_L} \tag{10}$$

$$f(\theta) = \frac{\theta - \theta_w}{\theta_f - \theta_w} \tag{11}$$

where $\mathrm{r_{st}}$ is the stomatal resistance, a_1 is the minimum stomatal resistance observed in optimal condition (see Appendix B), a_2, a_3 and a_4 are parameters to be fitted, LAI

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is the leaf area index (m^2/m^2), R_{si} is the incoming shortwave radiation (W/m^2), T_a is the air temperature (^oC), T_L is the lower temperature limit to transpiration (0^oC was assumed by Stewart, 1998), T_H is the upper limit to transpiration (40^oC was assumed by Stewart, 1998), D_a is the vapor pressure deficit (kPa), θ is the soil water content (m^3/m^3), θ_w is the wilting point (m^3/m^3) and θ_f is the field capacity (m^3/m^3).

In this study, two kinds of the modified Jarvis model were used to estimate canopy resitance:

3.2.1 Jarvis type model (Jarvis f(R_{si}, Da))

In this study the traditional Jarvis multipliacative model (i.e., equation (7)) was simplified to the following equation:

$$r_c = \frac{a_1}{f(R_{si}) * f(D_a)} \tag{12}$$

where a_1 is the minimum canopy resistance in the calibration dataset. a_2 and a_3 were derived from the regression coefficients. The leaf area index was omitted because land was fully covered and LAI was constant (around 2 m^2/m^2, Peichl et al., 2011) during analysis period. Additionally, the air temperature and soil moisture content were omitted because the data showed no relationship with the canopy resistance at this site.

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3.2.2 Jarvis-Blanken and Black method

Blanken and Black (2004) compared several methods and showed that canopy conductance can be best parameterized by the modified Ball-Woodrow-Berry index ($\mathrm{BWB} = \mathrm{A_n}/(D_0 x_0^c)$), where $\mathrm{A_n}$ is the net CO_2 assimilation, D_0 is the leaf level vapor pressure deficit, and x_0^c is the CO_2 mole fraction. However, due to the difficulty for measuring CO_2 concentration, another method (which only included vapor pressure deficit) was proposed, which has the following form:

$$\mathrm{r_c} = \frac{a_1}{f(D_a)} \tag{13}$$

where a_1 was derived from the regression coefficients. The detailed procedure is showed as below:

First, an average canopy conductance was calculated at binned 0.25 kPa intervals of vapor pressure deficit. Then, an exponential regression was fit between these average canopy conductance values and the corresponding vapor pressure deficit. Finally, parameters were determined from over 20 equally spaced bins. In order to compare outcomes to other methods, average canopy conductance was replaced by average canopy resistance. Thus, this relationship is similar to the Jarvis multiplicative model but only contains vapor pressure deficit. Due to the humid conditions in this study,

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parameters were determined from means of only 6 equally spaced bins, at same binned 0.25 kPa intervals of vapor pressure dificit.

3.3 Todorovic method (TD)

Todorovic (1999) assumed that if the vegetated surface is not fully wet (r_c>0), part of the available energy is required to heat the canopy to extract water. Therefore, this additional energy would raise the canopy temperature by an amount t, which is the temperature difference between the mean level ($\mathrm{d} + \mathrm{z}_{0\mathrm{M}}$) of source or sink for H and LE and the level in canopy. Assuming that the resistance for heat transferred from canopy to $\mathrm{d} + \mathrm{z}_{0\mathrm{M}}$ is equal to r_c, r_c could be estimated by a quadratic equation including isothermal resistance, also termed as climatological resistance by Todorovic. This quadratic equation is defined as:

$$a\left(\frac{r_c}{r_i}\right)^2 + b\left(\frac{r_c}{r_i}\right) + c = 0 \tag{14}$$

where

$$\mathrm{a} = \frac{s + \gamma(r_i/r_a)}{s + \gamma}\left(\frac{r_i}{r_a}\right)(D_a) \tag{15}$$

$$\mathrm{b} = -\gamma\left(\frac{r_i}{r_a}\right)\mathrm{t} \tag{16}$$

$$\mathrm{c} = -(s + \gamma)t \tag{17}$$

In equations (14-16), r_i is the isothermal resistance firstly introduced by Monteith (1965) and defined as:

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$$r_i = \frac{\rho_a C_p \delta q}{\gamma(R_n - G)} \tag{18}$$

Isothermal resistance (r_i) is simply the sum of rc+ra under the isothermal condition ($\partial T_a / \partial z = 0$), which H =0 and LE= Rn-G.

A linear relationship between saturation vapor pressure and temperature and neutral atmospheric conditions were assumed by Todorovic (1999). As a result, the temperature difference could be defined as:

$$\mathrm{t} = \frac{\gamma D_a}{s(s + \gamma)} \tag{19}$$

Solving for equation (14), the unknown r_c could be solved as:

$$\frac{\mathrm{r_c}}{r_i} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{20}$$

and only one positive solution ($+r_c$) would be adopted. Because only climatic variables are needed, calibration is not needed in this method. Therefore, only a validation dataset were applied to estimate r_c.

3.4 Katerji and Perrier method (KP)

Katerji and Perrier (1983) derived a linear relationship between canopy, aerodynamic, and climatic resistances (r*) based on the experimental studies. This canopy resistance model can be written as:

$$\frac{\mathrm{r_c}}{r_a} = a_1 \frac{r^*}{r_a} + a_2 \tag{21}$$

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where a_1 and a_2 are empirical coefficients to be determined, and r* is the climatic resistance defined as:

$$r^* = \frac{s+\gamma}{s\gamma}\frac{\rho_a C_p \delta q}{R_n - G} = \frac{s+\gamma}{s} r_i \tag{22}$$

Climatic resistance is linked to the isothermal resistance and the term “climatic” references all factors dependent on climate. In addition, climatic resistance is the critical resistance when LE equals to the equilibrium evapotranspiration, and then we have $r^*=r_c$. Thus, r* is also termed as “critical” resistance.

By combining equations (21) and (22), it can show that

$$r_c = a_1 \frac{s+\gamma}{s\gamma}\frac{\rho_a C_p \delta q}{R_n - G} + a_2 r_a = a_1 \frac{1}{\gamma}\frac{\rho_a C_p \delta q}{LE_{eq}} + a_2 r_a \tag{23}$$

Comparing equation (23) with (6), a_1 is the reciprocal of the dimensionless parameter (see 3.5) proposed by Priestley and Taylor (1972) when $(s/\gamma)\beta - 1$ (i.e., the third term in equation (6)) approaches zero, and a_2 is related to β.

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3.5 New approach

Priestley and Taylor (1972) proposed a method which is based on the assumption that under humid conditions the contribution to LE by the mass transfer term is smaller than the energy term, leading to equilibrium evapotranspiration. Equilibrium evapotranspiration would occur if the near surface is saturated. However, equilibrium conditions rarely occur. Therefore, a dimesionless parameter, Priestley-Taylor coefficient (α), was suggested to compensate for the mass transfer term. The LE can be calculated as

$$\mathrm{LE} = \alpha \mathrm{LE}_{\mathrm{eq}} = \alpha \frac{s}{s+\gamma}(R_n - G) \quad (24)$$

By rearranging equation (24), α could be estimated as a coefficient by a linear relationship between observed LE and $\mathrm{LE}_{\mathrm{eq}}$. Then, substituting equation (24) for LE and Rn-G-LE for H in equation (6), a new method for estimating r_c could be expressed as:

$$\mathrm{r_c} = \frac{\rho_a C_p \delta q}{\gamma} \frac{s+\gamma}{\alpha s(R_n - G)} + \left(\frac{s+\gamma-\alpha s}{\alpha\gamma} - 1\right) r_a \quad (25)$$

In equation (25), only the Priestley –Taylor coefficient (α) is needed.

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3.6 Constant canopy resistance

In order to simplify the predicted model, an optimized constant r_c was used in this study. In optimization, the minimum root mean square error (RMSE) between the observed LE with observed r_c, derived from equation (6) and predicted LE with constant r_c, was tried to find in the calibration dataset. Then, this optimized constant $r_{c,}$ which could minimize RMSE between observed LE and predicted LE, would be applied in the validation dataset to predict LE. Hseih et al. (2005) recommended about a 100 (s/m) of canopy resistance value through out the year in this study site.

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4 Results and discussion

4.1 Daily pattern of observed r_c and LE

Figure 1 and Figure 2 show the observed daytime r_c and LE for the specific days (25-26 June, 2013) and the daytime course of observed mean r_c and LE, respectively. For the mean r_c, r_c remains relatively constant from about 10:00 to 17:00, and then r_c tends to steadily increase since stomata tend to close in the late afternoon. According to the data, when LE is smaller than 50 W/m^2, the mean r_c is about 300 s/m. Thus, a r_c value of 300 (s/m) assumes stomata closing to reduce LE. (Lecina et al. (2003) proposed that r_c was 200 s/m during nighttime). Another factor which controls the magnitude of the LE is the available energy (R_n-G). Due to a low available energy during sunrise and sunset, the magnitude of LE stays low value in the morning and late afternoon.

Comparing the observed daytime r_c in this study to other literatures (see appendix C), the value of observed r_c, which range from 10 to 250 s/m, are similar to other results of grass type, and are different from the result of forest type.

doi:10.6342/NTU201703681

4.2 Calibration of models

Table 3 and Figure 3-5 show the results of the parameters determined by regression fit for the calibration dataset, which is the top one third of the dataset in the analyzed period. For the Jarvis type model (Jarvis f(R_{si}, Da)), the regression coefficients of a_1, a_2 and a_3 are 10.58, 240.10 and 1.94, respectively in equation (7)-(9) and the coefficient of determination (R^2) is 0.32. For the Jarvis-Blanken and Black method, the regression coefficients of a_1 and a_3 are 38.03 and 1.00, respectively in equation (13) and the R^2 value is 0.93, showing a high relationship because only 6 binned values were made for regression. Nevertheless, this result of the regression coefficients is similar to the method which only fits a simple exponential regression between original r_c and D_a ($r_c = 38.03/\exp(-1.02 * D_a)$ and the R^2 value is 0.33). For the Katerji and Perrier method (KP), the regression coefficients of a_1 and a_2 are 0.48 and 0.95, respectively, in equation (21), and the R^2 value is 0.18, showing a poor relationship. The reason for the poor performane for KP method will be discussed in the next section (see 4.3). For the new approach we proposed, the parameter α in equation (24) is 0.87 and the R^2 value is 0.87 in this study area.

doi:10.6342/NTU201703681

4.3 Comparison of models in predicting r_c

Table 4 and Figure 6-10 show linear regression and statistics of comparison between the observed r_c and the predicted r_c calculated by each method, which are the Jarvis type equation, Jarvis-Blanken and Black method, Todorovic method, Ketriji and Perrier method, and the new approach we proposed. For all methods, statistic results show poor estimation for predicting r_c. The root mean square errors (RMSE) range from 72.05 to 93.94, and the coefficients of determination (R^2) range from 0.20 to 0.37. For an optimized constant r_c value, a 63.26 (s/m) (the average and standard deviation of r_c are 71.94 s/m and 46.14 s/m, respectively) r_c value could minimize the RMSE in calibration dataset.

Reasons for the poor estimation for r_c might be result from several factors not considered in each of the methods. As we mentioned in section 4.1, stomata would close when r_c is greater than 300 s/m. Figure 18 depicts the predicted r_c not accurately estimating when stomata are closing in the late afternoon, because methods we applied in this study are used to estimate r_c when stomata is open. Furthermore, previous studies (Todorovic,1999, Fig. 7; Perez et al., 2006, Fig. 5; Pauwels and Samson, 2006, Fig. 7) showed that it is common to have a bad performance on estimating r_c regardless of a monthly or hourly basis.

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In the case of the TD method, although TD method is convenient for there is no need of determining the coefficients a priori, the estimation results are shown to be the poorest estimations in this study. Katerji et al. (2011) indicated that assumptions in TD method do not correspond to reality. For example, resistance for heat transferred from canopy to $d + z_{0M}$ is not equal to r_c and TD method mainly depends on D_a, whereas negligence of the significance from r_a and R_n occurs. Nevertheless, if the TD method is still used to estimate r_c, the irrigated grass with low sensitivity to r_c continues as recommended for the use of the TD method. The TD method can still be adopted for a LE estimation when the site is an irrigated grassland where evapotranspation is less sensitive to r_c.

In the case of KP method, Perez et al. (2006) shows that parameters in KP method are dependent on Bowen ratio values, which are in the interval [-0.5, 0.5]. During summer, Bowen ratios in this study are ranges from 0 to 2.5. By considering the dependence on Bowen ration values, the estimation for r_c would be improved (not shown). However, as the Bowen ratio value is not available in normal experimentation, other ways to enhance the accuracy of the KP method have to be considered.

In the case of a new approach we proposed, the estimated result is related to the performance of the parameter (α) in equation (24). Besides, it also depends on β.

doi:10.6342/NTU201703681

Figure 11 depicts that if β is remained in equation (25) (only substitute LE_{eq} for LE), the performance on estimating r_c shows best results, the RMSE and R^2 are 25.65 and 0.97, respectively.

As for an optimized constant value in the analyzed period, the value (63.26 s/m) we calculated is lower than the value (100 s/m) Hsieh et al. (2005) recommended. Because only daytime data are concerned, the constant r_c we calculated is reasonable to be lower than the value calculated for whole day. In addition, the mean and standard deviation value of r_c in the validation dataset are 75.95 s/m and 90.45 s/m, respectively. This indicates that there is a difference between optimized r_c and the mean value in the validation dataset.

doi:10.6342/NTU201703681

4.4 Comparison of models in predicting LE

Table 5 and Figure 12-17 show linear regression and statistics of comparison between the observed LE and the predicted LE by each method, which are the Jarvis type equation, the Jarvis-Blanken and Black method, the Todorovic method, the Ketriji and Perrier method, a new approach, and constant canopy resistance. Instead of poor results for estimating r_c, the statistic results demonstrated good LE estimations. The RMSEs range from 32.16 to 57.84 and the R^2 ranges from 0.73 to 0.90.

Table 5 demonstrated that constant r_c can also predict LE well, but varied r_c calculated by models can improve this estimation by reducing LE RMSE from 53.70 to 32.16 (40% increased) and increase R^2 from 0.73 to 0.90.

