國立臺灣大學生物資源暨農學院森林環境暨資源學系

碩士論文

School of Forestry and Resource Conservation
College of Bioresources and Agriculture
National Taiwan University

Master Thesis

台灣中部柳杉林之長期林分蒸散量推估:熱消散樹液流法的校正及其於野外資料的應用

Long-term stand transpiration estimates in a Japanese cedar forest, central Taiwan: Calibration of thermal dissipation sap flow measurements and its application to field data

蘇曼萍

Man-Ping Su

指導教授：久米朋宣 博士

Advisor: Tomonori Kume, Ph.D.

中華民國 106 年 8 月

August 2017

doi:10.6342/NTU201702787

國立臺灣大學（碩）博士學位論文
口試委員會審定書

台灣中部柳杉林之長期林分蒸散量推估:熱消散樹液流法的校正及其於野外資料的應用

Long-term stand transpiration estimates in a Japanese cedar forest, central Taiwan: Calibration of thermal dissipation sap flow measurements and its application to field data

本論文係蘇曼萍君（R04625010）在國立臺灣大學森林環境暨資源學系研究所完成之碩士學位論文，於民國 106 年 06 月 22 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：

久米 朋宣 （簽名）

（指導教授）

梁偉立

賴彥任

系主任、所長 柯淳涵 （簽名）

（是否須簽章依各院系所規定）

doi:10.6342/NTU201702787

誌謝

碩士班兩年期間受到許多許多的幫忙才得以順利完成論文。感謝家人的支持，使我可以無後顧之憂的專注於實驗上。感謝久米老師給予的教導與指正，從實驗進行到論文撰寫，包括兩年期間課業上的幫助，研討會摘要及海報的修改，都非常感謝老師的細心指教。感謝篠原慶規老師來台灣教導進行樹液流的校正實驗，提供了實驗上非常大的幫助。感謝梁偉立老師提供許多建議，使能夠發覺更多實驗上的問題。感謝台大實驗林提供溪頭通量塔及農業氣象站的氣象資料。感謝實驗林 Sophie 學姊和彭小姐幫我們處理每次出差的住宿。感謝實驗林余瑞珠學姊，每次出差總是麻煩學姊跟學姊借用儀器。感謝關秉宗老師借用生長錐以及阿坤學長幫忙才能得到年輪寬度的資料。感謝鄭智馨老師借用電子秤及溫婕妤借用三角瓶使校正實驗能順利進行。感謝梁小姐幫我們處理出差、儀器購買等的相關事宜。感謝實驗室的大家，每個月一起開車到溪頭做實驗。感謝 sophie 學姊教導我如何進行樹液流實驗、樣區維護工作以及解決探針的許多問題。感謝林松駿學長教我如何製作樹液流探針以及樹液流量測方法。感謝林伯宣學長每次一起去溪頭幫忙做實驗，包括生長錐的操作、校正實驗的進行等。感謝陳至威及林雋雅學姊幫忙進行溪頭野外的實驗以及室內的校正實驗。感謝鐘敏華、江明珊、陳奕宏、邱均幫忙進行溪頭野外的實驗。感謝實驗室的學姊們長久以來的努力，才能讓我有長年的資料可以進行分析觀察。還要感謝許多人的幫忙與協助，讓我可以順利完成碩士論文!

doi:10.6342/NTU201702787

中文摘要

為了解氣候變遷及森林經營對水循環的影響，長期林分蒸散量的推估是不可或缺的。樹液流量測方法是推估林分蒸散量的方式之一，且其由 Granier 在 1985 年校正的熱消散樹液流方法於現今廣為所用。然而，一些前人研究進行校正實驗發現並非所有樹種都適用於 Granier 的經驗公式，且柳杉為台灣山區森林重要樹種之一，但還無研究進行校正實驗測定 Granier 樹液流方式對量測柳杉樹液流的精確度。並且甚少研究檢測推估林分蒸散時，樹木生長的影響。因此本研究目的為 1) 使用樹幹片段進行校正實驗以確認 Granier 樹液流方法對量測中部台灣柳杉之樹液流的精確度；2) 利用近 7 年野外量測之樹液流資料檢測真實邊材長度與樹木生長對林分蒸散量推估的影響；3) 將校正實驗之結果應用於野外資料以改增進的林分蒸散量推估的精確度；4) 研究長期林分蒸散及氣象資料之年間變異。校正實驗結果顯示使用 Clearwater 公式修正可以大幅提升推估的精確度，因此真實邊材長度的量測是很重要的。且校正實驗結果顯示 Granier 經驗公式推估的結果會低估真實流量約 30%。由於真實邊材長度的量測十分重要，我們在野外樹液流量測樣區進行染劑注射實驗，且量測樹木生長量，用以檢測邊材長度的改變對蒸散量推估的影響，亦檢測由樹木生長所造成的邊材面積的改變對長期蒸散量推估的影響。在本研究中，由樹木生長造成的邊材面積的改變與邊材長度的改變對每年林分蒸散量推估的影響不大，因為 1) 在本研究期間樹木生長量小，及 2) 因染劑注射實驗修正之邊材長度造成 2-4 公分之樹液流速變大，雖 2-4 公分樹液流速變大使推估量增加，但其會與邊材面積減少所造成的推估降低互相抵銷。而為了得到可良好推估蒸散的方法，我們嘗試將校正實驗之結果使用五種不同方法應用於野外資料。結果顯示五種方式的差距出乎預期之大。藉由比較其各自的樹液流日變化曲線，以及比較五種方式計算之年林分蒸散量與潛在蒸發量，得到年林分蒸散量推估的可能範圍大致為原本推估方式的 1.5 至 3 倍。最後，本實驗推估近 7 年的林分蒸散量。林分蒸

doi:10.6342/NTU201702787

散量的年間變異很小，因為林分蒸散量主要受水蒸氣壓虧缺及太陽輻射影響，而其年間變異亦不大。溪頭的氣象狀況在過去近 7 年間似乎維持滿穩定的狀態。

關鍵字:校正、樹液流、蒸散

doi:10.6342/NTU201702787

英文摘要

Long-term stand scale transpiration estimation is indispensable for understanding climate change impacts and the effects of forest management on the water cycle. Sap flow measurement is a robust approach for estimating stand transpiration; a thermal dissipation method calibrated by Granier (1985) has already been widely implemented. However, some experimental sap flow calibration studies have claimed that Granier's empirical formula is not universally applicable. Japanese cedar is a dominant tree in the mountain forests of Taiwan; however, no experimental calibration studies have been conducted to determine the accuracy of the Granier sap flow method for this species. Additionally, the potential for incorporating tree growth effects on stand transpiration into the formula has not been examined. Therefore, this study aimed to 1) determine the accuracy of the Granier sap flow method on Japanese cedar in central Taiwan by conducting a calibration experiment using stem segments; 2) examine the effect of actual sapwood depth and tree growth on transpiration estimates based on near 7-year field measurements; 3) apply the results from the calibration experiment to field data to improve the accuracy of transpiration estimates; and 4) investigate inter-annual variation due to long-term transpiration and meteorological factors in a Japanese cedar plantation in Xitou, central Taiwan. The results of the calibration experiment showed that the application of Clearwater formula substantially improved the accuracy of transpiration estimates,

doi:10.6342/NTU201702787

indicating the importance of accurate sapwood depth measurements. The calibration experiments showed that the Granier formula underestimated actual water uptake by approximately 30%. Thus, a dye injection experiment was conducted using samples from the field study site; tree growth was also measured to examine the effects of changes in sapwood depth and area due to tree growth on long-term transpiration estimates. These effects were small, because 1) there was little tree growth during the study period and 2) the 2–4 cm sap flow rate became high due to the correction of sapwood depth for dye injection. However, the increase in the inner sap flow rate was balanced by the decrease in sapwood area due to the sapwood depth correction. To determine the better method to estimate stand transpiration, the calibration results were applied to field data using five different methods. Contrary to expectations, there were distinct differences among the results produced by these methods; stand-scale transpiration, was found to be 1.5–3 times larger than that obtained using the original method. We then conducted stand transpiration estimates for the near 7-year field data. There was little inter-annual variation in stand transpiration, because stand-scale transpiration was mainly affected by vapor pressure deficit and solar radiation, which exhibited little inter-annual variation. Meteorological conditions in Xitou appear to have been stable over the past 7 years.

Keywords: calibration, sap flow, transpiration

doi:10.6342/NTU201702787

目錄 Table of contents

doi:10.6342/NTU201702787

doi:10.6342/NTU201702787

圖目錄 Figure list

doi:10.6342/NTU201702787

doi:10.6342/NTU201702787

表目錄 Table list

doi:10.6342/NTU201702787

Chapter 1 Introduction

1-1 Background

Water is indispensable to creatures also for human beings, hence understanding the mechanism of hydrological cycle is helpful for human life. Evapotranspiration plays a significant part in hydrological cycle and also in climate system, which is a pass that water can move from land or ocean to atmosphere. Evapotranspiration contains two elements, which one is evaporation from land or ocean, and the other one is transpiration from plants. Transpiration may change according to plant communities (Gerten *et al.*, 2004, Sterling *et al.*, 2013). In recent years, terrestrial evapotranspiration has a decreasing trend probably due to climate change (Jung *et al.*, 2010). Understanding forest transpiration is helpful for predicting potential changes in water cycling in response to climate changes. Also, the accurate estimation of forest transpiration can help us to understand impacts of deforestation or forest management on water cycle.

1-2 Meteorological factors for stand-transpiration

In hydrological cycle, transpiration is one of the processes that can be influenced by plant (Gerten *et al.*, 2004), which are not only directly regulated by plant physiology, but also indirectly environmental meteorological factors. Therefore, several factors may affect transpiration, such as tree species, tree vigor, soil water content, solar radiation,

doi:10.6342/NTU201702787

precipitation, air temperature, humidity, fog and vapor pressure deficit (VPD) (saturated vapor pressure – ambient vapor pressure) (Granier, 1987; Granier *et al.*, 1996; Komatsu *et al.*, 2010; Klimešová *et al.*, 2013; Pataki & Oren, 2003; Shen *et al.*, 2015; Wullschleger *et al.*, 2001).

Generally, under the condition of drought, plants face of drought stress, so transpiration mechanism from plants are different from that in usual and less affected by other meteorological factors (Granier, 1987; Klimešová *et al.*, 2013; Wullschleger *et al.*, 2001). While water supply is sufficient, daily and seasonally patterns of plant transpiration are mainly regulated by solar radiation and VPD (Wullschleger *et al.*, 2001). Although precipitation might increase transpiration, there was no statistically significant relationship between them (Shen *et al.*, 2015). Fog also may affect tree transpiration in three ways. One is that fog lets leaf surface become wet, makes VPD decrease and may cover some stoma so that transpiration decrease (Lin *et al.*, 2015; Misson *et al.*, 2002; Ritter *et al.*, 2009). Second is that leaf may absorb water from saturated atmosphere or from wet surface of leaf, which probably moderates water stress (Burgess & Dawson, 2004). The third is that fog as a horizontal precipitation which may provide additional input of water so that supplies water source to plants for transpiration (Dawson, 1998).

doi:10.6342/NTU201702787

1-3 Transpiration in Taiwan

In Taiwan, there is about 60% of area covered with forest (林務局第四次全國森林資源調查，2017), therefore understanding forest transpiration characteristics is indispensable for realizing forest water cycle. Since forests in Taiwan are mostly located at mountainous area and elevated from 500 to 3,100 m, every place has its own microclimate depending on different meteorological factors. Also, Taiwan is situated between subtropical and tropical region, in which there are widely distributed montane cloud forests which show high biodiversity and contain more water resource (徐嘉君, 2015). In some previous studies in Taiwan, although transpiration was affected by VPD, radiation, and fog (林祐竹, 2011; 陳俐如, 2005; 蔡孜奕, 2013; 羅勻謙, 2004; Chen, 2013; Laplace, 2013), the main factor was different because of different microclimate. 陳俐如 (2005) claimed that transpiration was affected by local circulation induced specific climate condition such as fog. Other research suggested that fog could affect transpiration (林佑竹, 2011), but fog showed significant daily variation and it may cause different effects to transpiration. All-day fog with rain made transpiration maintain lower, but afternoon fog with rain could not make transpiration become very low. Instead, if fog with rain was sufficient in the afternoon, it could make transpiration become higher because of water supply (林佑竹, 2011).

doi:10.6342/NTU201702787

Xitou located in central Taiwan, fog duration in a year reached up to about 2,000 hours and always appeared in the afternoon and disappeared after sunset (Wey *et al.*, 2011), so plant transpiration might be affected by fog. Also, VPD is related to fog, because VPD may decrease while fog formation (Burgess & Dawson, 2004; Ritter *et al.*, 2009). Consequently, transpiration may be affected by fog through the changes in VPD in Xitou (Chen, 2013; Laplace, 2013). The formation of fog is related to environmental conditions, yet how climate change affects the formation of fog and the structure of cloudy forest is still unknown. Therefore, long-term investigation of transpiration and meteorological factors are needed for solving this problem.

1-4 Sap flow measurement

Various measurement techniques for evapotranspiration have been developed in the last 50 years, such as sap flow measurement, eddy covariance techniques and catchment water balance methods (Wilson *et al.*, 2001). Each method has its own advantages and shortcomings. They are different from the spatial and time scale. Sap flow measurement is the method that can estimate individual tree transpiration. Therefore, using sap flow measurement can help understanding different tree species' transpiration characteristics. Moreover, sap flow measurement is also an ideal method to understand how plants react to environmental conditions, managements (thinning, pruning and harvest), and climate

doi:10.6342/NTU201702787

changes (Smith & Allen, 1996). Many kinds of sap flow measurement methods were developed. Among these methods, thermal dissipation method has been widely used because of its low cost and easily installed (Smith & Allen, 1996; Steppe *et al.*, 2010).

Sap flow measurement just measures sap flow of one individual tree, so there are uncertainties using this approach to estimate stand scale transpiration. From sensor to whole tree transpiration, azimuthal variation, radial variation and sapwood area determining variation can affect the estimation of whole tree transpiration (Clearwater *et al.*, 1999; Chiu *et al.*, 2016; Delzon *et al.*, 2004; Kume *et al.*, 2012; Nadezhdina *et al.*, 2002; Shinohara *et al.*, 2013; Tsuruta *et al.*, 2010). Azimuthal variation may be caused from tree crown fraction or anisotropic radiation. Radial variation results from wood anatomy, that is, new vessel and tracheid have better ability to transport water. From tree to stand scale transpiration, tree to tree variation, sampling strategy and scaling approach may affect the estimation of stand scale transpiration (Köstner *et al.*, 1998; Kume *et al.*, 2010; Lu *et al.*, 2004). According to different plant species and different environment conditions, tree to tree variation is different everywhere. Thus, sampling strategy is different, too. For long-term transpiration estimation, some research have investigated about that. Clausnitzer *et al.* (2011) and Oishi *et al.* (2008) published 4-7 years sap flow experiments, they consider tree growth while calculating from sap flow rate to whole tree

doi:10.6342/NTU201702787

transpiration. They found a relationship between sapwood area and DBH, but they did not show how much tree growth affects the amount of transpiration.

Variations mentioned above must be considered to ensure the accurate estimation of stand transpiration. In study site Xitou, Tseng (2011) has measured azimuthal variations of Japanese cedar in four directions and measured radial variations in different depth of xylem. The results implied that the azimuthal variations in this stand less impacted on transpiration estimation than the radial variations. To estimate long-term near 7 years stand transpirations, careful determination of sapwood depth, considering radial variation and considering tree growth are indispensable.

1-5 Calibration of Granier probe

In addition to the variations that mentioned above, an uncertainty in estimating stand transpiration based on the sap flow method still exists. The thermal dissipation probe was previously calibrated by Dr. Granier in 1985, and an empirical formula has been widely used (Granier, 1987). Although some studies using this thermal dissipation probe found that the original empirical formula could produce real sap flow densities (Braun & Schmid, 1999; Clearwater *et al.*, 1999; Do & Rocheteau, 2002; Granier *et al.* 1996; Lu *et al.* 2002), some tree species materials in previous studies were not suitable for this empirical formula due to difference of wood characteristics among tree species (Bush *et al.*, 2010;

doi:10.6342/NTU201702787

Niu *et al.*, 2015; Steppe *et al.*, 2010; Sun *et al.*, 2012). Therefore, recently calibration experiment has been recommended for estimation of stand transpiration based on thermal dissipation method for each species. In recent years, calibration experiments were conducted for testing the accuracy of thermal dissipation sensor, and some investigated the effect of different wood characteristic, while some investigated the effect of different structure of thermal dissipation sensor (Ayutthaya *et al.*, 2009; Hultine *et al.*, 2010; Hölttä *et al.*, 2015; Paudel *et al.*, 2013). By absorbing or pushing water through tree trunk or branch segment, they measured the amount of water that passes through segment, and compared it with sap flow measurements to recalculate their own parameters of the original formula. Generally, sap flow densities calculated by original Granier empirical formula were underestimated, though it were overestimated in some cases (Sun *et al.*, 2012). Therefore, calibration experiment is necessary, which can substantially improve the accuracy of the Granier probe.

1-6 The goals of this study

Japanese cedar is one of the dominant species in mountainous area in Taiwan. Quantifying the transpiration of Japanese cedar trees is indispensable to understand water cycling there. There are still few studies have done long-term forest transpiration measurements in Taiwan, therefore long-term investigation of transpiration and

doi:10.6342/NTU201702787

meteorological factors are needed for understanding forest transpiration characteristics including inter-annual variation. For the purpose of estimating long-term stand transpiration based on Granier method, the variations derived from scaling, tree growth and the applicability of this method to sample tree species should be examined. No one tested the accuracy of thermal dissipation methods-based sap flow for Japanese cedar trees in Taiwan. Thus, the goals of this study are:

1) To determine the accuracy of thermal dissipation method-based sap flow measurement for Japanese cedar trees in Taiwan using indoor calibration experiments.

2) To provide a method that can estimate long-term stand scale transpiration in terms of potential error from sapwood depth and tree growth to sapwood area.

3) To obtain stand scale transpiration estimation with the consideration of potential error resulting from different application ways of the indoor calibration results.

4) To investigate inter-annual variation of stand scale transpiration of Japanese cedar and meteorological factors such as radiation, soil water content, air temperature, precipitation and VPD.

doi:10.6342/NTU201702787

Chapter 2 Materials and methods

2-1 Sap flow measurement

Thermal dissipation method was adopted in this study for field long-term sap flow measurement and for indoor calibration experiment on Japanese cedar (*Cryptomeria japonica*). The thermal dissipation sensors used in this study were handmade which has the same specification with the sensor in Granier (1987). One thermal dissipation sensor set consists of two probes which have copper-constantan thermocouple junction each other to sensor temperature; one is named heater probe that contains a heating and a temperature-sensing device, and the other one is called referenced probe that contains only a temperature-sensing device. These two probes are about 2 cm long. Before inserting sensors, the bark of the position which sensor will be inserted should be removed to reveal sapwood, and to ensure that the temperature which measured by sensor represented the average temperature of the 2cm long probe in wood. These two probes are inserted into xylem of trees, which one in upper side is heater probe and that in lower side is referenced probe (Fig. 1). Heater probes are provided 0.2W constant heating energy from electricity. Through the temperature difference between the two probes, sap flow density can be calculated by the empirical formula from Granier (1987). The Granier's empirical formula was used to calculate the sap flow density ($cm^3cm^{-2}s^{-1}$):

$$\text{Sap flow density } (\mathrm{cm^3 m^{-2} s^{-1}}) = 119 \times \mathrm{K}^{1.231} \quad (1)$$

doi:10.6342/NTU201702787

$$K = \frac{\Delta T_M - \Delta T}{\Delta T} \quad (2)$$

where K is the dimensionless flow index; ΔT_M is the value ΔT obtained under zero sap flow condition; ΔT is the difference of temperature between heater and reference probe. Small temperature difference represents that sap flows quickly in xylem, and vice versa. Thermal dissipation sensors were connected to data logger which recorded every 30 seconds and calculated mean temperature difference every 30 minutes from the field data. For calibration experiment, data logger recorded every 1 second and calculated mean temperature difference every 10 seconds. Because the sap flow density calculation formula of the thermal dissipation method required the temperature difference under zero sap flow condition, for field data, ΔT_M was different every day depending on the highest ΔT in each day. For calibration experiment, after installing sensors, started providing heat and recorded temperature difference without water uptake till the difference of temperature became stable, and took the highest ΔT as the ΔT_M for each segment.

If the sapwood depth was less than 2 cm, a correction formula from Clearwater would be applied to recalculate sap flow density to reduce the effective of inactive xylem. Because thermal dissipation method assumed that probes integrate temperature and sap flow density along the probe length (2cm) (Lu *et al.*, 2004), the ideal case is when sapwood depth equal to the length of the probes. But, when sapwood depth was smaller than 2 cm, the sap flow density which sensor measured always underestimated true mean

doi:10.6342/NTU201702787

sap flow density. It is because that when some part of the probe is in inactive sapwood, the temperature integrated in the probe will be higher, and then the difference of temperature becomes higher to make the sap flow density underestimated. Therefore, Clearwater *et al.* (1999) provided a method to calculate sap flow density that just in active xylem to deal with this problem of underestimation when active sapwood depth is below 2 cm:

$$\Delta T = a\Delta T_{SW} + b\Delta T_M ,$$

$$\Delta T_{SW} = \frac{\Delta T - b\Delta T_M}{a} \quad (3)$$

This formula considered that the temperature which probe measured contains two parts, one is the temperature measured in sapwood called ΔT_{SW}, and the other is the temperature measured in inactive xylem called ΔT_M. While a is the proportion of probe in sapwood and b is the proportion of probe in the inactive xylem. Under the condition that sapwood depth is known and lower than 2 cm, corrected sap flow density for the active xylem can be calculated by replacing ΔT in formula 2 with ΔT_{SW} in formula 3. However, because a and b are the proportions of sapwood and inactive xylem respectively, under the condition that the value of b higher than 0.5 (i.e. the width of inactive xylem is higher than 1.0 cm), the value of ΔT may be lower than the value of $b\Delta T_M$ or just a little bit higher than it. Therefore, the value of ΔT_{SW} may be lower than 0 or may be higher than 0 but close to 0. If the value of ΔT_{SW} is lower than 0, the value

doi:10.6342/NTU201702787

of K will also be lower than 0, so that sap flow density cannot be calculated. On the other hand, if the value of ΔT_{SW} is higher than 0 and close to 0, the value of K will be very high, so that sap flow density will be extremely high which is distinct from that in usual. Consequently, to prevent the abnormal phenomenon, since the value of b is higher than 0.5, the correct formula 3 from Clearwater *et al.* (1999) will not be adopted in this study.