We noticed that even when r_c is poorly predicted in the late afternoon, LE is actually not poorly estimated. This is due to closed stomata with a high value of r_c and can not be predicted well (Figure 18) However, at the same time, the low LE can be estimated not far away. Also, according to sensitivity analysis carried out from Rana and Katerji (1998), in the case of well watered crops, canopy resistance is responsible for 10-20% (case of grass) of the LE variation. Therefore, although the r_c estimation is poor, the results of LE estimation are still accurate.

doi:10.6342/NTU201703681

5 Conclusions

In this study, several methods (the Jarvis type equation, Jarvis-Blanken and Black method, Todorovic method, Katerji and Perrier method, the new approach, and constant canopy resistance) are used to estimate r_c of a humid grassland. The observed LE, by eddy covariance method, and the observed r_c, calculated by rearranging Penman-Monteith equation, are used to examine the performace of those methods. The results show that:

(1) each of r_c estimated methods shows poor estimations due to closed stomata, resulting in large r_c values in the late afternoon. Our new approach and the Katerji and Perrier method provide relatively better estimations than the others.

(2) contrary to r_c estimation, the results for LE estimation when applied estimated r_c in Penman-Monteith equation show well results.

(3) according to the results for LE estimation, though r_c is poorly estimated, the variable r_c estimation is still better than the constant value.

(4) our new approach strongly depends on the performance of the Priestley –Taylor coefficient (α) and the Bowen ratios (β).

(5) among the results for LE estimation, KP method provides the best performance.

doi:10.6342/NTU201703681

6 References

Allen, Richard G., et al. "Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56." FAO, Rome 300.9 (1998): D05109.

Anderson, Martha C., et al. "A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation." Journal of Geophysical Research: Atmospheres 112.D10 (2007).

Arnold, J. G., et al. SWAT input–output documentation, version 2012. Texas Water Resource Institute. TR-439, 2012.

Berry, Joseph A., David J. Beerling, and Peter J. Franks. "Stomata: key players in the earth system, past and present." Current opinion in plant biology 13.3 (2010): 232-239.

Blanken, P. D., and T. A. Black. "The canopy conductance of a boreal aspen forest, Prince Albert National Park, Canada." Hydrological Processes 18.9 (2004): 1561-1578.

Bremer, Dale J., et al. "Evapotranspiration in a Prairie ecosystem." Agronomy Journal 93.2 (2001): 338-348.

Cheng, Shih-Min. "山地柳杉森林之地表通量量測." 臺灣大學生物環境系統工程學研究所學位論文 (2010): 1-115.

doi:10.6342/NTU201703681

Damour, Gaëlle, et al. "An overview of models of stomatal conductance at the leaf level." Plant, Cell & Environment 33.9 (2010): 1419-1438.

Hsieh, Cheng-I., et al. "Photosynthetic responses of a humid grassland ecosystem to future climate perturbations." Advances in water resources 28.9 (2005): 910-916.

Jarvis, P. G. "The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field." Philosophical Transactions of the Royal Society of London B: Biological Sciences 273.927 (1976): 593-610.

Katerji, N., and A. Perrier. "A Modelisation de l'evapotranspiration reelle ETR d'une parcelle de luzerne: role d'un coefficient cultural." Agronomy for sustainable development 3.6 (1983): 513-521.

Katerji, Nader, Gianfranco Rana, and Salim Fahed. "Parameterizing canopy resistance using mechanistic and semi-empirical estimates of hourly evapotranspiration: critical evaluation for irrigated crops in the Mediterranean." Hydrological Processes 25.1 (2011): 117-129.

KORENER, C. "Maximum leaf diffusive conductance in vascular plants." Photosynthetica 13 (1979): 45-82.

doi:10.6342/NTU201703681

Lecina, S., et al. "Fixed versus variable bulk canopy resistance for reference evapotranspiration estimation using the Penman–Monteith equation under semiarid conditions." Agricultural Water Management 60.3 (2003): 181-198.

Li, Sien, et al. "Comparison of several surface resistance models for estimating crop evapotranspiration over the entire growing season in arid regions." Agricultural and Forest Meteorology 208 (2015): 1-15.

Monteith, John L. "Evaporation and environment." Symp. Soc. Exp. Biol. Vol. 19. No. 205-23. 1965.

Monteith, J.L., 1981. Evaporation and surface temperature. Quart. J. Roy. Meteorol. Soc. 107, 1–27.

Norman, J. M., and G. S. Campbell. "An introduction to environmental biophysics." Springer, New York. (1998).

Pauwels, Valentijn RN, and Roeland Samson. "Comparison of different methods to measure and model actual evapotranspiration rates for a wet sloping grassland." Agricultural Water Management 82.1 (2006): 1-24.

Peichl, Matthias, Paul Leahy, and Gerard Kiely. "Six-year stable annual uptake of carbon dioxide in intensively managed humid temperate grassland." Ecosystems 14.1 (2011): 112-126.

doi:10.6342/NTU201703681

Penman, Howard Latimer. "Natural evaporation from open water, bare soil and grass." Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences. Vol. 193. No. 1032. The Royal Society, 1948.

Perez, Pedro J., et al. "A simple parameterization of bulk canopy resistance from climatic variables for estimating hourly evapotranspiration." Hydrological processes 20.3 (2006): 515-532.

Priestley, C. H. B., and R. J. Taylor. "On the assessment of surface heat flux and evaporation using large-scale parameters." Monthly weather review 100.2 (1972): 81-92.

Rana, G., and N. Katerji. "A measurement based sensitivity analysis of the Penman-Monteith actual evapotranspiration model for crops of different height and in contrasting water status." Theoretical and Applied Climatology 60.1-4 (1998): 141-149.

Shiklomanov, Igor A. World water resources: a new appraisal and assessment for the 21st century: a summary of the monograph World water resources. Unesco, 1998.

Stewart, J. B. "Modelling surface conductance of pine forest." Agricultural and Forest meteorology 43.1 (1988): 19-35.

doi:10.6342/NTU201703681

Sumner, David M., and Jennifer M. Jacobs. "Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration." Journal of Hydrology 308.1 (2005): 81-104.

Thom, AS 1972. "Momentum, mass and heat exchange of vegetation." Quarterly Journal of the Royal Meteorological Society 98.415 (1972): 124-134.

Todorovic, Mladen. "Single-layer evapotranspiration model with variable canopy resistance." Journal of Irrigation and Drainage Engineering 125.5 (1999): 235-245.

Tsai, Jeng-Lin, et al. "Surface energy components and land characteristics of a rice paddy." Journal of Applied Meteorology and Climatology 46.11 (2007): 1879-1900.

Twine, Tracy E., et al. "Correcting eddy-covariance flux underestimates over a grassland." Agricultural and Forest Meteorology 103.3 (2000): 279-300.

Wang, Kaicun, and Robert E. Dickinson. "A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability." Reviews of Geophysics 50.2 (2012).

Webb, E. Kì, Graeme I. Pearman, and Ray Leuning. "Correction of flux measurements for density effects due to heat and water vapour transfer." Quarterly Journal of the Royal Meteorological Society 106.447 (1980): 85-100.

doi:10.6342/NTU201703681

Wilczak, James M., Steven P. Oncley, and Steven A. Stage. "Sonic anemometer tilt correction algorithms." Boundary-Layer Meteorology 99.1 (2001): 127-150.

Wilson, Kell, et al. "Energy balance closure at FLUXNET sites." Agricultural and Forest Meteorology 113.1 (2002): 223-243.

doi:10.6342/NTU201703681

Tables

Table 1. Comparison between different r_c estimation methods in the literature

Reference	Climatic condition	Plant type	Methods	Performance
Lecina et al. (2003)	Semiarid	Grassland	Katerji and Perrier	--
			Todorovic	Better
			Constant r_c	For daily use
Perez et al. (2006)	Semiarid	Grassland	Katerji and Perrier	--
			Todorovic	Better
			Constant r_c	--
Pauwels and Samson (2006)	Humid temperate	Grassland	Katerji and Perrier	Better
			Todorovic	--
			Constant r_c	--
			Monthly averaged	Better
Li et al. (2015)	Arid	Maize and vineyard	Jarvis multiplicative model	Better (Maize)
			Katerji and Perrier	Better (Maize)
			Todorovic	--
present study	Humid	Grassland	Jarvis($f(R_{si},D_a)$)	--
			Jarvis-Blanken and Black	--
			Katerji and Perrier	Better
			Todorovic	--
			Constant r_c	--
			New approach	Better

doi:10.6342/NTU201703681

Table 2. Summary of the instrumentation

Variable	Instrument	Measurement height (m)
H_2O (mmol/m^3) CO_2 (ppm)	Open path infrared gas analyzer (LI-7500)	5
U, v, w (m/s)	3D Sonic anemometer (CSAT3)	5
Net radiation (W/m^2) Shortwave incoming radiation (W/m^2)	Net radiometer (CNR1)	4
Ground heat flux	Heat flux plate (Hfp01)	-0.1
Precipitation (mm)	Tipping bucket rain gauge (ARG100)	0
T_{air} (^{0}C) Relative humidity (%)	Temperature/humidity probe (HMP45C)	2.5

doi:10.6342/NTU201703681

Table 3. Coefficients of each canopy resistance model obtained by regression fit. a_1, a_2 and a_3 are the parameters need to be fitted in each method and R^2 is the coefficient of determination.

Method	a_1	a_2	a_3	R^2
Jarvis(f(Rsi,Da))	10.58	240.10	1.94	0.32
Jarvis-Blanken and Black	38.03	--	1.00	0.93*
Katerji and Perrier	0.48	0.95	--	0.18

*: Reason for the high R^2 value for Jarvis-Blanken and Black method is that only 6 binned values were made for regression.

doi:10.6342/NTU201703681

Table 4. Linear regression (observed$_{rc}$ = a*predicted$_{rc}$ + b) and statistics of the comparison between predicted and onserved values of canopy resistance. a and b are the parameters need to be fitted in each method, R^2 is the coefficient of determination and RMSE is root mean square error.

Method	**a**	**b**	**R^2**	**RMSE**
Jarvis(f(Rsi,Da))	0.99	12.11	0.32	75.62
Jarvis-Blanken and Black	1.60	-30.83	0.20	82.83
Todorovic	3.26	-27.96	0.30	93.94
Katerji and Perrier	1.63	-29.80	0.36	75.88
New approach	1.08	-6.81	0.37	72.05

Table 5. Linear regression (observed$_{LE}$ = a*predicted$_{LE}$ + b) and statistics of the comparison between predicted and onserved values of latent heat flux (LE). a and b are the parameters need to be fitted in each method, R^2 is the coefficient of determination and RMSE is root mean square error.

Method	**a**	**b**	**R^2**	**RMSE**
Jarvis(f(Rsi,Da))	0.88	24.57	0.88	35.22
Jarvis-Blanken and Black	1.07	4.29	0.82	45.23
Todorovic	0.77	18.16	0.89	57.84
Katerji and Perrier	0.90	21.34	0.90	32.16
New approach	0.90	29.38	0.89	34.75
Constant r_c	0.87	41.11	0.72	53.70

doi:10.6342/NTU201703681

Figures

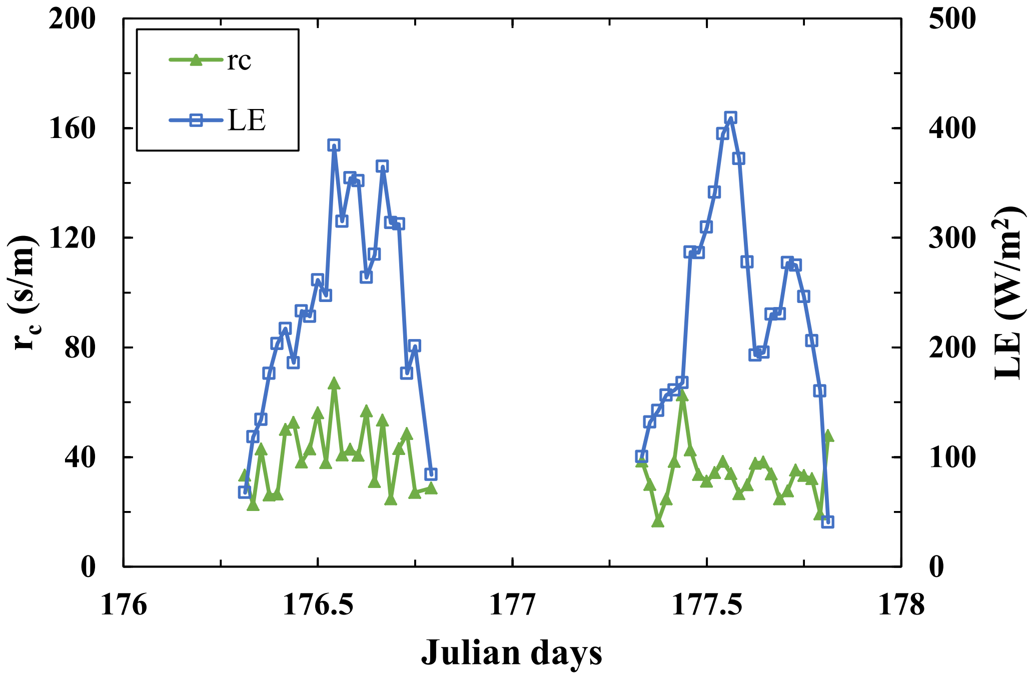

Figure 1. Observed daytime canopy resistance (r_c) and latent heat flux (LE) for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