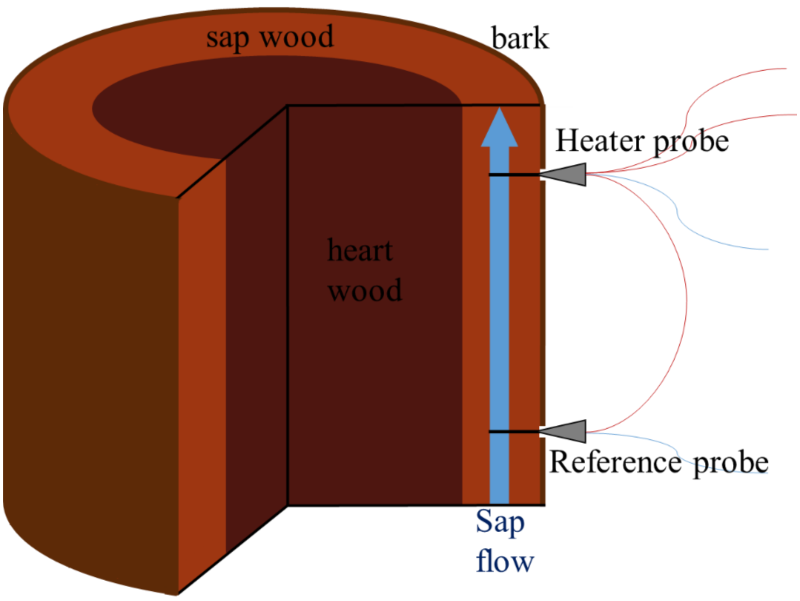


Fig. 1 Diagram of Granier thermal dissipation method.

doi:10.6342/NTU201702787

2-2 Calibration experiment

2-2-1 Samples and tree segment preparation

Six sample trees of Japanese cedar (*Cryptomeria japonica*) were harvested from Xitou tract, experimental forest of National Taiwan university. The stem diameter at breast high of these six samples were ranged from 15 to 20 cm. Twelve stem segments were cut from these six sample trees. Three sample trees were cut on 6 March 2016, and the other three trees were cut on 27 August 2016. In the first three sample trees, one segment was cut out from each tree (i.e., total three segments). In the last three sample trees, three segments were cut out from each tree (i.e., total nine segments). The height of segments should be lower than under branch height, and the north side and upside of the segment were recorded on each segment in the field. The tree height and diameter at breast height of each tree were measured and recorded. Also, the height of segments was recorded for the last three trees (9 segments). Segments were about 50 to 60 cm long and were covered with wet towels in two sides to avoid stem dehydration. Finally, segments were brought to laboratory to do experiments.

Before doing calibration experiment, following sample preparation must be carefully done as it had greatly impact on the success of the experiment. Each stem segment was recut in both sides in laboratory before doing experiments to assure conductivity of the segments. The bark on the up side of segments was removed about 3-5 cm strip to make

doi:10.6342/NTU201702787

sure that water passed segments only through xylem; also, removing bark can make attachment much easier to stick on the segment because of its smooth surface. Then, adhesive and silicone were applied to the inside of the attachment (a plastic cylinder with a cover) and the position which bark was removed from the segment. The attachment was putted on the tree segment and adjusted to fit the tree segment to tightly bounded avoiding leaking water or air. After the adhesive and silicone were dry, the segment was prepared to do a calibration experiment (Fig. 2).

Fig. 2 Photo of tree segment preparation.

doi:10.6342/NTU201702787

2-2-2 Process of calibration experiment

The calibration experiment (Fig. 3, Fig. 4) using twelve Japanese cedar stem segments were conducted as follow:

1) Scaffold (75cm high) were set up for hanging the tree segments.

2) A flask was equipped with two plastic tubes, which one was connected to pump and the other one was connected to attachment that stick on tree segment.

3) Tree segment was hung on the scaffold; a bucket with water was placed under a tree segment and the bottom side of the segment (about 4-5 cm) was under water.

4) Thermal dissipation probes were inserted into the tree segments to collected data.

5) By adjusting the pump pressure, water was pumped from bottom to top; also, constant water flow rates at different level were generated to test the accuracy of thermal dissipation methods-based sap flow under different sap flow rates.

6) A volumetric cylinder which was equipped with one plastic tube that connected to the bucket under tree segment was set up. Based on the principle of Pascal, the volume of water which took out from tree segment could be measured from the cylinder.

7) After the sap flow rate became stable under each pump pressure, the volume of water took out from tree segment was recorded every 1 minute in a 10 minutes period or every 30 seconds in a 5 minute period. Then the measurements with the values derived from Granier probe were compared with it during the period.

doi:10.6342/NTU201702787

8) Safranin stain solution was used to dye the tree segment to get the active sapwood area. After dying, tree segment about 1cm, 5cm and 10cm far from the bottom side were cut and photos were taken. Sapwood area and sapwood depth data were got from image processing using the photo which was about 1cm far from bottom side of each segment.

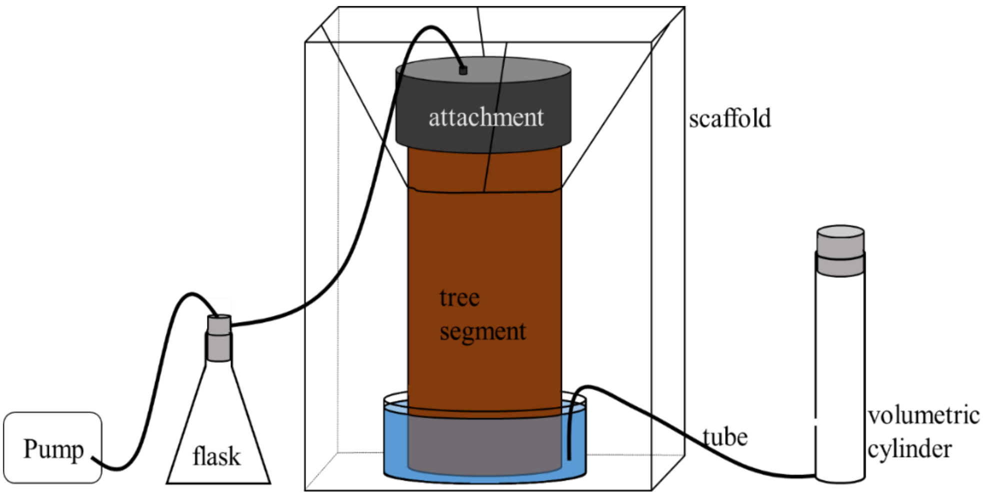


Fig. 3 Diagram of calibration experiment construction used to test the accuracy of thermal dissipation methods-based sap flow.

Fig. 4 Photo of calibration experiment construction used to test the accuracy of thermal dissipation methods-based sap flow.

doi:10.6342/NTU201702787

2-2-3 Sap flow measurement-sensor arrangement

In the calibration experiment, four sets of thermal dissipation sensors were inserted into four directions (north, east, south and west) for each stem segment. This was in order to prevent that the position where sensor inserted was a nod or without sap flowing, and to get more representative data of thermal dissipation sap flow for each segment. Finally, the sap flow rate calculated by Granier's empirical formula (formula 1 and 2) in four directions were averaged, and this averaged sap flow density represented the value that measured by Granier sensor for each segment, which was compared with sap flow density calculated by real water uptake.

As the calibration experiment compared sap flow densities that calculated from thermal dissipation sensor and from real water uptake, there were two kinds of sap flow densities were calculated. One was measured from thermal dissipation sensor and the other one was measured from the volumetric cylinder measurement system. For thermal dissipation sensor, the Granier's empirical formula (formula 1 and 2) was used to calculate sap flow density ($cm^3cm^{-2}s^{-1}$). If the sapwood depth was less than 2 cm, a correction formula from Clearwater (formula 3) would be applied to recalculate. For volumetric cylinder measurement, the sap flow density ($cm^3m^{-2}s^{-1}$) was calculated by the formula:

$$\text{Sap flow density } (\mathrm{cm^3m^{-2}s^{-1}}) = \frac{\mathrm{V}}{\mathrm{A} \times \mathrm{T}} \quad (4)$$

doi:10.6342/NTU201702787

where V is the volume (cm^3) of water uptake in the measurement period; A is the sapwood area (m^2) of the segment; and T is the time (s) of the measurement period.

2-2-4 Determining of sapwood area and sapwood depth

In order to determine active xylem area of each segment, 0.1 % safranin stain solution was used to dye each segment after calibration experiment for about 1 hour. After dying tree segments, about 1 cm long at the bottom side of segment was cut as a disk, in which appearance of active xylem can be identified. Then a photo was taken for image processing to get sapwood area and sapwood depth in four azimuths. Sapwood area and depth were calculated by image analysis software Image J and GNU Image Manipulation Program (GIMP). Sapwood depth for each azimuth was averaged from five point measurements. One point was at the azimuth, two points were 0.5 cm apart from the azimuth, and two points were 1.0 cm apart from the azimuth.

doi:10.6342/NTU201702787

2-3 Long-term measurement of sap flow and meteorological factors

2-3-1 Experiment site and samples

A long-term sap flow measurements plot is located at Xitou, which is situated in Nantou in central Taiwan. The area of our plot is 20*20 m (400 m^2). In Xitou, the average annual temperature is about 16.6 ^{0}C, and the average annual rainfall is about 2,600 mm (Wey *et al.*, 2011). The monthly precipitation and average temperature from Sep. 2010 to Mar. 2017 were shown in Figure 5, and air temperature and rainfall were high in summer and low in winter.

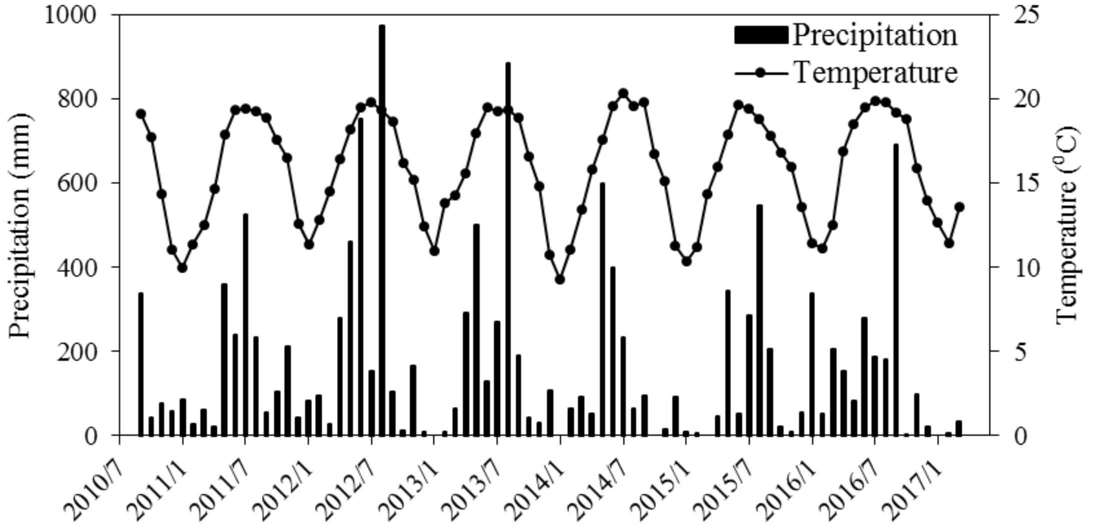


Fig. 5 Monthly precipitation and temperature from Sep. 2010 to Mar. 2017.