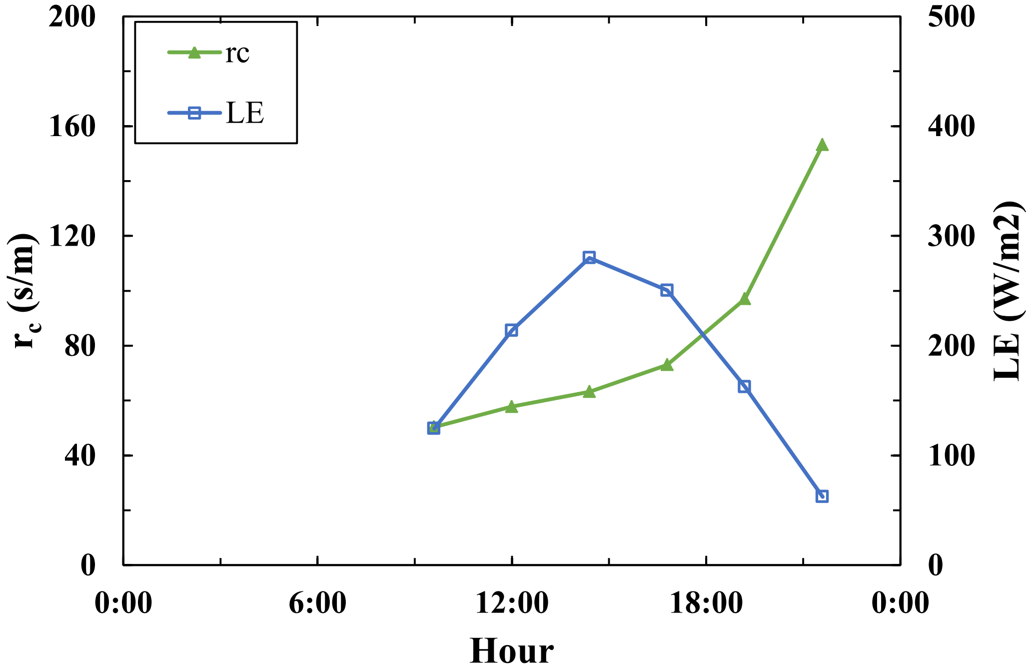

Figure 2. Observed daytime mean canopy resistance (r_c) and latent heat flux (LE)

doi:10.6342/NTU201703681

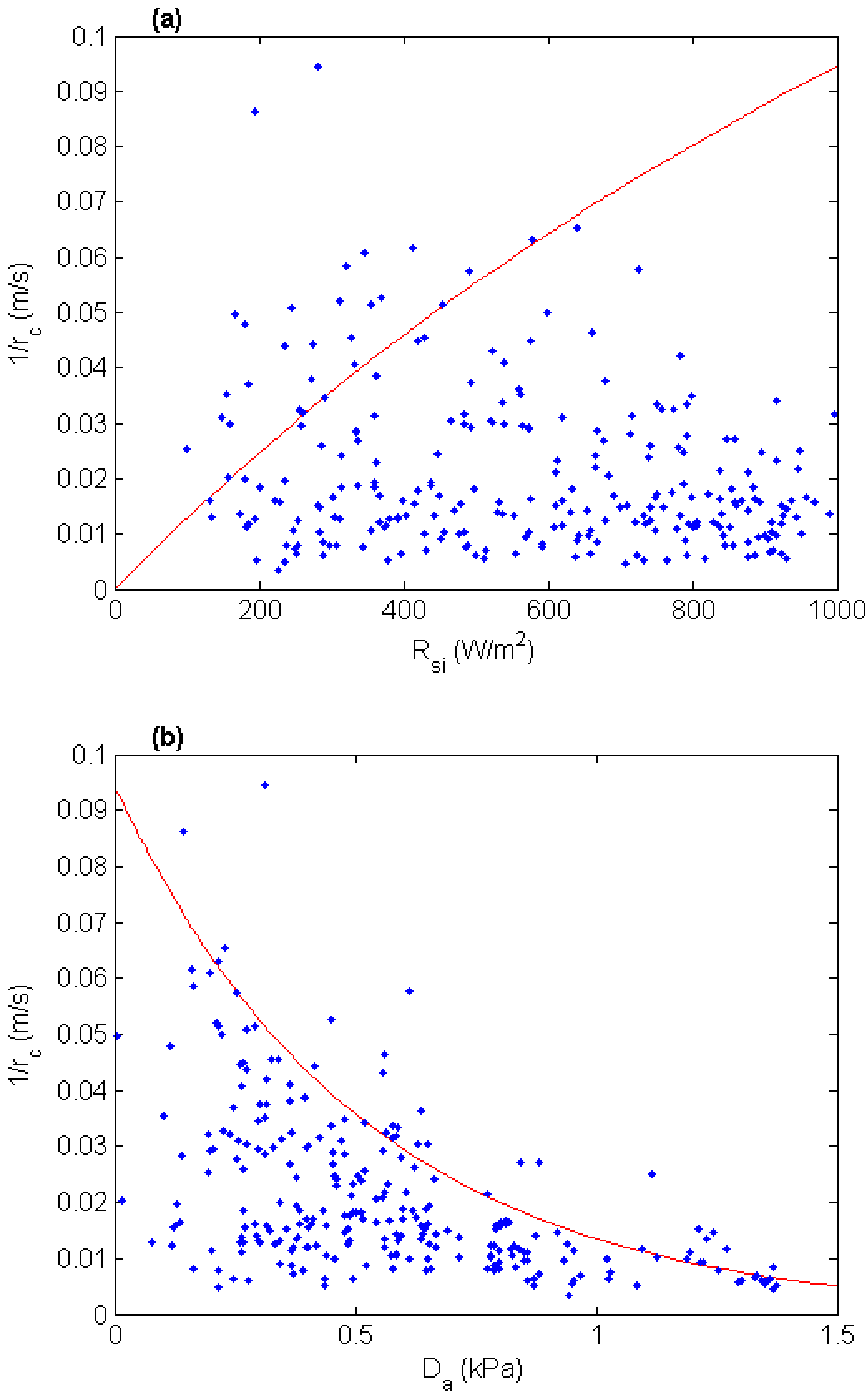

Figure 3. Relationship between the canopy conductance ($1/r_c$) and (a) shortwave incoming radiation (R_{si}) and (b) vapor pressure deficit (D_a) by Jarvis type model for the calibration dataset

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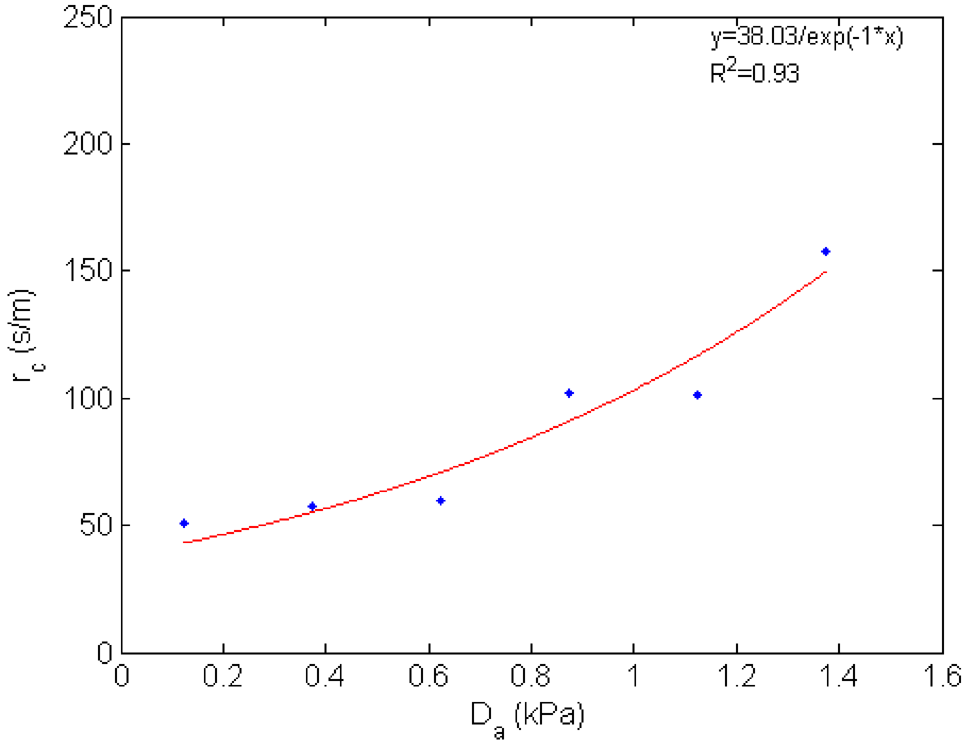

Figure 4. Relationship between canopy resistance (r_c) and vapor pressure deficit (D_a) by Jarvis-Blanken and Black method for the calibration dataset

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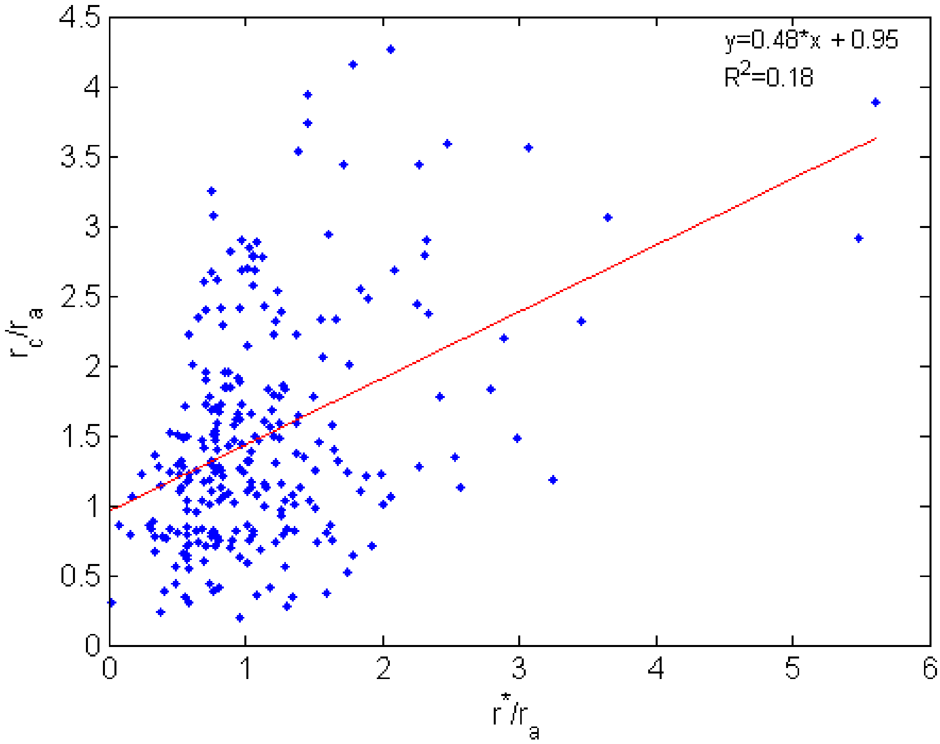

Figure 5. Relationship between r_c/r_a and r^*/r_a by Keterji and Perrier method for the calibration dataset, where r_c, r_a and r^* are canopy, aerodynamic and climatic resistance, respectively.

doi:10.6342/NTU201703681

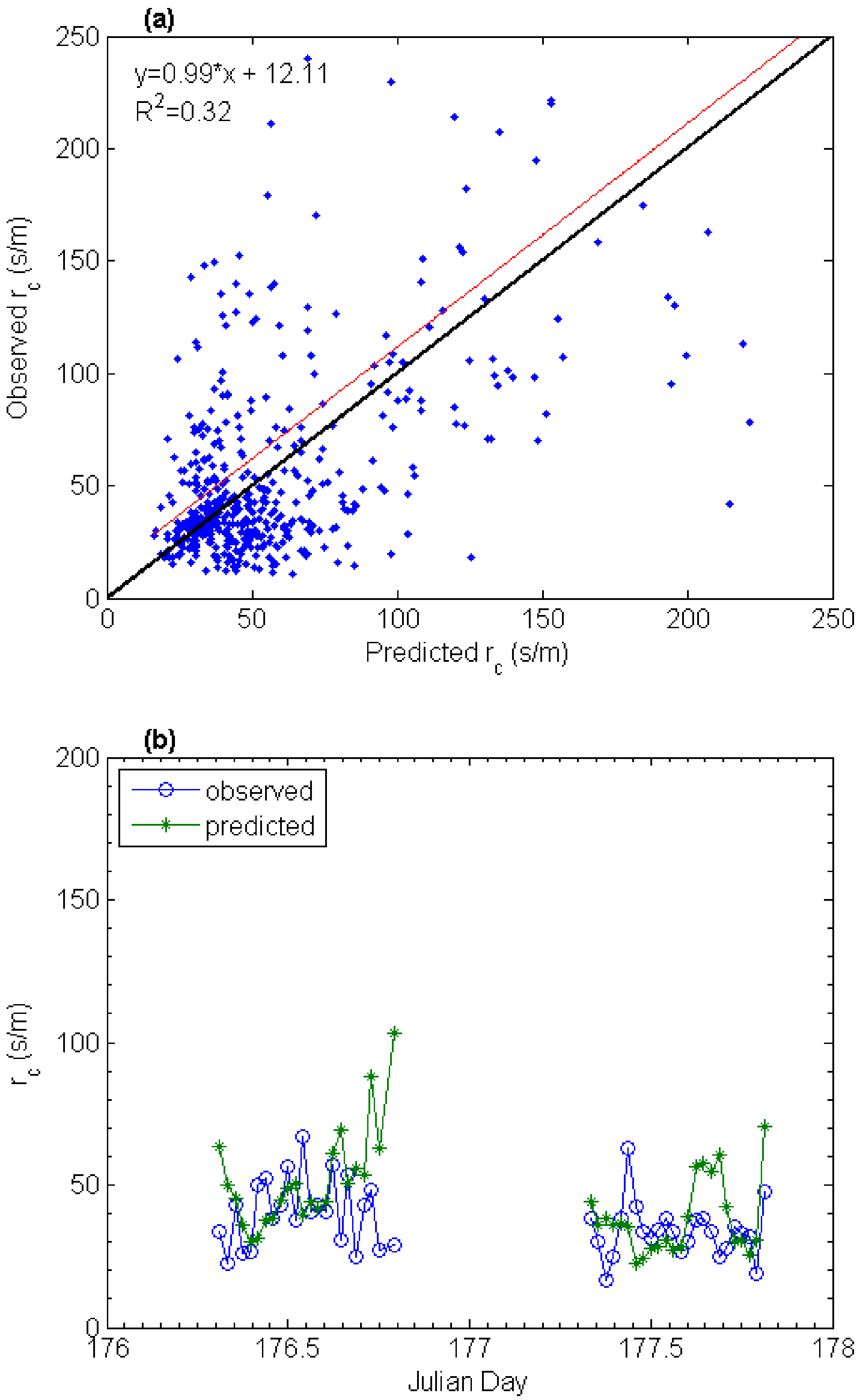

Figure 6. Comparison between observed and predicted daytime canopy resistance (r_c) by Jarvis type equation. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