In our plot, sap flow measurements for Japanese cedar (*Cryptomeria japonica*) trees have been conducted since August 2010. In this study, the period of sap flow data used to estimate stand transpiration was from 1 September 2010 to 31 March 2017, totally 6

doi:10.6342/NTU201702787

years plus 7 months. In this long-term period, the number of sample trees with sensors and the number of trees in the plot were not constant. In the period from August 2010 to 23 March 2012, sample size for sap flow measurements was 19 trees. While in the period 24 March 2012 to 31 March 2017, the sample size was 15 trees. On the other hand, for the number of trees in the plot, from August 2010 to 31 December 2014, there were total 25 trees; from 1 January 2015 to 31 June 2016, there were 24 trees; and from 1 July 2016 to 31 March 2017, there were 23 trees. The more details was shown in Tseng (2011).

2-3-2 Sapwood depth and sapwood area measurement

The sapwood depth of trees at breast height on east and west sides were measured in June 2010 by using increment borer and then determined sapwood depth visually. In August 2016, the sapwood depth of trees at breast height on east and west sides were measured again.

However, to improve the accuracy of stand transpiration estimation, the sapwood depth for each tree should be measured more carefully. To obtain sapwood depth accurately, dye injection method could be used (Gebauer *et al.*, 2008; Meinzer *et al.*, 2001). Therefore, the dye injection method was adopted in this study to measure sapwood depth in 17 trees covering sap flow measurement samples. The dye injection experiment in this study was conducted as follow (Fig. 6). First, a cup was fastened on tree stem and

doi:10.6342/NTU201702787

filled with water. Second, a hole was drilled which diameter was 8 mm into tree xylem under water. Third, water was replaced with 0.1 % safranin stain solution. Finally, about 3-5 hours later, increment borer was used to get increment core above the hole about 1 to 2 cm, and then sapwood depth which the portion had been dyed was measured; also, the sapwood depth visually determined was recorded. Sapwood depth measured by dye experiment was compared with that determined by eye, and the relation between these two was established in this study. This relationship was applied to sapwood depth which was determined by eye in June 2010, to convert to the more accurate sapwood depth based on dye experiment. Sapwood area estimation was performed based on the accurate sapwood depth:

$$\text{Sapwood area } (\text{m}^2) = \pi\left[\left(\frac{\text{DBH}}{2}\right)^2 - \left(\frac{\text{DBH}}{2} - \text{sapwood depth}\right)^2\right] \quad (5)$$

Fig. 6 Picture of dye injection experiment.

doi:10.6342/NTU201702787

2-3-3 Biometric parameters measurement

In order to understand the basic information of all trees in the plot, tree height and diameter in the breast height were measured in June 2010. For long-term tree growth measurements, in August 2016, the increment cores of trees at breast height on east and west sides were obtained by using an increment borer. The width of growth rings of each increment core in each year for 7 years was measured under a magnifier. Then the width of growth rings in east and west side were averaged, and the double of the values represented the diameters of tree growth in each year.

2-3-4 Meteorological factors

Several meteorological factors were used in this study, which were provided from the Experimental Forest of National Taiwan University. Environment data contain solar radiation, relative humidity, air temperature, precipitation and soil water content (weighted averaged from 5 cm, 20cm and 50 cm depth under soil), which have been continuously measured by Xitou flux tower and Xitou agricultural weather station. Lack of air temperature data were filled with other data which use the relationship between these two places data. The period of data was from 1 September 2010 to 31 March 2017. Vapor pressure deficit was calculated from air temperature and relative humidity.

doi:10.6342/NTU201702787

2-3-5 Sap flow measurement-sensor arrangement

From 10 August 2010 to 23 March 2012, there were 19 trees that inserted sensors. In these 19 trees, there were three kinds of sensor arrangement. One is that 5 sensors were inserted in each tree, another one is that 4 sensors were inserted in each tree, and the other one is that 2 sensors were inserted in each tree. For the first kind, there were totally 6 trees. Among these 5 sets of sensors, 4 sets were inserted into four directions (north, east, south and west) and in the deep of 0-2 cm, while 1 set was inserted into the deep of 2-4 cm. For the second kind, there were 2 trees only. Four sensors were inserted in four directions and were in the deep of 0-2 cm. For the third kind, there were 11 trees. Two sensors were inserted in the directions of east and west with the deep of 0-2 cm. The more detail information was shown in Tseng (2011).

From 24 March 2012 to 31 March 2017, there were 15 trees for sap flow measurements. Two sets of sensors were inserted into tree xylem in the directions of north and south at the depth of 0-2cm in the 15 trees.

For stand scale transpiration estimation in this study, data of 15 trees with two sets of sensors from Sep 2010 to Mar 2017 were used. For radial variation examination, data of 2 trees with five sets of sensors from 10 Aug 2010 to 10 Feb 2011 were used.

doi:10.6342/NTU201702787

2-4 Data processing for long-term stand scale sap flow

2-4-1 Estimation of stand scale transpiration

Transpiration from one tree can be scaled up to stand scale (Clausnitzer *et al.*, 2011; Chiu *et al.*, 2016; Kume *et al.*, 2010; Oishi *et al.*, 2008; Shinohara *et al.*, 2013). The formula used in this study was:

$$\mathrm{Et\ (mm/day)} = \mathrm{J_s}\frac{\mathrm{A_{s\_stand}}}{\mathrm{A_G}} \quad (6)$$

$$\mathrm{J_s(cm^3m^{-2}s^{-1})} = \frac{\sum_{i=1}^{n}\mathrm{Q_i}}{\sum_{i=1}^{n}\mathrm{A_{s\_treei}}} \quad (7)$$

$$\mathrm{A_{s_{stand}}(m^2)} = \sum_{i=1}^{x}\mathrm{A_{s\_treei}} \quad (8)$$

$$\mathrm{Q_i(cm^3/s)} = (\mathrm{F_{d0-2}} \times \mathrm{A_{s0-2}}) + (\mathrm{F_{d2-4}} \times \mathrm{A_{s2-4}}) \quad (9)$$

where $\mathrm{J_s(cm^3m^{-2}s^{-1})}$ is the mean stand sap flow rate; $\mathrm{A_{s\_stand}(m^2)}$ is the sum of sapwood areas of all trees in sample plot; $\mathrm{A_G(m^2)}$ is the area of the plot, n is the number of sample trees with sap flow measurements; $\mathrm{A_{s\_tree}}$ is the sapwood area of each tree; x is the total number of trees in the plot. $\mathrm{F_{d0-2}}$ is sap flow density in 0-2cm; $\mathrm{F_{d2-4}}$ is sap flow density in 2-4cm; $\mathrm{A_{s0-2}}$ is sapwood area in 0-2cm; $\mathrm{A_{s2-4}}$ is sapwood area in 2-4cm.

The data (0-2cm and 2-4cm sap flow density) in the period (from 8/10/2010 to 2/10/2012) were used to calculate the ratio between 0-2cm and 2-4cm, and then this ratio was used to estimate 2-4cm sap flow density from 0-2cm sap flow density for all data.

doi:10.6342/NTU201702787

2-4-2 Effect of sapwood depth and growth on stand transpiration estimates

In order to know the change of sapwood depth during about 6 years, in August 2016, the sapwood depth of trees at breast height on east and west sides were measured again, and sapwood depths were determined by eye. Besides, after conducting dye injection experiment, sapwood depth determined by dye were compared with that determined by eye, and the regression line between them was used to correct all sapwood depth determined by eye in 2010. Also, the radial variation was examined by comparing sap flow rate in 0-2 cm and 2-4 cm with the corrected sapwood depth and Clearwater formula (formula 3); the ratio of sap flow rate between 0-2 cm and 2-4 cm was calculated.

In order to estimate long-term stand transpiration, this study examined effect of tree growth on stand transpiration. To investigate tree growth, the measurement of growth ring width was conducted in August 2016 using increment cores, which were derived from east and west side of the individuals. The DBH change for each year was double of growth ring width (i.e. average of east and west), so DBH in each year can be calculated by accumulating DBH change to DBH which was measured in 2010. Then, sapwood area for each year was estimated according to the formula 5.

To identify the effect of sapwood depth and tree growth to stand transpiration estimation, sap flow data in 2015 was used. Here, three kinds of estimations were tested, one was “original”, another was “consider new sapwood depth” and the other was

doi:10.6342/NTU201702787

“consider tree growth”. The “original” one did not consider corrected sapwood depth and ratio of sap flow rate between 0-2 cm and 2-4 cm obtained in this study. The sapwood depth determined by eye in 2010 was used to calculate sapwood area and to determine the ratio of sap flow rate between 0-2 cm and 2-4 cm without Clearwater formula (formula 3). Also, the DBH measured in 2010 was used to calculated sapwood area. On the other hand, the “consider new sapwood depth” one used corrected sapwood depth and ratio of sap flow rate between 0-2 cm and 2-4 cm based on the corrected sapwood depth with Clearwater formula (formula 3) to stand transpiration estimation, but still used DBH measured from 2010. Last, the “consider tree growth” one did not consider corrected sapwood depth and ratio of sap flow rate between 0-2 cm and 2-4 cm obtained based on it; DBH in 2015, which was calculated by accumulating DBH change to DBH that was measured in 2010, was used to calculate sapwood area. By comparing yearly stand scale transpiration estimated from “original” and the other two methods, the effect of sapwood depth and tree growth on stand transpiration can be identified.

2-4-3 Application of calibration experiment results to field sap flow data

To improve the accuracy of stand scale transpiration estimation, the results of calibration experiment were applied to the long-term field data to correct the sap flow

doi:10.6342/NTU201702787

density measured by thermal dissipation sensor. Five methods were used in this study. Here, sap flow data in 2015 was used to examine applicability of the five methods.

The concept figure of five methods was shown in figure 7. Y axis was considered as the sap flow density calculated by real water uptake, and X axis was considered as the sap flow density calculated by original Granier's empirical formula (formula 1). First method, y=ax (blue line in Fig. 7) was used for all field data. Second method, y=ax+b (orange line in Fig. 7) was used for all field data. Third method, both y=ax+b (orange line in Fig. 7) and y=ax (grey line in Fig. 7) were used. y=ax+b (orange line in Fig. 7) corrected field data which were higher than the lowest value of y that calibration experiment had tested. While, y=ax (grey line in Fig. 7) was used when field data was lower than the lowest value of y that calibration experiment had tested. Forth method, y=ax+b (orange line in Fig. 7) corrected field data which were higher than the lowest value of y that calibration experiment was conducted. On the other hand, for field data which were lower than the lowest value of y that calibration experiment was conducted, there was no correction. Fifth method, based on calibration experiment, new parameters were calculated to correct the formula 1, so I used a new formula to calculate sap flow.

After correcting field data, this study examined which one had better correction for sap flow density estimation. According to the diurnal variations in sap flow and comparisons with potential evaporation (Thornthwaite and Hamon, which calculation

doi:10.6342/NTU201702787

was same with Alkaeed *et al.*, 2006). Also, these five methods also applied to data from calibration experiment to identify which one had better correction for sap flow density estimation. Through above, the better methods for estimating the most likely stand transpiration was examined. Here, the estimation of transpiration in 2015 considered new sapwood depth and tree growth.

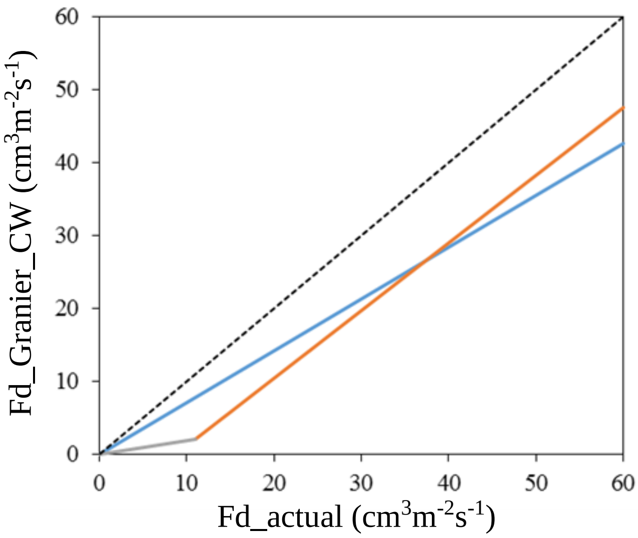


Fig. 7 Concept figure of formula used in 5 methods from calibration experiment. Fd_actual represents the sap flow rate which was calculated by real water uptake. Fd_Granier_CW represents the sap flow rate which was calculated by Granier empirical formula and Clearwater formula.

doi:10.6342/NTU201702787

Chapter 3 Results and discussions

3-1 Calibration experiment

3-1-1 Sample segments

The information of all twelve segment samples was shown in Table 1. The age of trees was 37 years old for tree No.1, 2 and 3; and was 35 years old for tree No. 4, 5 and 6. Diameter at breast height of all segments ranged from 15.5 to 19.8 cm, and tree height ranged from 26.5 to 19.3 m. Height of segments were not recorded for No.1, No.2 and No.3 segments, while it were recorded in another nine segments. The diameter of segment for the first three segments were smaller than other nine segments, it was about 12 cm. For another nine segments, diameter of segment ranged from 12 to 15 cm. For 12 segments, sapwood depths in 7 segments were less than 2 cm. Sapwood depth in No. 3 was the smallest, and sapwood depths in three azimuths (east, south and west) were smaller than 1 cm. For those sapwood depth less than 2 cm, Clearwater formula (Eq. 3) was applied to avoid underestimating. However, if sapwood depth was less than 1 cm (No. 3 E, S, W; No. 5-1 S; No. 5-2 W; No. 5-3 S; No. 6-1 S), the sap flow density corrected by Clearwater formula will be extremely high, so this data would not be used in this study.

Response of sap flow density to pump pressure changes in segment No. 1 was shown in Fig. 8. When pump pressure changed, sap flow density changed obviously, but it took about 1 hour to reach a stable state. The thermal dissipation method underestimated the

doi:10.6342/NTU201702787

corresponding real water uptake, while after applying corrected formula from Clearwater, the estimation of thermal dissipation probe was closer to real water uptake.

The photos of sapwood area after dye experiment for each segment and response of K (Eq. 2) to pump pressure changes in each segment were shown in Figure 9 and Figure 10. We can see that in most cases, the position of dyed area in the tree segments in 1 cm, 5cm and 10cm did not change a lot except for segment No. 1. So that we used the averaged sapwood depths from each azimuth, which was calculated from five points measurements. One point was at azimuth, two points were 0.5 cm apart from azimuth and the other two points were 1.0 cm apart from azimuth. For the response of K to pump pressure changes in all segments (Fig. 10), it showed that there was azimuth variation in these 6 trees, but sap flow rates did not be highest in only one azimuth. From the dyed sapwood area in 1 cm, 5cm and 10cm, we could identify the azimuth with higher sap flow density, and it was mostly agree with that determining from the figure of response of K to pump pressure changes. We also could find that sapwood depth was not the reason that cause underestimated under the low sap flow rate condition. Because although sapwood depth was about 2 cm, the accuracy of the Granier sensor was low under the low sap flow rate condition.

doi:10.6342/NTU201702787

3-1-2 Effect of sensor number

In calibration experiment, four sets of Granier sensors were used for each tree segment in order to improve the accuracy of real sap flow density estimation. To confirm potential errors due to the number of azimuthal direction, we calculated the ratio of sap flow density calculated by Granier and Clearwater formula (Fd_Granier_CW) and sap flow density calculated by real water uptake (Fd_actual) for the four combinations (1, 2, 3 and 4 sensors) (Fig. 11). The results showed that the estimations from just one set of sensor and from two sets of sensors might overestimate or underestimate real sap flow density significantly. While sensor number increased, the ratio of sap flow density calculated by Granier and Clearwater formula to real water uptake got closer to 1. That is to say, more sensor number could lead to more accurate estimation.

3-1-3 Effect of segment height

To understand whether different height of segments in the same tree may have similar results or not, tree No.4, 5 and 6 were cut into three segments for each tree. If different height of segment had dissimilar results, all sample segments should cut at sensor installed height. While if different height of segment had similar results, sample segments can be taken from anywhere under the first living branch height.

doi:10.6342/NTU201702787

Therefore, sap flow densities measured by Granier probes (Fd_Granier) and calculated by water uptakes (Fd_actual) in tree No.4, 5 and 6 were compared (Fig. 12). In figure 12, three segments of each tree in No.4, 5 and 6 showed similar trends. Height of segments has little impact on relationship between Fd_actual and Fd_Granier. However, it was obvious that different trees had their own trend. So, the effect of different trees was larger than different height of segments. To sum up, different height of segments might have similar results, so all twelve sample segments in this study could have high representative in each whole sample tree.

3-1-4 Accuracy of thermal dissipation probe for Japanese cedar trees

Sap flow densities calculated by real water uptakes (Fd_actual) and measured by thermal dissipation probe (Fd_Granier) were compared in all sample segments (Fig. 13). In Figure 13, the value of $F_{d\_Granier}$ was calculated only by Granier empirical formula without applying the corrected formula from Clearwater. So, thermal dissipation probes in most of sample segments were underestimated because the sapwood depths were shorter than 2 cm. Under this condition, Granier probes underestimated about 40% of the real water uptakes.

Fd_actual and measured by thermal dissipation probe with applying the corrected formula from Clearwater (Fd_Granier_CW) were compared in all sample segments (Fig.

doi:10.6342/NTU201702787

14). With the corrected formula from Clearwater, Fd_Granier_CW in most of sample segments corresponded to Fd_actual accurately. Under this condition, Granier probes could estimate the real water uptakes accurately less than 10% error. This result implied that the original Granier formula may be suitable for Japanese cedar, and that sapwood depth significantly impacted on the accuracy of thermal dissipation method; hence, careful determination of sapwood depth was the key for the transpiration estimates.

On the other hand, in long term field sap flow density data, we found that the sap flow density of Japanese cedar trees in Taiwan ranged from 0 to 50 ($cm^3m^{-2}s^{-1}$). Under the condition, Fd_Granier_CW may underestimate about 30% of Fd_actual (Fig. 15). This result suggested that the original Granier formula may not be suitable for Japanese cedar trees with the sap flow rate ranging from 0 to 50 ($cm^3m^{-2}s^{-1}$) in central Taiwan.

3-1-5. Comparison with other calibration studies

Some studies showed that thermal dissipation original formula was not suitable for some tree species, and thermal dissipation methods in most cases were underestimated real sap flow rate though some cases were overestimated (Table 2). Previous studies that shown in Table 2 all used Granier 2 cm probe to conduct calibration experiment.

The accuracy of Granier estimation was low under low sap flow rate, while the accuracy of Granier estimation was relatively high when considerating both high and low

doi:10.6342/NTU201702787

sap flow rate (Gutierrez & Santiago, 2006; Sun *et al.*, 2012; Wiedemann *et al.*, 2016), which was same with this study. Although the measurement errors was high when sap flow rate was high in some cases (Bush *et al.*, 2010, Steppe *et al.*, 2010; Sun *et al.*, 2012).

After applying Clearwater formula (formula 3), the substantial improvement in accuracy of estimation could be found in Bush *et al.* (2010) and Paudel *et al.* (2013), which was the same with this study. However, some results showed that the application of Clearwater formula did not approve the accuracy (Sun *et al.*, 2012).

In these previous studies, sample materials were derived from branches or stem segments, the range of sap flow rate may be affected by the origin of the materials. For branches, the data in low sap flow rate could be obtained, but for stem segments the data in low sap flow rate were rarely found (Table 2).

This study showed that the Fd_Granier_CW underestimated Fd_actual, probably due to xylem anatomy but not due to sapwood depth, pump pressure (see appendix 1), and azimuthal variations in Fd. Consequently, this study suggested that simple calibration experiment can approve the accuracy of Granier probe, and it is recommended to conduct calibration experiment for each species. The Granier probes and original formula were mostly suitable for softwood species, although it were not suitable for some softwood species (Table 2; Bush *et al.*, 2010).

doi:10.6342/NTU201702787

Table 1 Information of all twelve Japanese cedar tree segments.