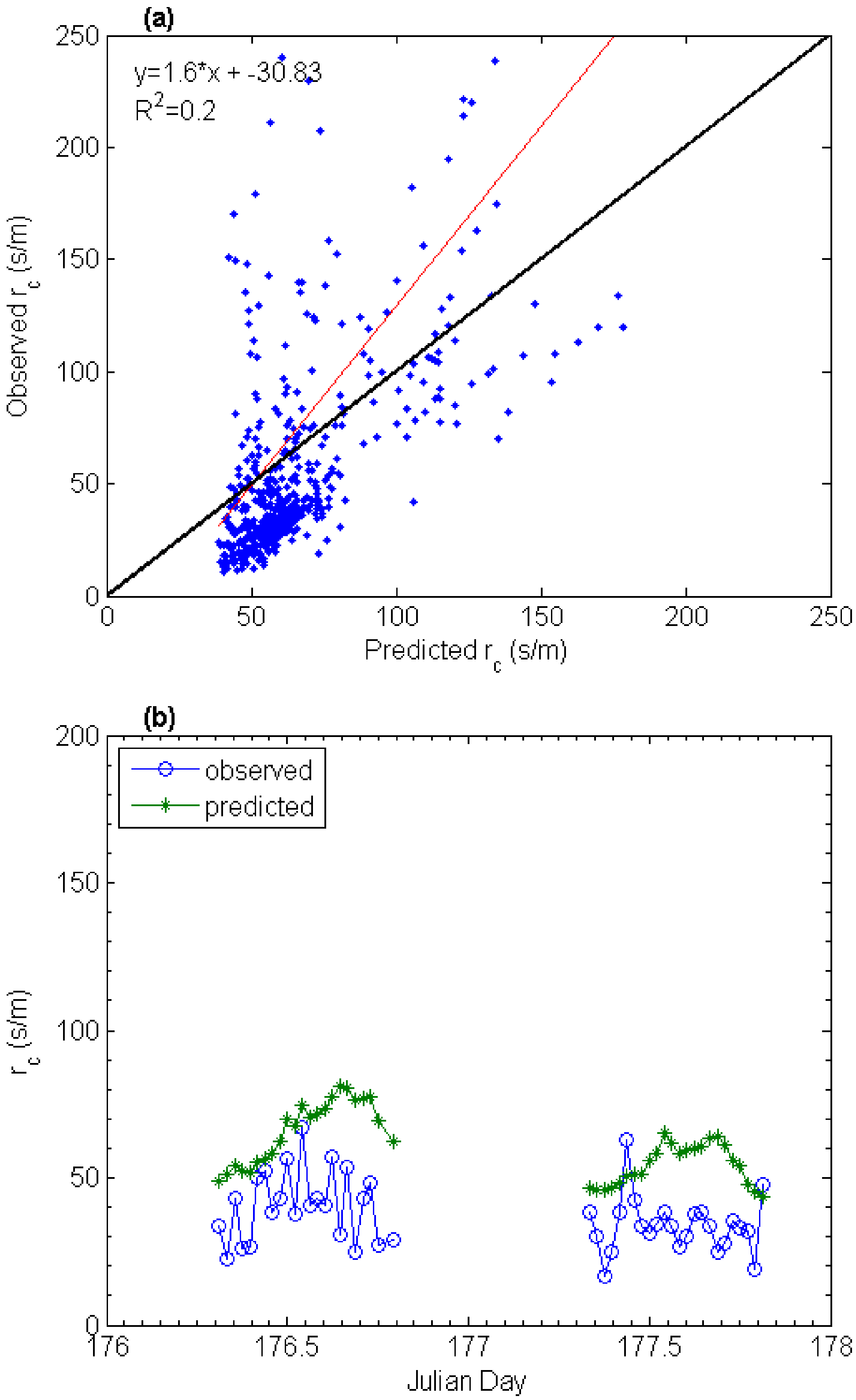

Figure 7. Comparison between observed and predicted daytime canopy resistance (r_c) by Jarvis-Blanken and Black method. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

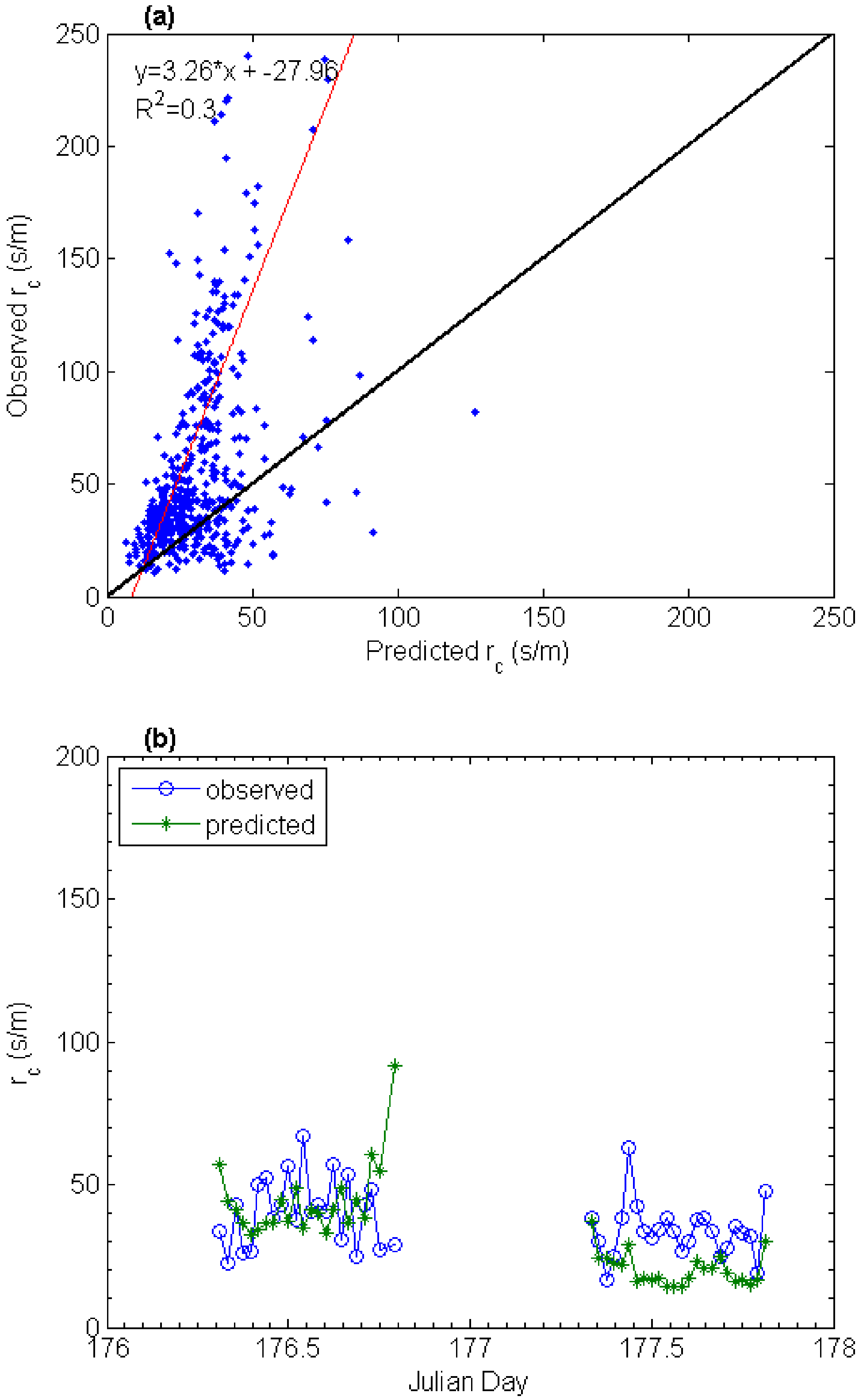

Figure 8. Comparison between observed and predicted daytime canopy resistance (r_c) by the Todorovic method (TD). (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

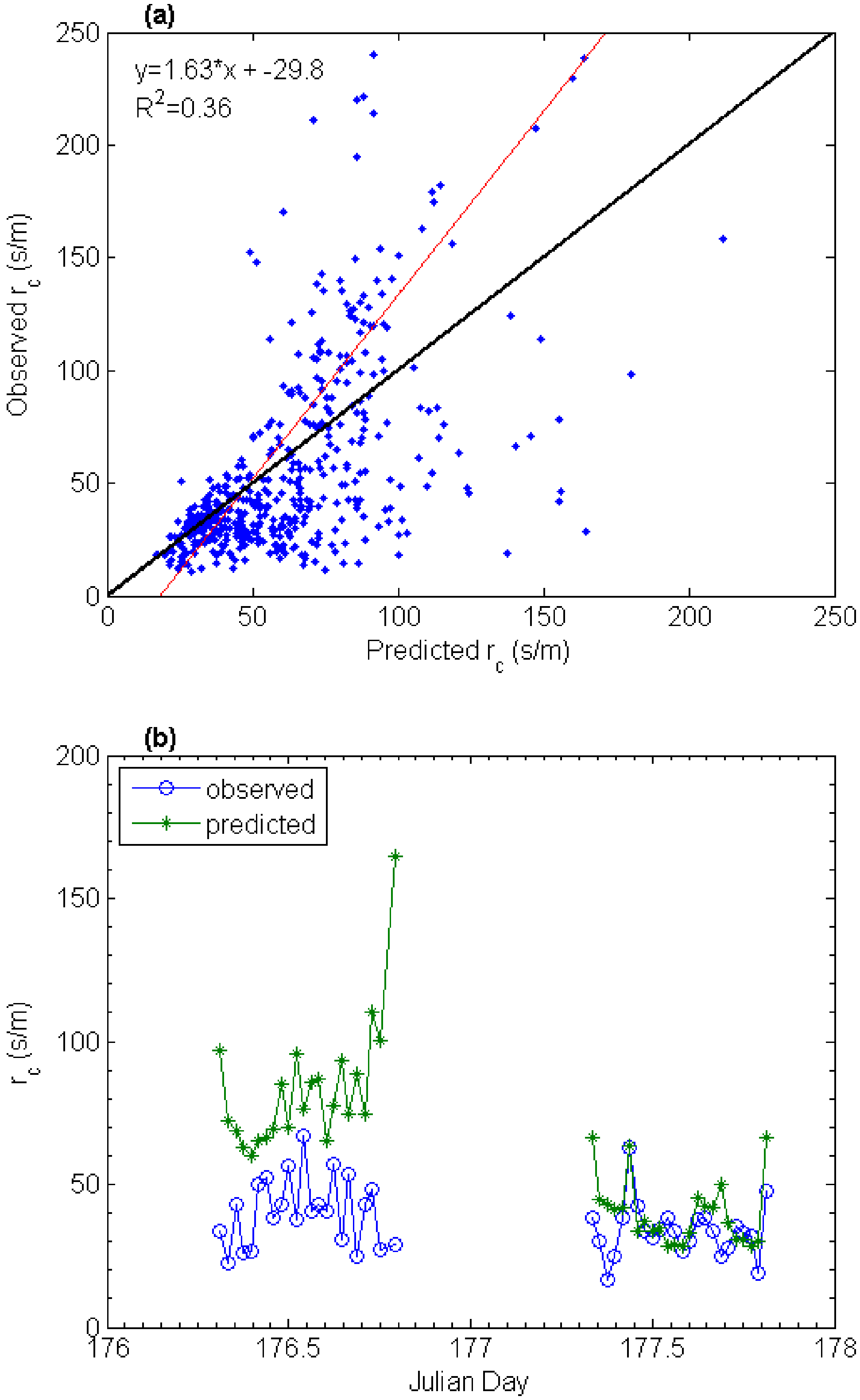

Figure 9. Comparison between observed and predicted daytime canopy resistance (r_c) by the Keterji and Perrier method (KP). (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

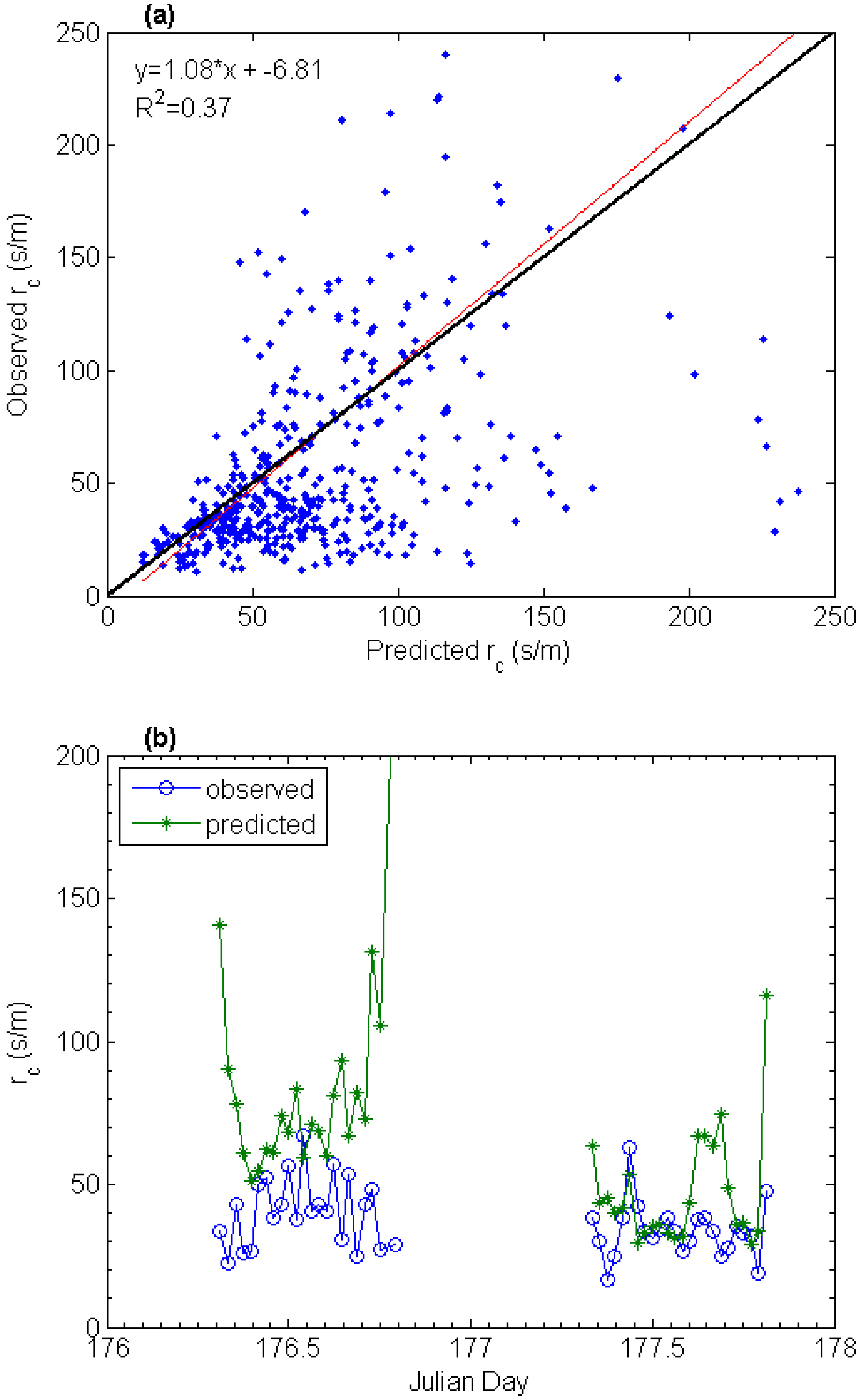

Figure 10. Comparison between observed and predicted daytime canopy resistance (r_c) by the new approach. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

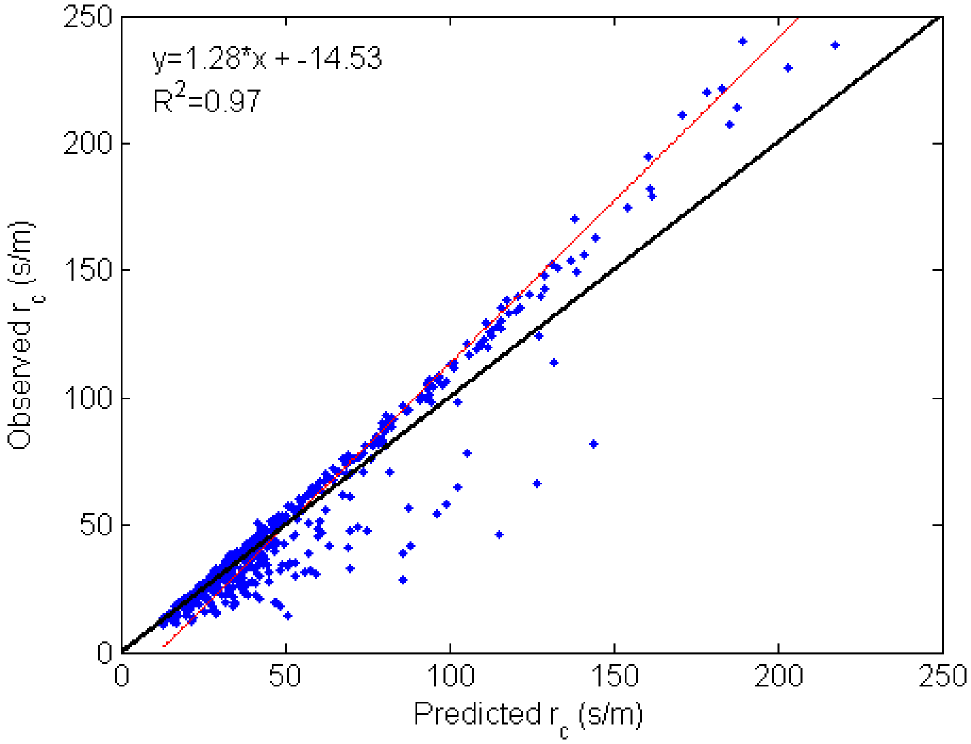

Figure 11. Comparison between observed and predicted daytime canopy resistance (r_c) by the new approach for analysis periodif only LE is substituted in equation (25).

doi:10.6342/NTU201703681

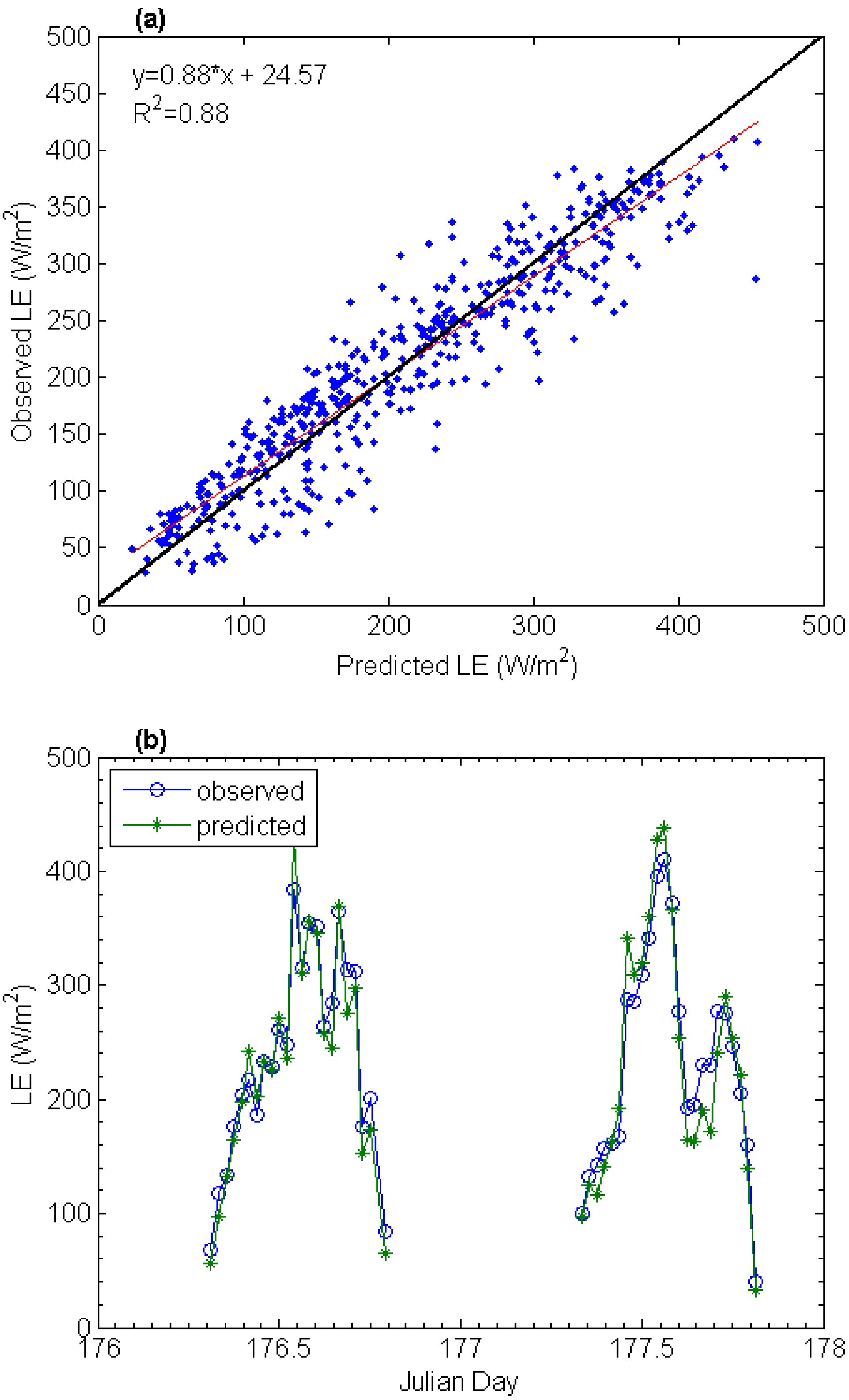

Figure 12. Comparison between observed and predicted daytime latent heat (LE) by Jarvis type equation. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

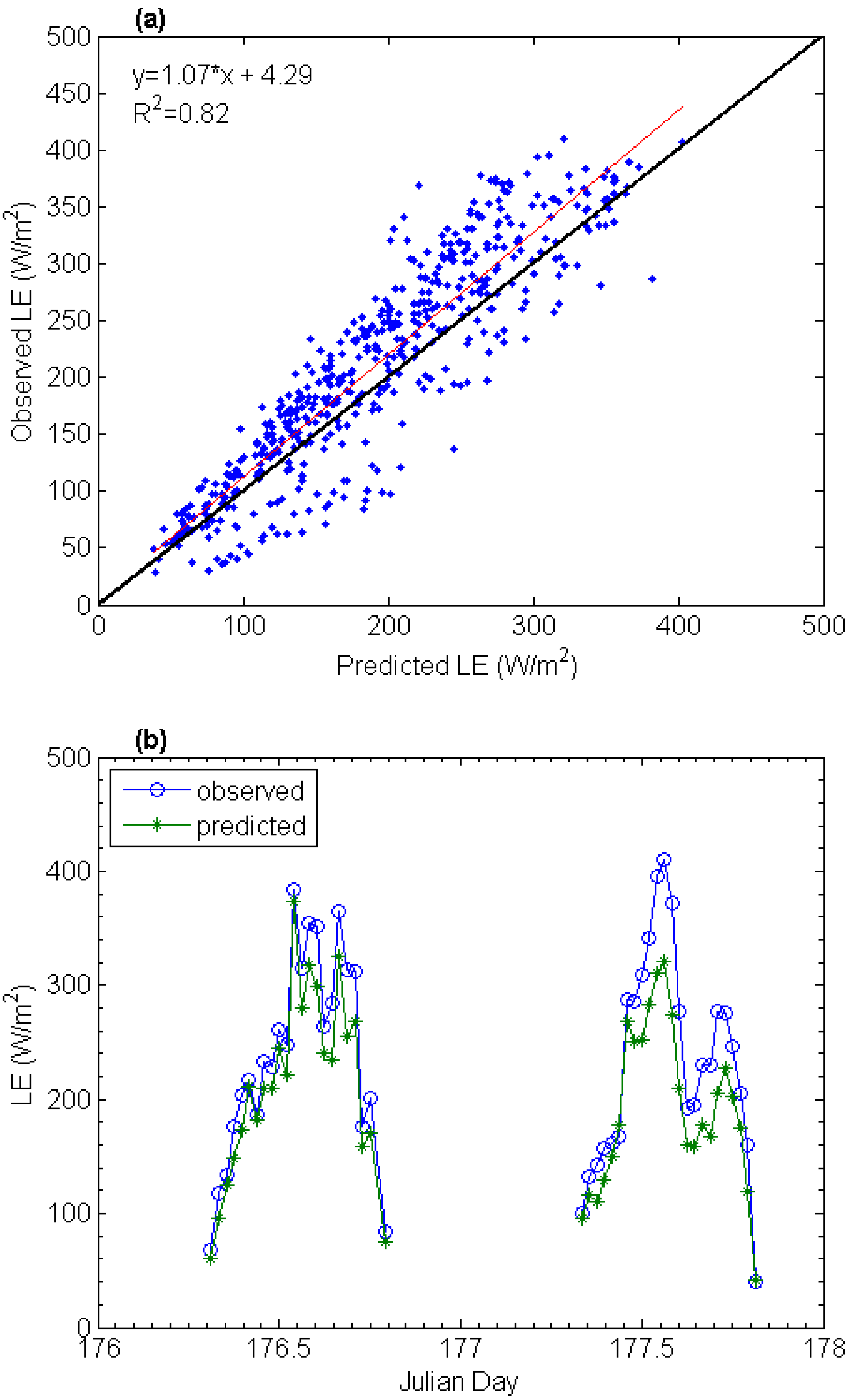

Figure 13. Comparison between observed and predicted daytime latent heat (LE) by Jarvis-Blanken and Black method. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

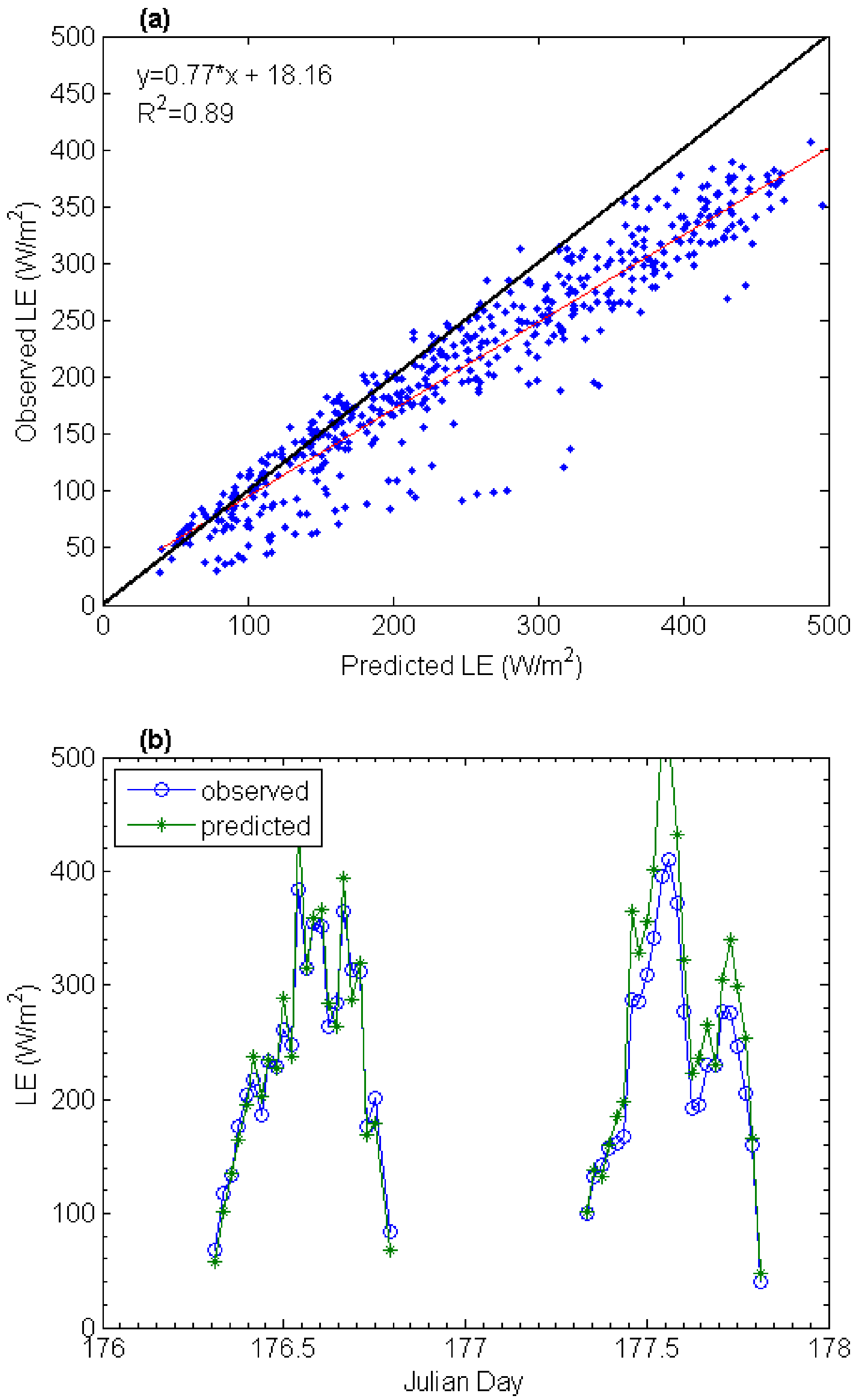

Figure 14. Comparison between observed and predicted daytime latent heat (LE) by the Todorovic method (TD). (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