Segment No.	DBH (cm)	Diameter of segment (cm)	Tree height (m)	Sapwood depth (cm) N	E	S	W	average	sapwood area (cm^2)	Height of segment (cm)	Experiment Date
1	15.5	12.0	17.8	1.3	1.7	2.1	1.9	1.8 ± 0.4	43.9	-	2016/3/11
2	15.8	12.0	19.0	1.5	1.2	1.3	1.9	1.5 ± 0.3	41.0	-	2016/3/8
3	16.8	12.0	16.6	1.3	0.3	0.5	0.9	0.8 ± 0.4	23.6	-	2016/3/13
4-1		14.6		1.8	1.5	1.8	1.9	1.8 ± 0.2	69.9	3.6	2016/9/1
4-2	16.8	13.5	16.8	2.0	1.9	1.9	2.1	2.0 ± 0.1	76.6	5.1	2016/9/2
4-3		12.3		2.0	1.8	2.4	2.0	2.0 ± 0.2	67.6	6.2	2016/9/6
5-1		14.7		1.6	1.8	0.1	1.6	1.3 ± 0.8	50.2	2.0	2016/9/4
5-2	16.1	14.0	16.5	2.3	2.4	1.4	0.8	1.7 ± 0.7	56.9	2.7	2016/9/5
5-3		13.7		2.4	1.8	1.0	2.2	1.9 ± 0.6	55.7	3.5	2016/9/7
6-1		14.5		2.7	2.0	1.0	2.8	2.1 ± 0.8	87.9	5.2	2016/9/4
6-2	19.8	14.2	19.3	2.3	2.2	1.9	2.1	2.1 ± 0.2	79.6	5.9	2016/9/6
6-3		13.9		2.3	2.2	2.0	1.5	2.0 ± 0.3	75.8	8.5	2016/9/8

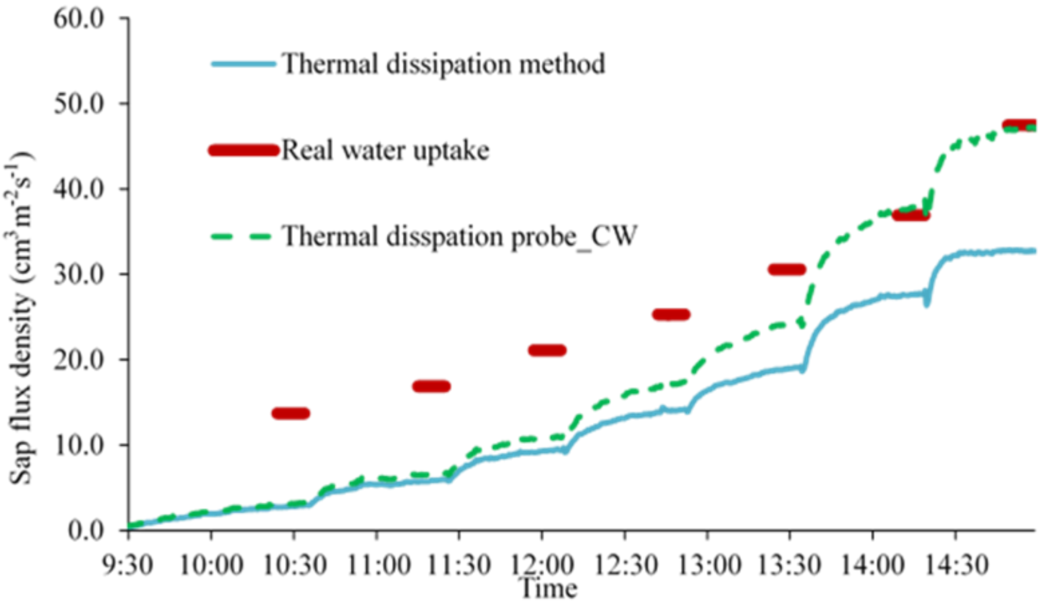
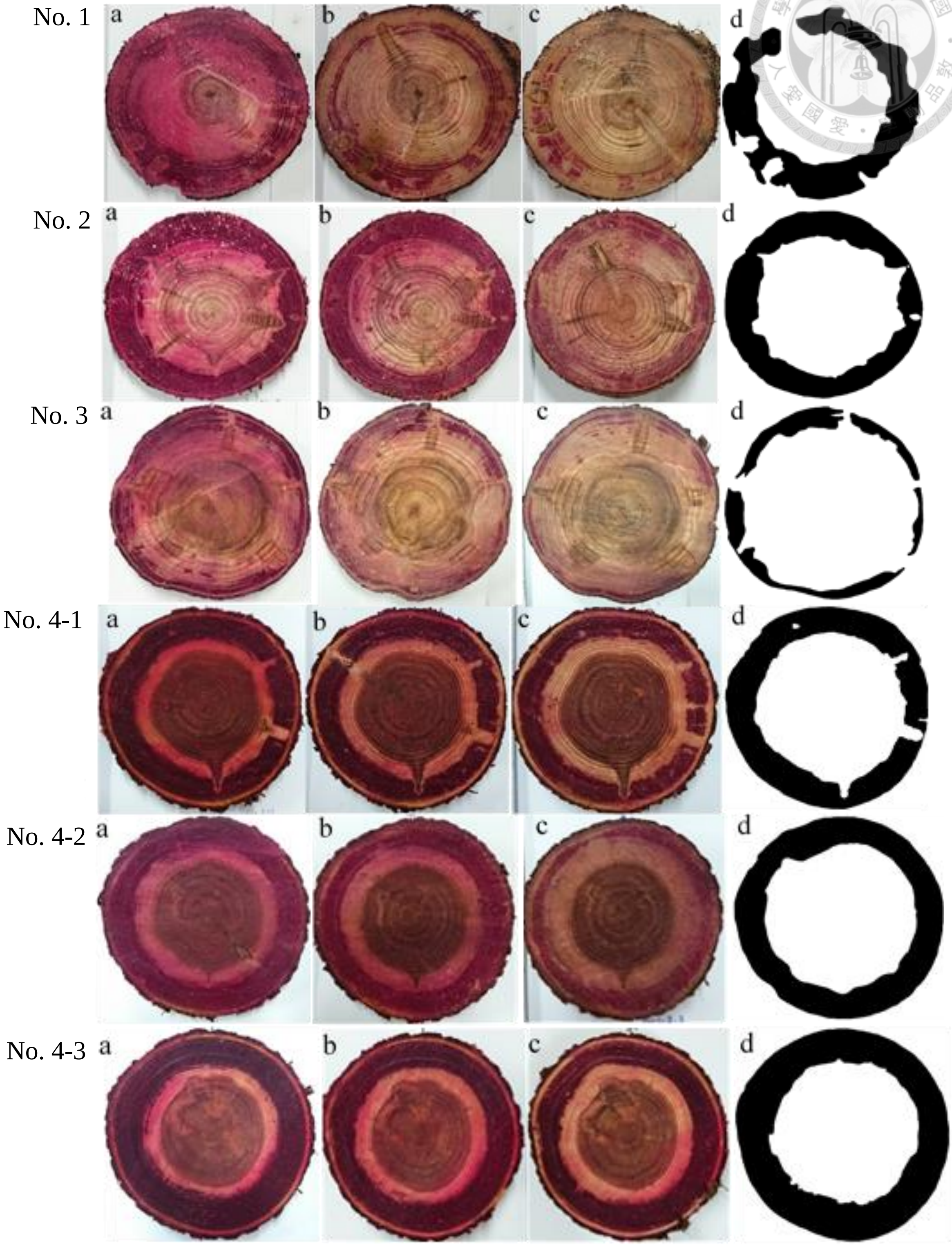


Fig. 8 Response of sap flow densities to pump pressure changes in segment No.1. The red line represents the period that recorded real water uptake through volumetric cylinder and also represents sap flow density which calculated from real water uptake.

doi:10.6342/NTU201702787



doi:10.6342/NTU201702787

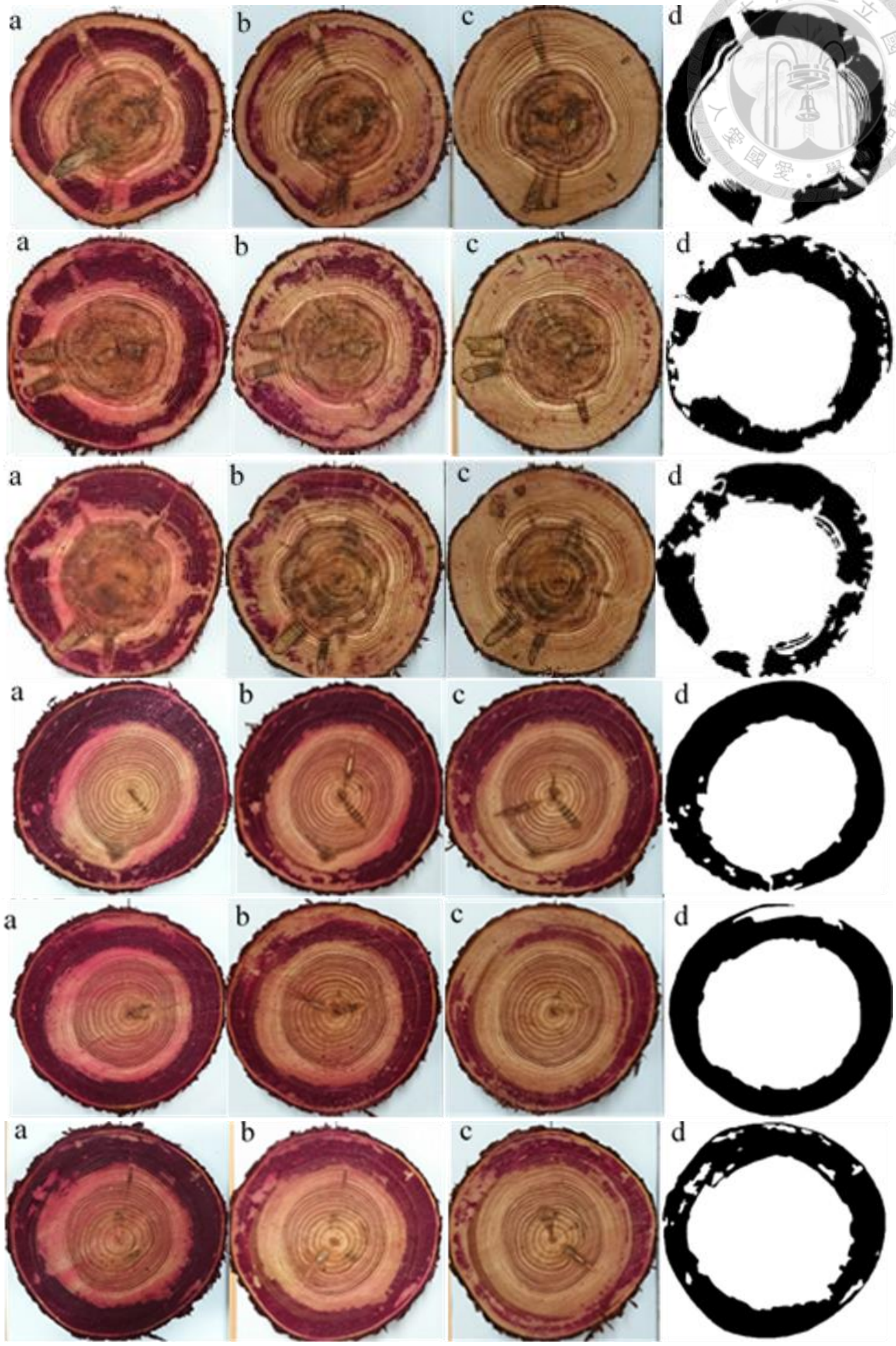


Fig. 9 Sapwood area for every 12 segment at 1 cm (a), 5cm (b) and 10 cm (c), and figures of sapwood area determined through GIMP (d).