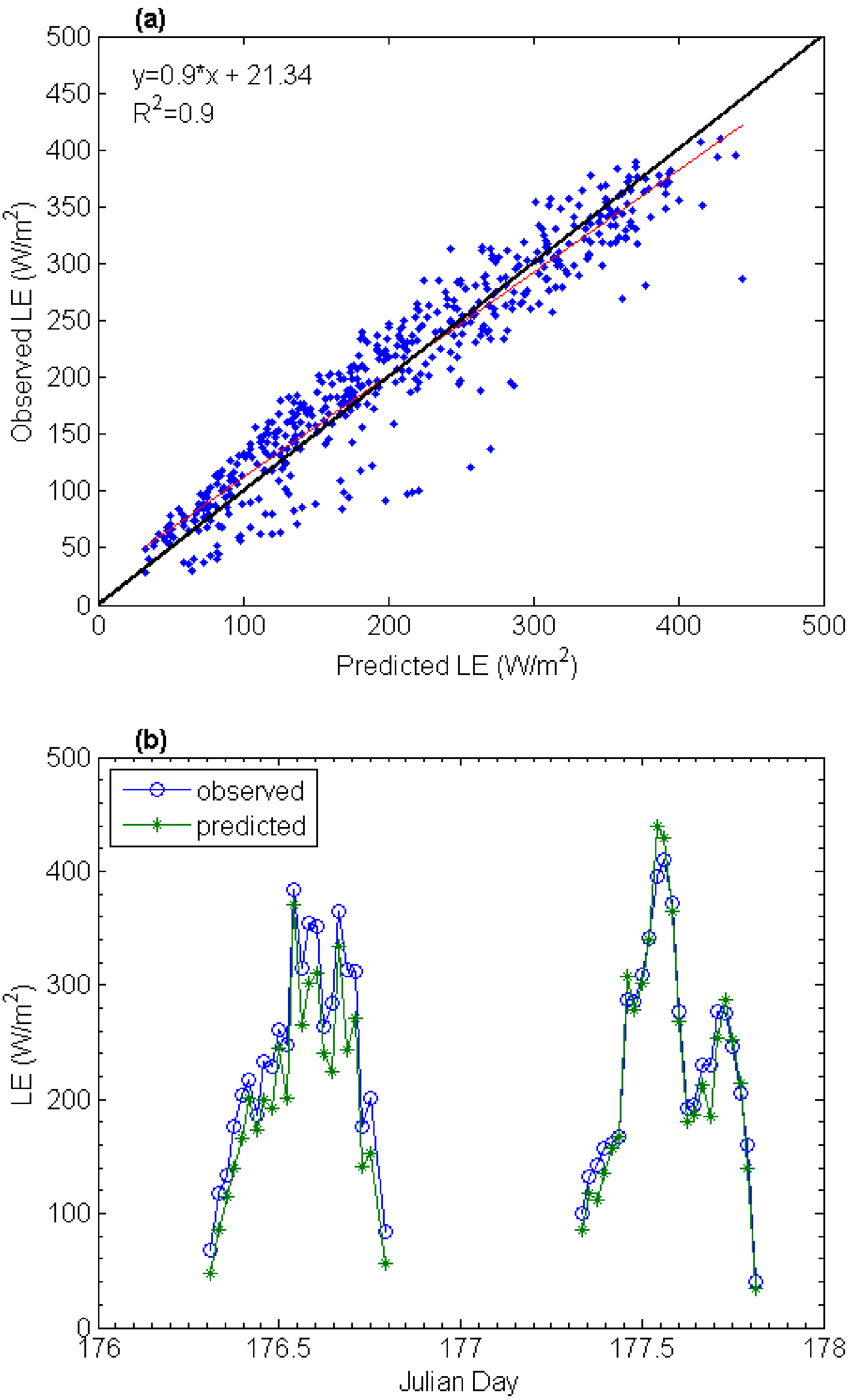

Figure 15. Comparison between observed and predicted daytime latent heat (LE) by the Keterji and Perrier method (KP). (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

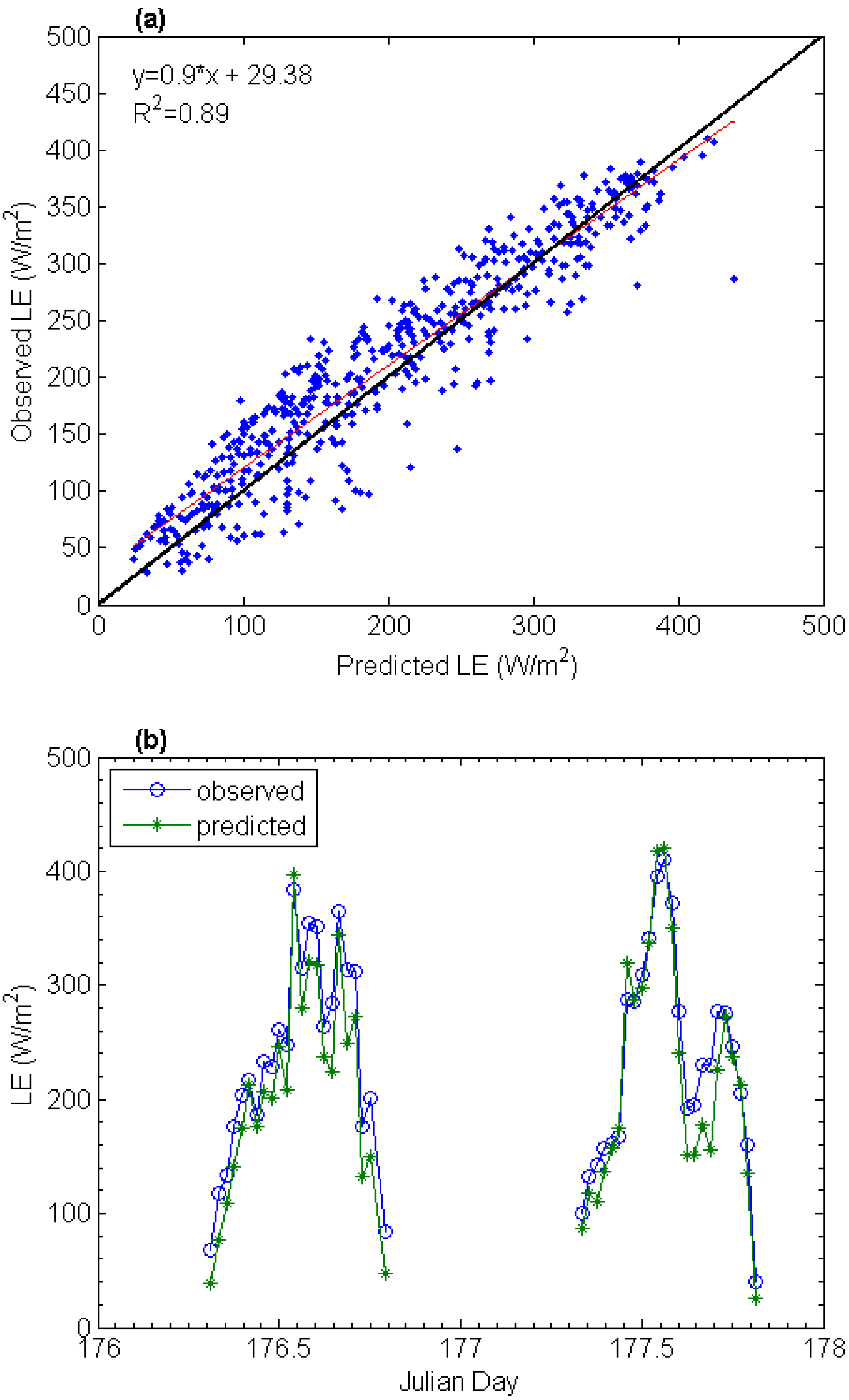

Figure 16. Comparison between observed and predicted daytime latent heat (LE) by the new approach. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

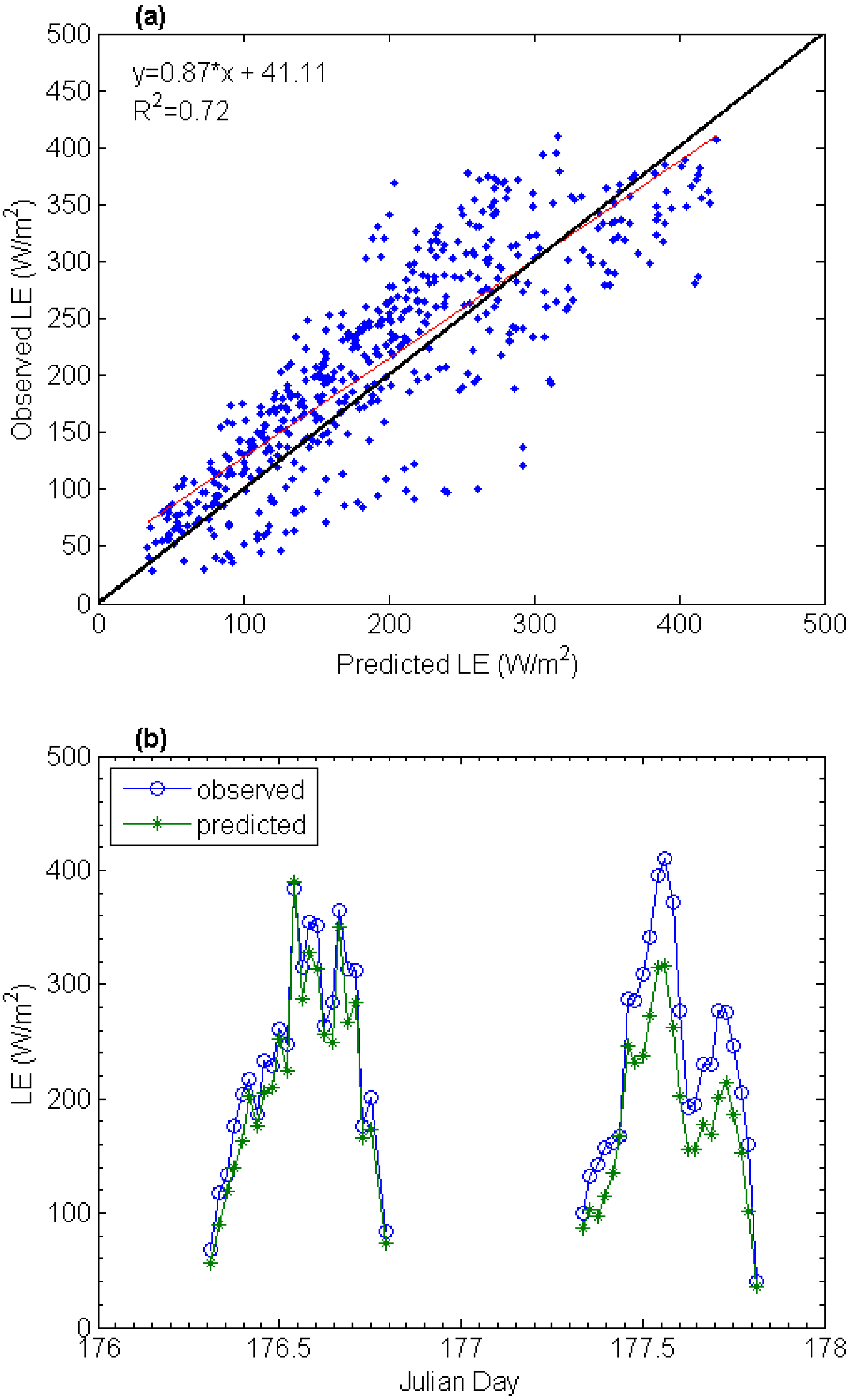

Figure 17. Comparison between observed and predicted daytime latent heat (LE) by constant canopy resistance. (a) scatter plot for analysis period, (b) time series plot for specific days (25-26 June, 2013)

doi:10.6342/NTU201703681

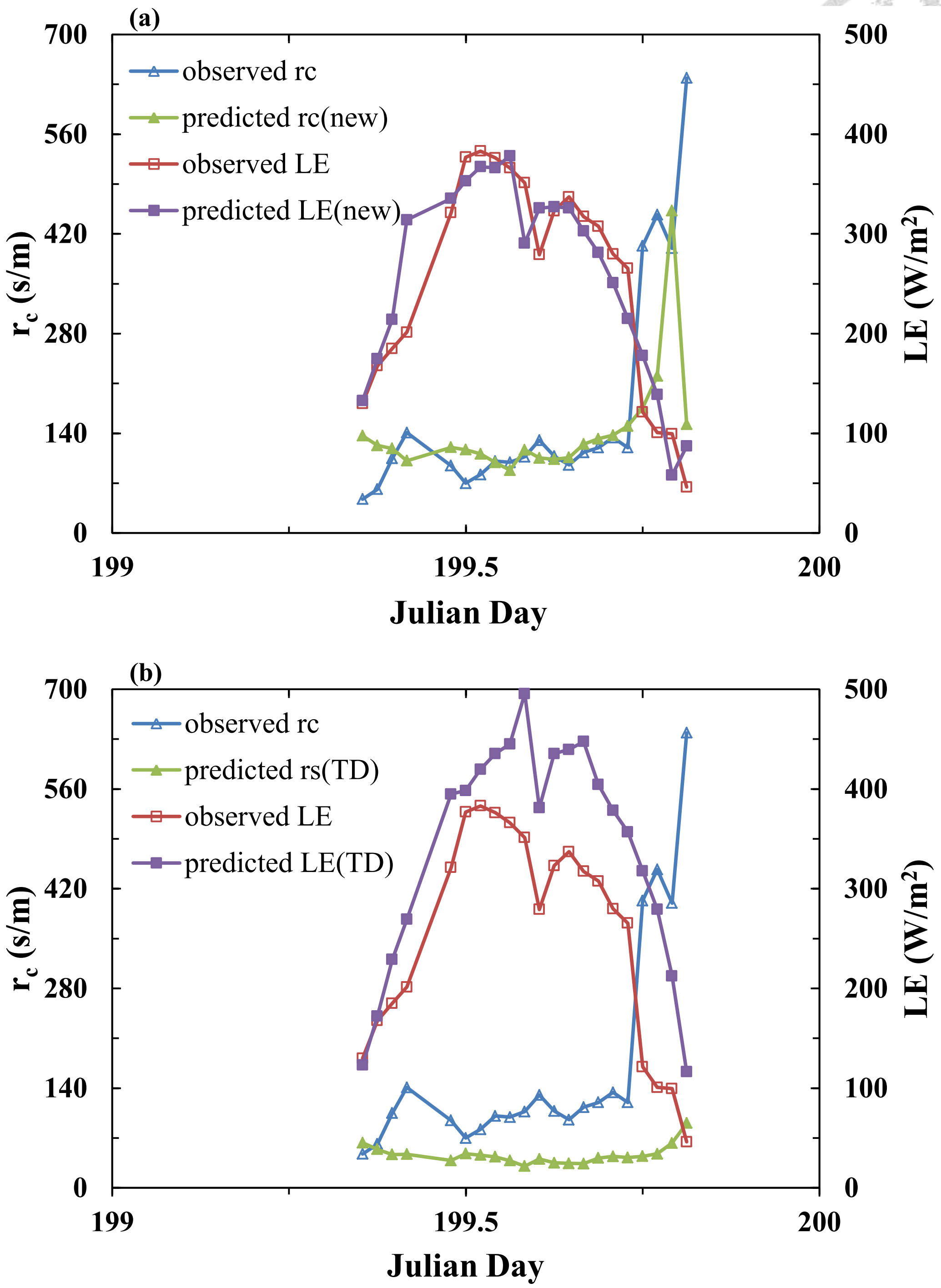

Figure 18. Comparison between observed and predicted daytime canopy resistance (r_c) and latent heat flux (LE) for specific days (18 July, 2013). The predicted models are (a) the new approach and (b) the Todorovic method (TD).

doi:10.6342/NTU201703681

Appendix

A. Sitou experiment site

In order to compare different vegetation types to humid grassland, the Sitou experiment site which consists of humid forest is considered (see A.1). Results show that there is a high relationship between the cnopy reisistance estimation and Bowen raitos (see A.2). Owing to the wide fluctuation of Bowen ratios at Sitou experiment site, the canopy resistance estimation shows poorer estimation than the humnid grassland (see A.3).

A.1 Description

The Sitou experiment site which is a valley is located in Nantou, Taiwan. The climate is warm and humid. The measurement towers, A (23^{o}39’50.01”N, 120^{o}47’46.4”E) and B (23^{o}39’51.09”N, 120^{o}47’44.57”E), are set up in the experimental forest (Cryptomeria japonica). The heights of tower A and B are 35 m and 40 m, respectively. Three eddy covariance systems are set up on those towers and the meteorological measurements including net radiometer, rain gauge, temperature and relative humidity probe, etc. are installed at each tower. More details can be found in Cheng (2010).

doi:10.6342/NTU201703681

A.2 Relationship between the canopy resistance estimation and Bowen raitos

By Considering the Bowen ration energy balance equation, the equation (6) can be expressed as:

$$r_c = (1+\beta) * \frac{\delta q * \rho_{air} * C_p}{\gamma * A} + \left(\beta * \frac{s}{\gamma} - 1\right) * r_a \quad \text{(A.1)}$$

Comparing equation (A.1) to equation (23) in Keterji and Perrier method and equation (25) in new approach, it can show that

$$(1+\beta) = a_1 * \frac{S+\gamma}{S} = \frac{S+\gamma}{\alpha * S} \quad \text{(A.2)}$$

$$\left(\beta * \frac{s}{\gamma} - 1\right) = a_2 = \left(\frac{S+\gamma-\alpha * S}{\alpha * \gamma} - 1\right) \quad \text{(A.3)}$$

Therefore, the relationship between both canopy resistance estimation methods and Bowen ratios can be inferred. To understand the importace of Bowen raitos, observed Bowen ratios are used (the second term in equation (25)) in new approach to calculate canopy resistance, i.e. only LE is substituted in equation (25). Figure (A.10a) and (A.1a) are results of the canopy resistance estimation by new approach at two different sites. Figure (11) and (A.1b) are results of the canopy resistance estimation when observed Bowen ratios are used. It can be found that estimations at both the humid grassland and the humid forest are improved when observed Bowen ratios are used. However, the improvement of the humid grassland is greater than the humid forest due to the smaller range of Bowen ratios at the humid grassland (Figure A.2).

doi:10.6342/NTU201703681

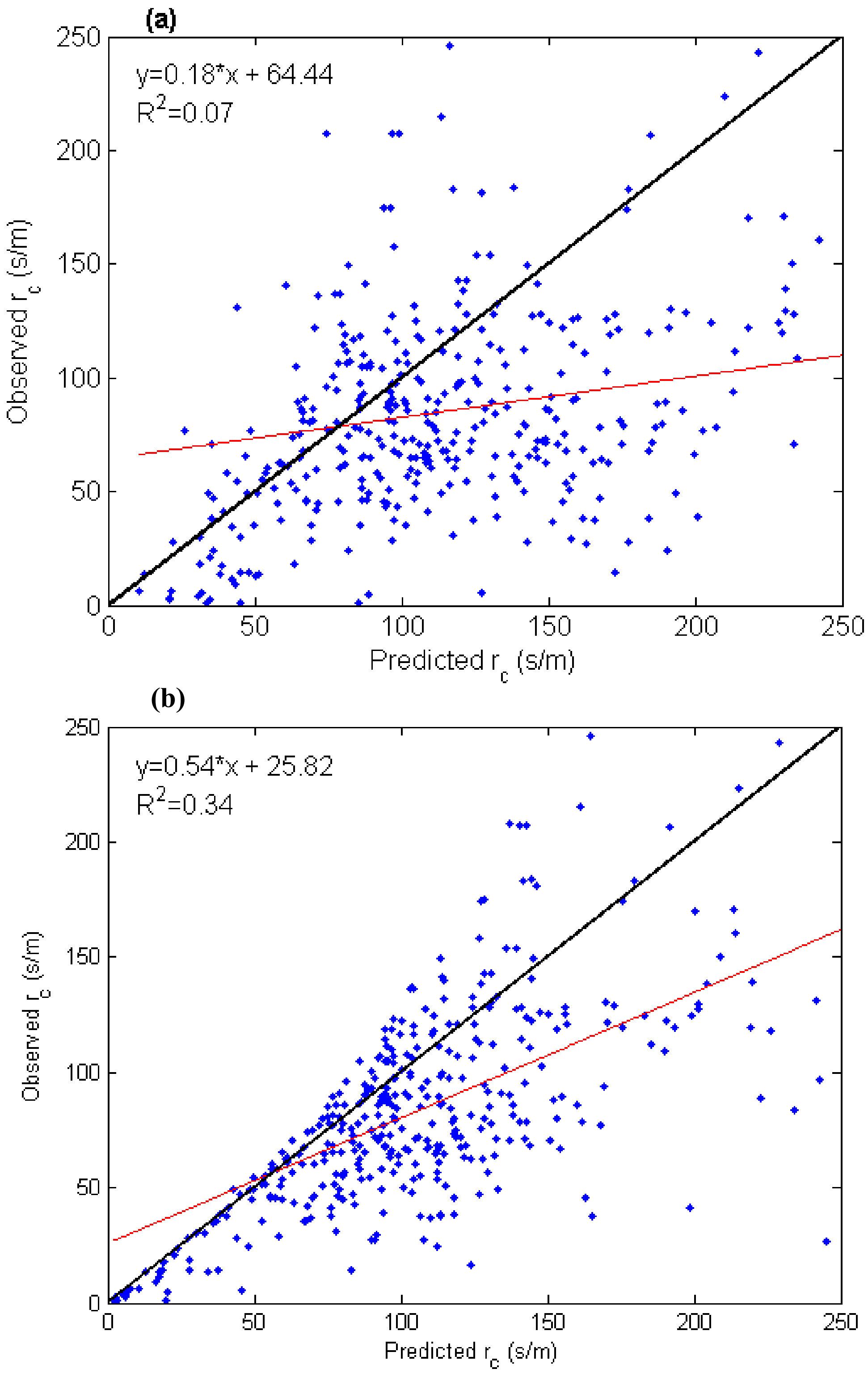

Figure A.1. Comparison between observed and predicted daytime canopy resistance (r_c) by new approach at humid forest. (a) new aapoach, (b) new approach with only LE is substituted in equation (25)

doi:10.6342/NTU201703681

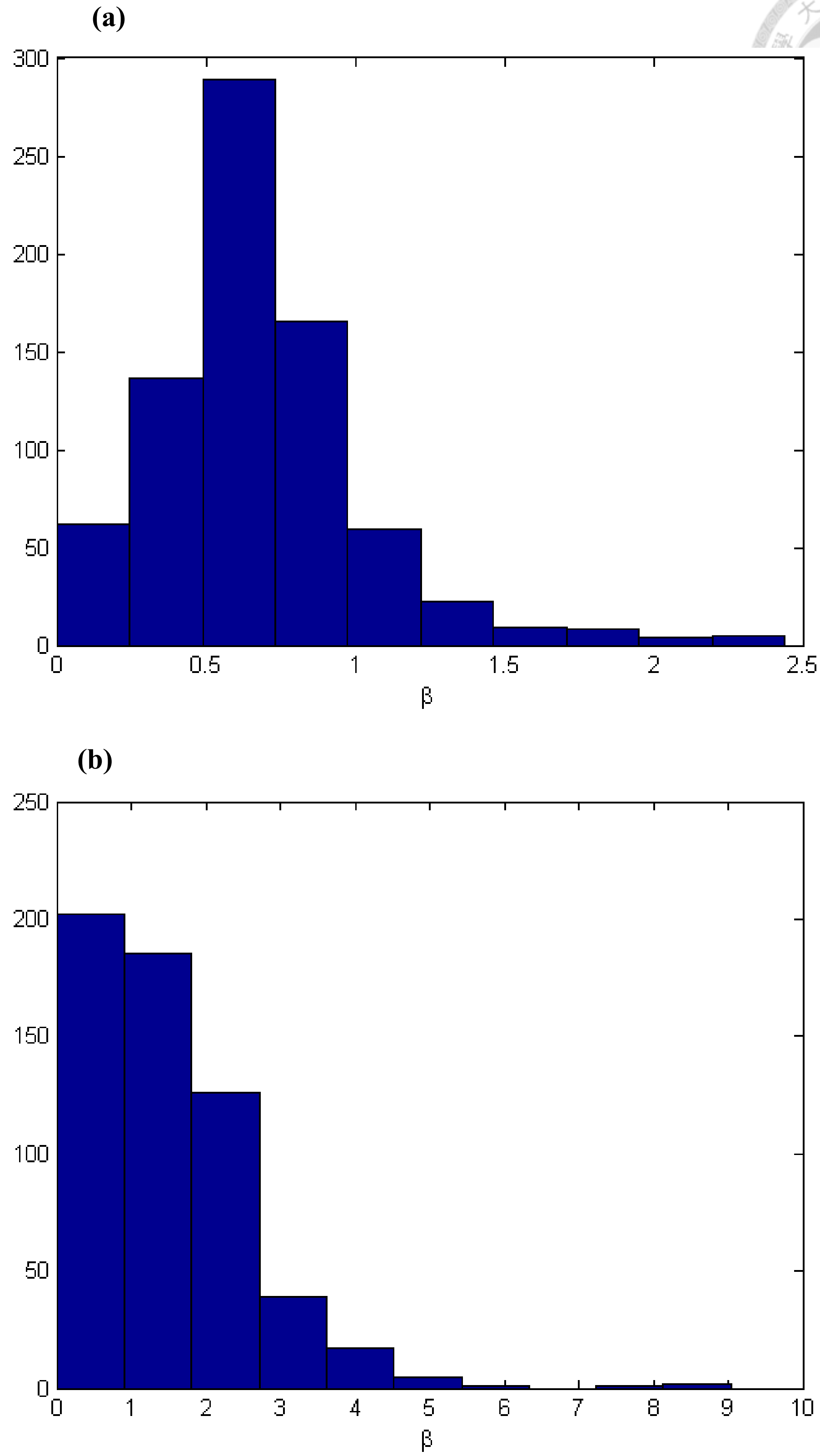

Figure A.2. Histogram of Bowen ratios at (a) humid grassland and (b) humid forest.

doi:10.6342/NTU201703681

A.3 Result

Table A.1. Coefficients of Keterji and Perrier method obtained by regression fit. a_1, a_2 and a_3 are the parameters need to be fitted in each method and R^2 is the coefficient of determination.

Method	a_1	a_2	a_3	R^2
Katerji and Perrier	1.07	5.88	--	0.36

Table A.2. Linear regression ($observed_{rc}$ = a*$predicted_{rc}$ + b) and statistics of the comparison between predicted and onserved values of canopy resistance. a and b are the parameters need to be fitted in each method, R^2 is the coefficient of determination and RMSE is root mean square error.

Method	a	b	R^2	RMSE
Todorovic	0.01	88.12	0.00	98.43
Katerji and Perrier	0.07	79.87	0.01	95.32
New approach	0.18	64.44	0.07	102.26

Table A.3. Linear regression ($observed_{LE}$ = a*$predicted_{LE}$ + b) and statistics of the comparison between predicted and onserved values of latent heat flux (LE). a and b are the parameters need to be fitted in each method, R^2 is the coefficient of determination and RMSE is root mean square error.

Method	a	b	R^2	RMSE
Todorovic	0.01	152.26	0.04	1518.55
Katerji and Perrier	0.77	56.99	0.47	68.86
New approach	0.91	47.83	0.44	73.00
Constant r_c	0.84	37.25	0.56	58.71

doi:10.6342/NTU201703681

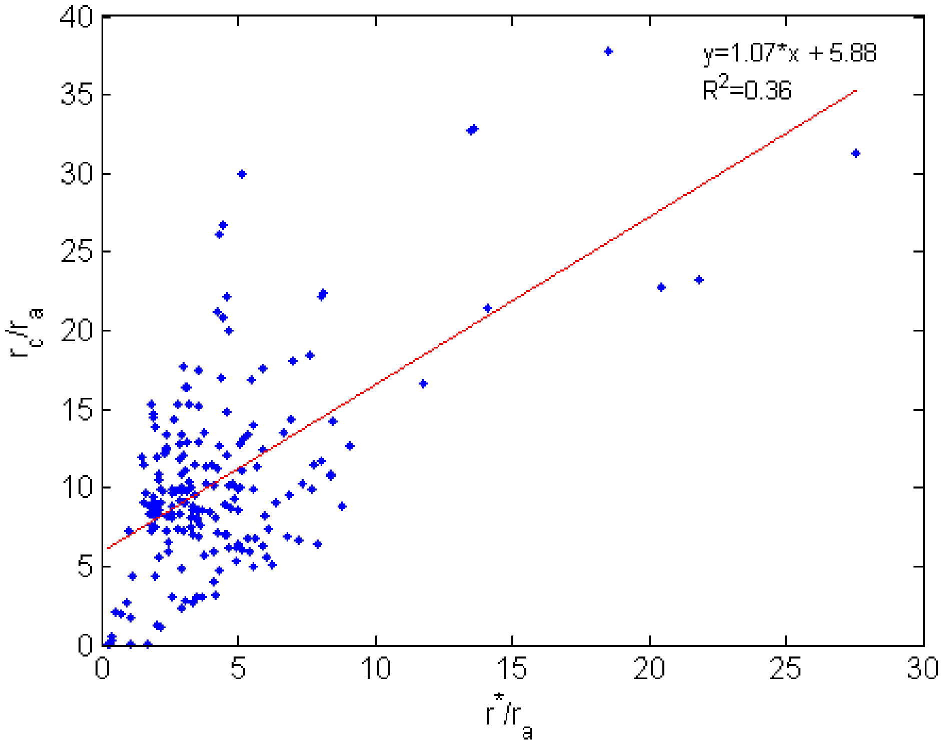

Figure A.3. Relationship between r_c/r_a and r^*/r_a by the Keterji and Perrier method for the calibration dataset, where r_c, r_a and r^* are canopy, aerodynamic and climatic resistance, respectively at humid forest.