doi:10.6342/NTU201702787

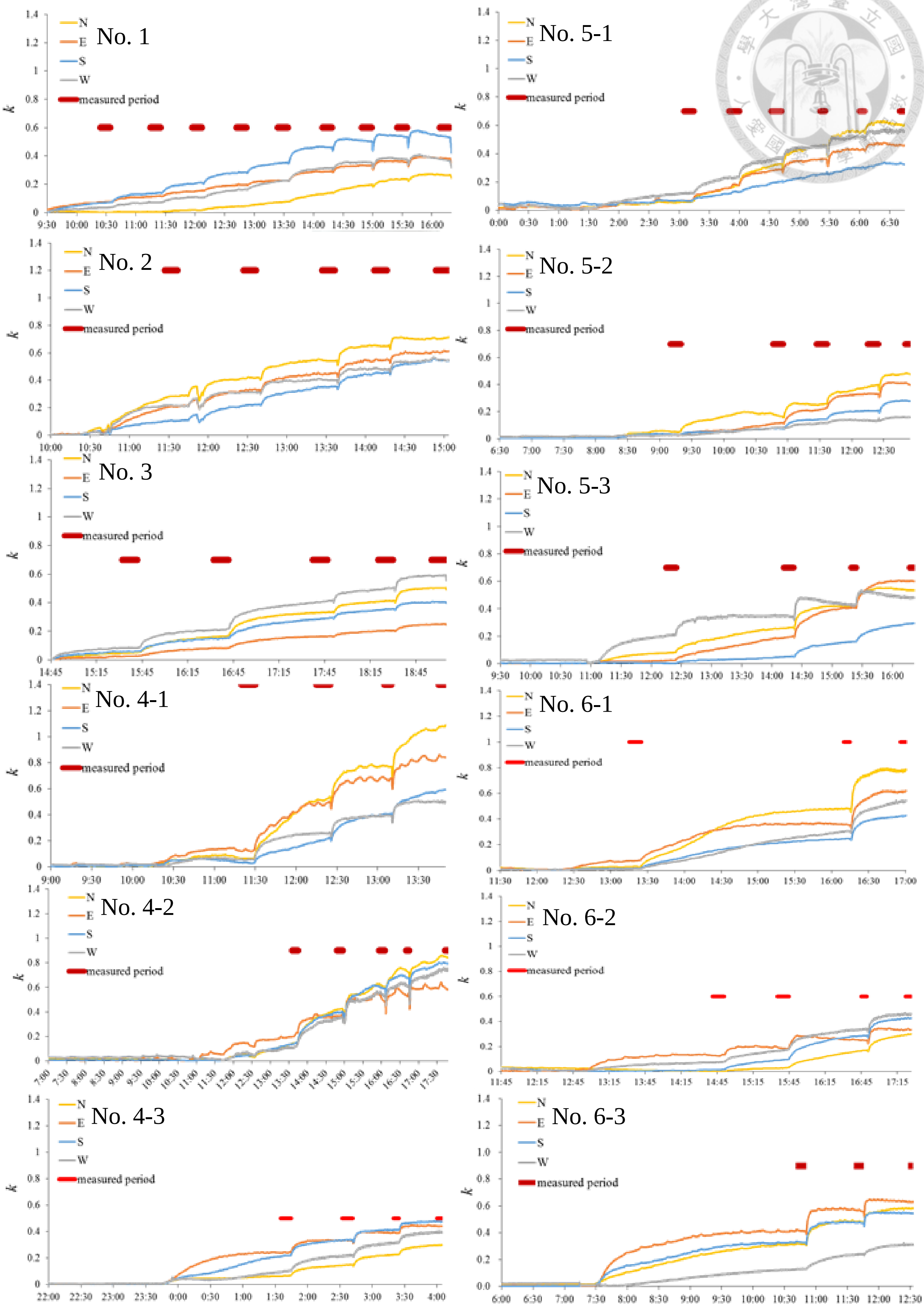


Fig. 10 Response of K to pump pressure changes in each segment. Measured period represents the measured time of volumetric cylinder.

doi:10.6342/NTU201702787

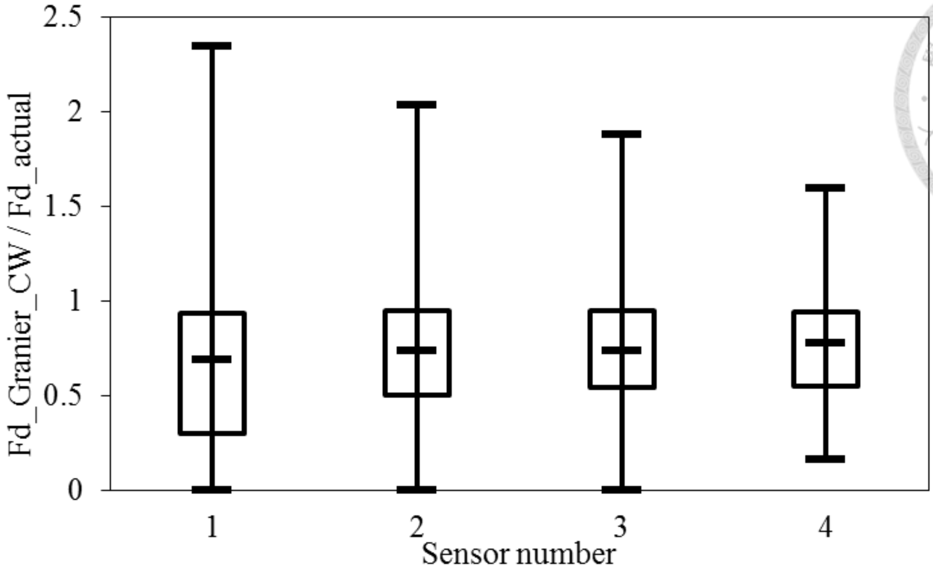


Fig. 11 The effect of sensor number to the accuracy of estimation from Granier sensor.

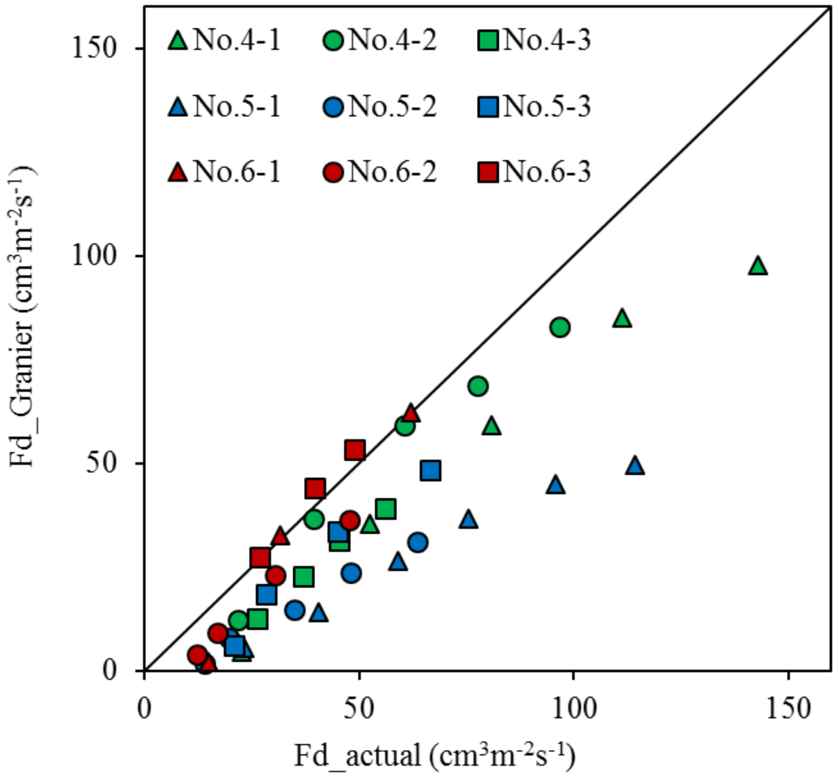


Fig. 12 Comparison of sap flow densities measured by Granier probes and calculated by real water uptakes in segment No. 4-1, 4-2, 4-3, 5-1, 5-2, 5-3, 6-1, 6-2, 6-3. Every dot is averaged from four azimuths in each segment, and the black solid line is one by one line.

doi:10.6342/NTU201702787

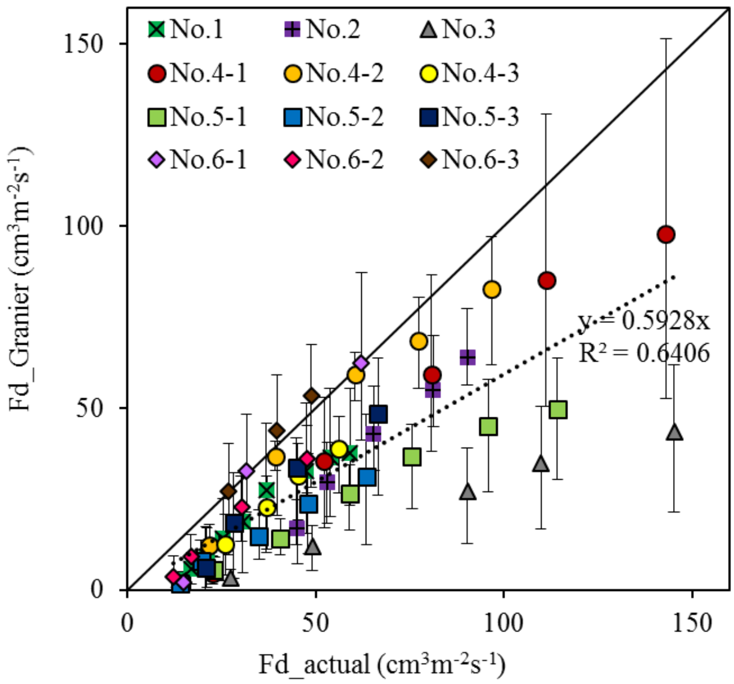


Fig. 13 Comparison of sap flow densities calculated by real water uptakes and measured by Granier probes without applying corrected formula from Clearwater in all sample segments. Every dot is averaged from four azimuths in each segment, and the bar represents maximum and minimum value. The black solid line is one by one line.