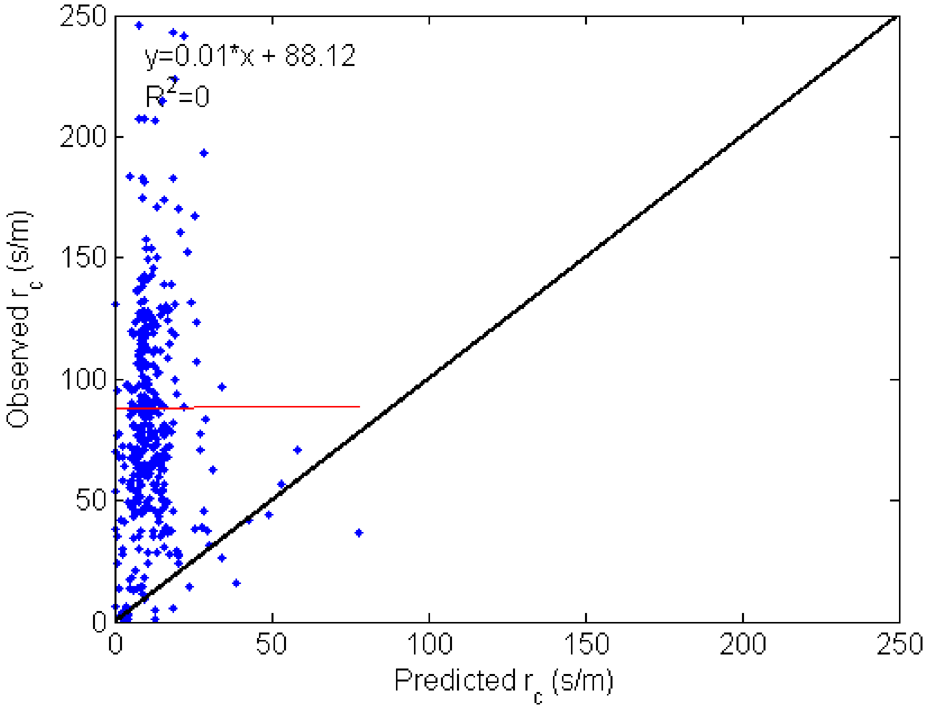

Figure A.4. Comparison between observed and predicted daytime canopy resistance (r_c) by the Todorovic method (TD) at humid forest

doi:10.6342/NTU201703681

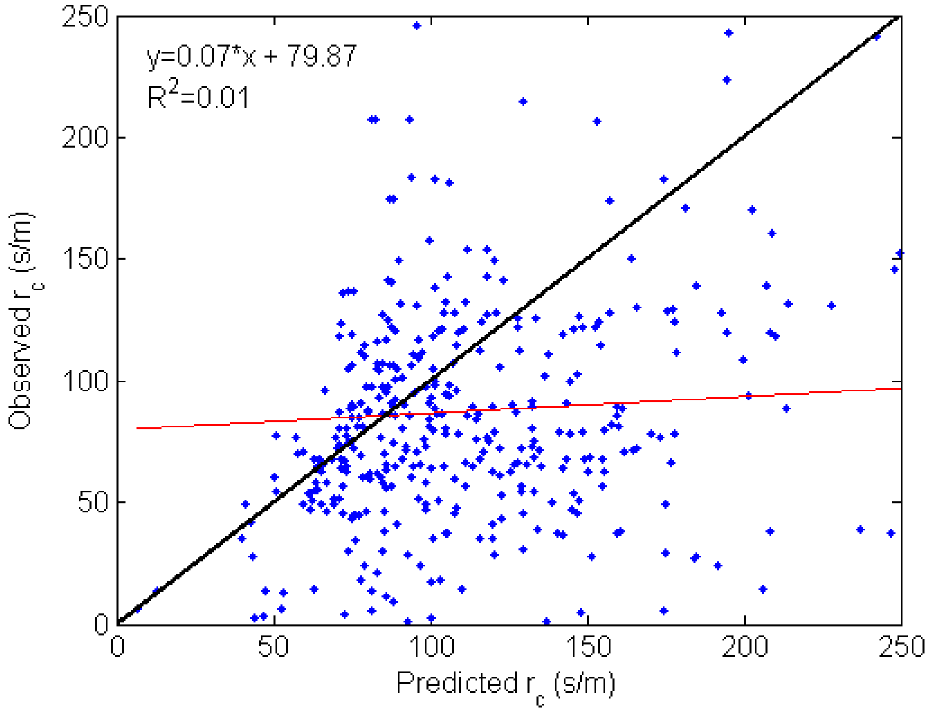

Figure A.5. Comparison between observed and predicted daytime canopy resistance (r_c) by the Keterji and Perrier method (KP) at humid forest

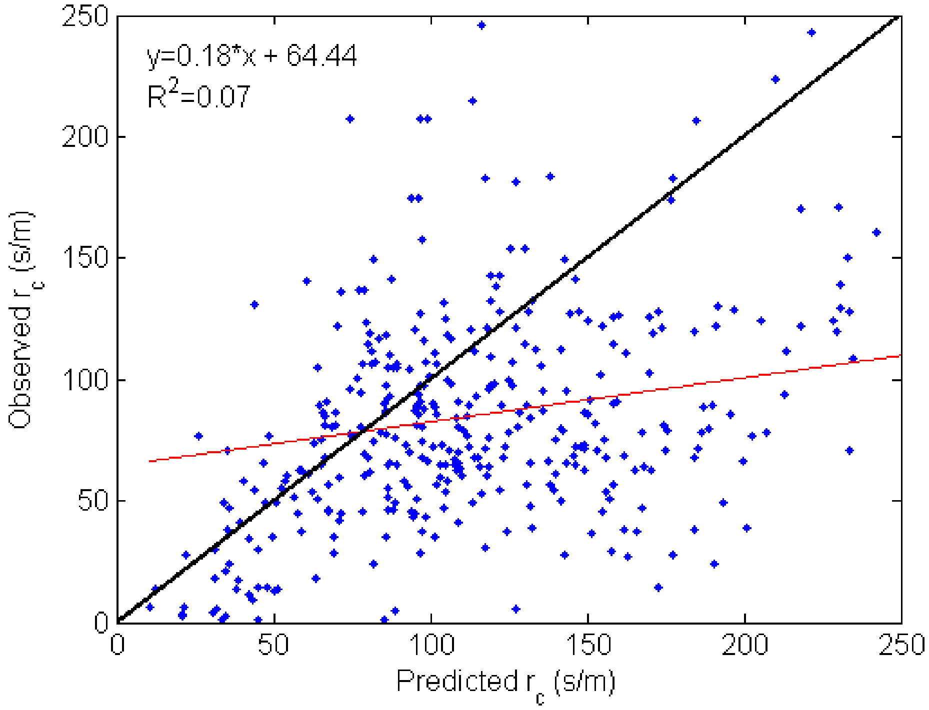

Figure A.6. Comparison between observed and predicted daytime canopy resistance (r_c) by the new approach at humid forest

doi:10.6342/NTU201703681

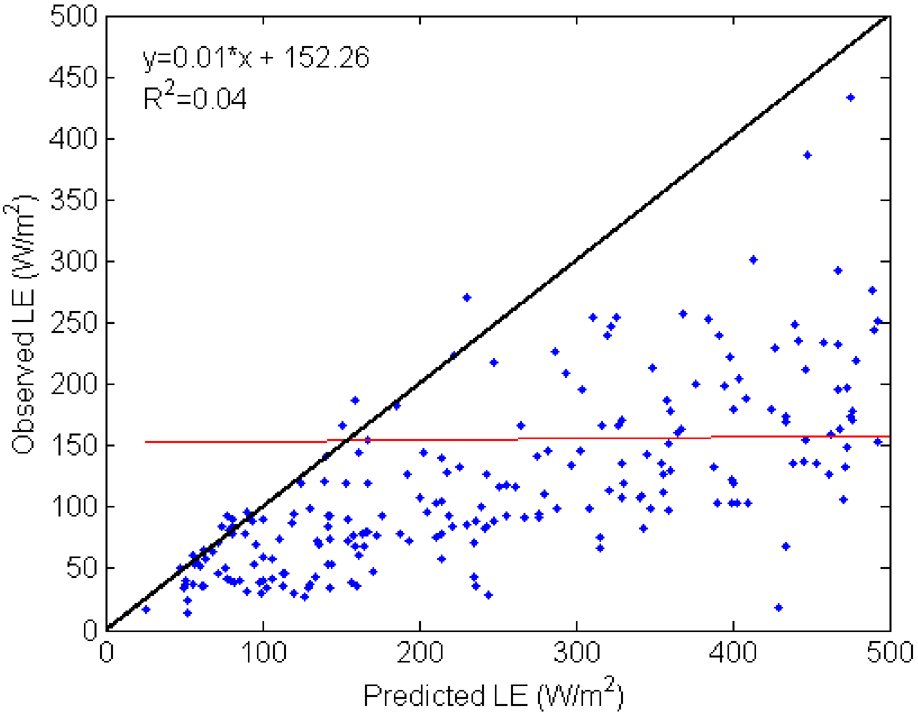

Figure A.7. Comparison between observed and predicted daytime latent heat (LE) by the Todorovic method (TD) at humid forest

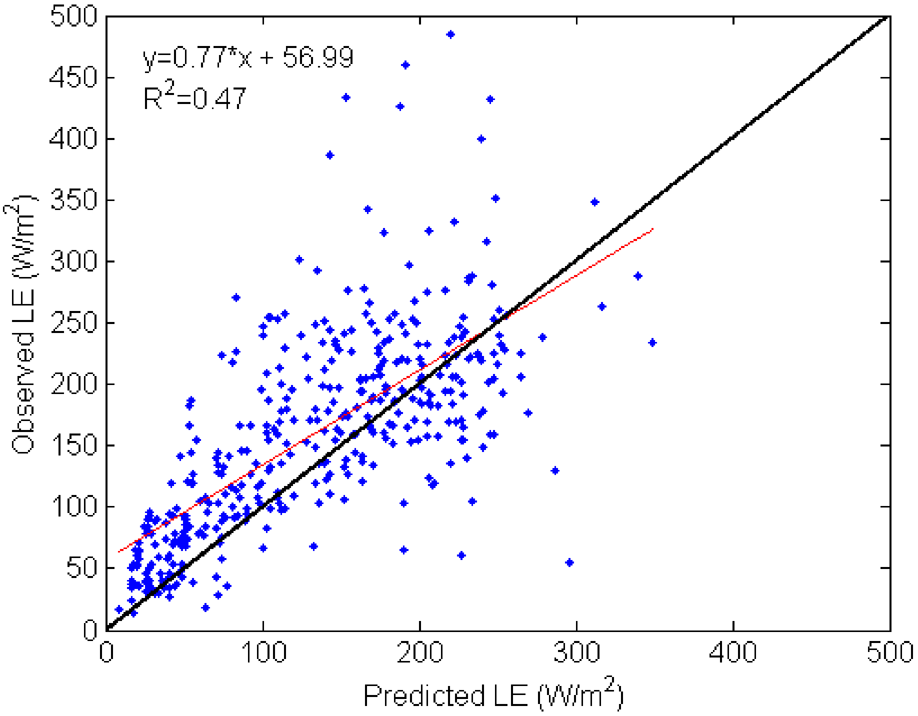

Figure A.8. Comparison between observed and predicted daytime latent heat (LE) by the Keterji and Perrier method (KP) at humid forest

doi:10.6342/NTU201703681

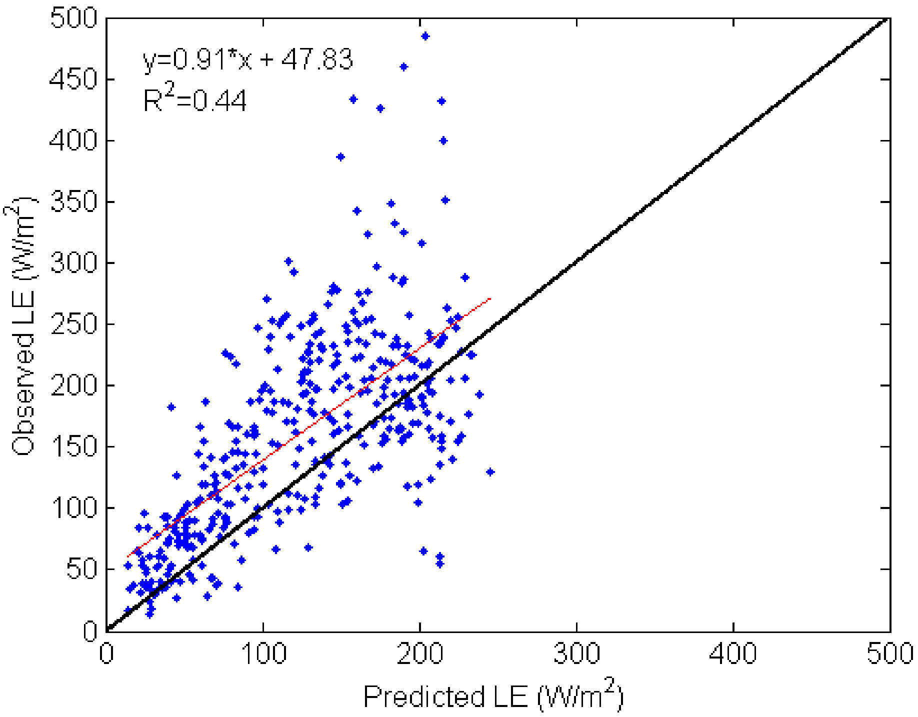

Figure A.9. Comparison between observed and predicted daytime latent heat (LE) by the new approach at humid forest

doi:10.6342/NTU201703681

B. Minimum stomatal resistance

Minimum stomatal resistance is defined as the largest value of the observed stomatal resistance under the optimal condition which is at high solar radiation, low vapor pressure deficit, well-watered, natural outdoor CO_2 concentration, and sufficient nutrient supply (Körner et. al., 1979). Data in Table B.1 are collected from Arnold et.al. (2012).

Table B.1. Summary of minimum daytime values of the stomatal resistance (r_{st} min) for several vegetation types

Vegetation	**r_{st} min (m/s)**
Corn	140.85
Eastern gamagrass	181.82
Spring wheat	178.57
Rye	100.00
Rice	128.21
Italian (annual) ryegrass	181.82
Soybean	140.85
Tobacco	208.33
Carrot	153.85

doi:10.6342/NTU201703681

C. Stomatal resistance and canopy resistance of different vegetation types

Table C.1. Summary of daytime values of stomatal resistance (r_{st})

Vegetation	r_{st} (m/s)	reference
Beta Vulgaris	160.26	
Gossypium hirsutum	111.11	
Maize	126.26	Norman and Campbell (1998)
Betulua verrucosa	115.74	
Pinus monticola	126.26	

Table C.2. Summary of daytime values of canopy resistance (r_c)

Vegetation	r_c (m/s)	reference
Aspen canopy	80-420	Blanken and Black (2004)
Festuca arundinacea	50-200	Perez et. al. (2006)
Grass	20-220	Pauwels and Samson (2006)
Present study	10-250	--

doi:10.6342/NTU201703681