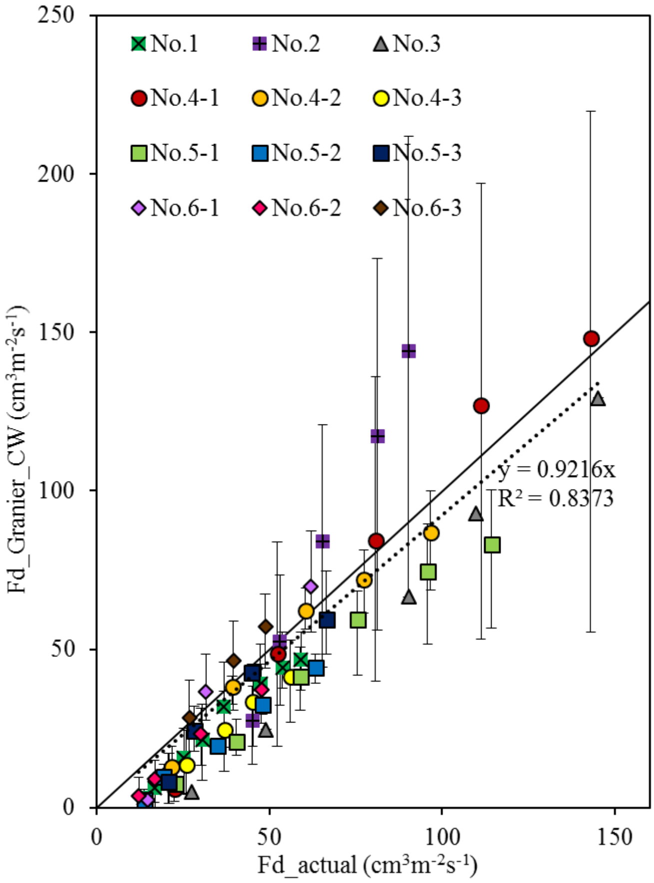


Fig. 14 Comparison of sap flow densities calculated by real water uptakes and measured by Granier probes with applying corrected formula from Clearwater in all sample segments. Every dot is averaged from four azimuths in each segment, and bar represent maximum and minimum. Black solid line is one by one line.

doi:10.6342/NTU201702787

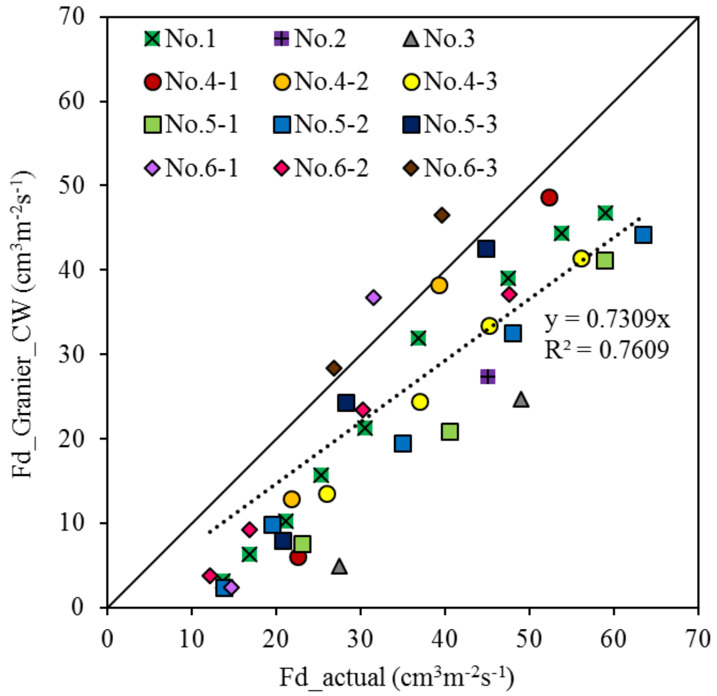


Fig. 15 Comparison of sap flow densities calculated by real water uptakes and measured by Granier probes with applying corrected formula from Clearwater in all sample segments (sap flow density ranged from 0 to 50 $cm^3m^{-2}s^{-1}$). Every dot is averaged from four azimuths in each segment. Black solid line is one by one line.

Table 2 Comparisons of calibration experiment with other studies.

Place	Tree species	Diameter of segment	Range of sap flow rate	Error	Reference
Taiwan	Cryptomeria japonica	12.5-15 cm	2.3-148 ($cm^3m^{-2}s^{-1}$)	-0.04	this study
Taiwan	Cryptomeria japonica	12.5-15 cm	2.3-50 ($cm^3m^{-2}s^{-1}$)	-0.29	this study
America Georgia	Fagus grandifolia	15 & 21cm (DBH)	5-80 ($cm^3m^{-2}s^{-1}$)	-0.61	Steppe *et al.* (2010)
America Georgia	Liquidambar styraciflua	7.5±0.4 cm	0.05-1.0 ($l\ h^{-1}$)	-0.13	Sun *et al.* (2012)
America Georgia	Populus deltoides	7.5±0.4 cm	0-0.7 ($l\ h^{-1}$)	-0.32	Sun *et al.* (2012)
America Georgia	Quercus alba	7.5±0.4 cm	0-0.15 ($l\ h^{-1}$)	-0.20	Sun *et al.* (2012)
America Georgia	Ulmus americana	7.5±0.4 cm	0-0.6 ($l\ h^{-1}$)	-0.11	Sun *et al.* (2012)
America Georgia	Pinus echinata	7.5±0.4 cm	0-0.4 ($l\ h^{-1}$)	-0.13	Sun *et al.* (2012)
America Georgia	Pinus taeda	7.5±0.4 cm	0-1.4 ($l\ h^{-1}$)	0.49	Sun *et al.* (2012)
Costa Rica	Hyeronima alchorneoides	12-12.6 cm	high	-0.09	Gutiérrez and Santiago. (2006)
Costa Rica	Hyeronima alchorneoides	12-12.6 cm	low	-0.19	Gutiérrez and Santiago. (2006)
Costa Rica	Ochroma lagopus	13-15 cm	high	-0.13	Gutiérrez and Santiago. (2006)
Costa Rica	Ochroma lagopus	13-15 cm	low	-0.55	Gutiérrez and Santiago. (2006)
America utah	Populus fremontii	5.08±0.15	15-1100 ($cm^3m^{-2}s^{-1}$)	0.04	Bush *et al.* (2010)
America utah	Tilia cordata	4.83±0.15	15-255 ($cm^3m^{-2}s^{-2}$)	-0.01	Bush *et al.* (2010)
Israel Bet-Dagan	Malus domestica	4.06 cm	0-1026 ($cm^3m^{-2}s^{-1}$)	-0.05	Paudel *et al.* (2013)
Israel Bet-Dagan	Peltophorum dubium	3.98 cm	0-267 ($cm^3m^{-2}s^{-1}$)	-0.07	Paudel *et al.* (2013)
Israel Bet-Dagan	Prunus persica	3.98 cm	0-729 ($cm^3m^{-2}s^{-1}$)	-0.04	Paudel *et al.* (2013)
Germany Thuringen	Fagus sylvatica	31cm	13.5-67.5 ($cm^3m^{-2}s^{-1}$)	-0.15	Wiedemann *et al.* (2016)

doi:10.6342/NTU201702787

3-2 Estimation of long-term stand scale transpiration

3-2-1 Measurement of sapwood depth

The difference of sapwood depth between 2010 and 2016 of each tree was shown in Figure 16 (see appendix 2). In most cases, sapwood depth showed < 10 mm increases or < 10 mm decreases (Fig. 16) with the average difference of -0.06 cm (appendix 2), so that we could assume that sapwood depth in this Japanese cedar plantation was not changed through these near 7 years period.

Results from calibration experiment showed that actual sapwood depth with Clearwater formula (formula 3) can substantially improve the accuracy of Granier probe, therefore dye injection experiment was conducted on 17 trees in the plot for field sap flow experiment in this study. Figure 17 showed relationship between sapwood depth determined by visual and by dye experiment (data see appendix 3). The intercept at the x-axis (Fig. 17) corresponded to the width of white zone in Japanese cedar which water content was lower than that in heartwood and there was no water movement in it; also, the dye solution did not go into white zone (Kumagai *et al.*, 2005; Nakada *et al.*, 1999; Ohashi *et al.*, 1985; Okada *et al.*, 2012). Kumagai et al. (2005) showed that the width of white zone was about 1.0 cm for its study (i.e. about 0.6 cm in this study). So that we used the regression line to recalculate sapwood depth to get more accurate value which

doi:10.6342/NTU201702787

named new sapwood depth in this study (Table 3). Average sapwood depth was 3.41 cm in original, while it was 2.81 cm after recalculated. Difference between them was 0.6 cm.

3-2-2 Effect of sapwood depth and radial variation on transpiration estimation

For field data, sapwood depth can affect stand transpiration estimation not only by radial variation (with Clearwater formula 3) but also by sapwood area estimation. In our study, because the sapwood depths were almost over than 2cm, we should consider the radial variation. Tseng (2011) compared sap flow density in 0-2cm and 2-4cm calculated without Clearwater formula in 6 sample trees, and concluded the sap flow density in 2-4cm was half of sap flow density in 0-2cm. Because at that time the actual sapwood depth was unknown, the Clearwater formula was not used. In this study, the actual new sapwood depth was obtained (Table 3), the sap flow density in 0-2cm and in 2-4cm with Clearwater correction was compared and new ratio (averaged of ratio for #5 and #7) of sap flow density between 0-2cm and 2-4cm was obtained (Fig. 19). The ratio of sap flow density calculated without Clearwater formula in 0-2 and 2-4 cm in #5 and #7 tree was about 50% (Fig. 18) which was similar with that in Tseng (2011). New ratio calculated from the 2 trees shows that sap flow density in 2-4 cm was about 80% of that in 0-2cm (Fig. 19), which was 30% larger than that in Figure 18. Although 6 trees were examined for radial variation in Tseng (2011), the new sapwood depth in 4 trees of the 6 trees was too short

doi:10.6342/NTU201702787

to apply Clearwater formula (i.e. < 3.2 cm). If we just consider new sapwood depth (Table 3), and do not consider tree growth, the data of sapwood area were shown in Table 4. Compared with original one in Table 6, it showed the effect of new sapwood depth to sapwood area. The average sapwood area of all trees in original one (Table 6) was 368 cm^2, while average sapwood area of all trees in Table 4 was 310 cm^2. The new sapwood depth made averaged sapwood area become smaller (difference was 58 cm^2).

If sapwood depth change, there were two things affected by it, one was 2-4 cm sap flow rate and the other was sapwood area. Result showed that the difference of annual stand transpiration between that "considered new sapwood depth" and the "original" one was 0.29 mm, which neared 0 (Fig. 20). The green dotted line with square (Fig. 20) showed that if just 2-4 cm sap flow rate (F_{d2-4} in formula 9) changed from 0.5 to 0.8, the yearly transpiration would become 122.28 mm which was 16 mm higher than that in "original". The blue dotted line with triangle (Fig. 20) showed that if just sapwood area (A_{s_stand} in formula 6, $\sum_{i=1}^{n} A_{s\_treei}$ in formula 7, A_{s2-4} and A_{s0-2} in formula 9) changed, the yearly transpiration was estimated as 96.04 mm, which was 10.07 mm lower than that in "original". Therefore, although sap flow density in 2-4 cm became higher due to Clearwater correction, the sapwood area became small, interaction of this two factors decreased the difference between the "considered new sapwood depth" and the "original" one.

doi:10.6342/NTU201702787

The Clearwater formula can substantially approve the accuracy of estimation because it just changed sap flow rate but not changed sapwood area. Here, one hypothesis have been proposed, that is, if sapwood depth lower than 2 cm, but we assumed it as 2 cm, the underestimation from inactive xylem could be compensated for the overestimation from sapwood area (Lu *et al.*, 2004). Results in this study seemed to agree with this hypothesis. Despite the difference was small, this new sapwood depth was more accurate in theory, so it should be adopted in the following estimation of stand transpiration.

3-2-3 Changes in biometric parameters

The growth of DBH for each tree from 2010 to 2016 was shown in Figure 21. Table 5 showed DBH for each tree from 2010 to 2016 which was calculated from the DBH growth shown in appendix 4. Tree DBH growth ranged from around 0.5 mm to 4.5 mm per year, and DBH growth in tree # 3 and # 16 was relatively higher than other trees (Fig. 21). The average difference of DBH growth between 2010 and 2016 was 1.2 cm, and the highest was 2.3 cm for tree #3 and #16.

doi:10.6342/NTU201702787

3-2-4 Effect of tree growth

Because of the long-term data (near 7 years), we would like to know the effect of tree growth on estimation of stand scale transpiration. Therefore, based on the calculated DBH in every year (Table 5), and sapwood depth obtained in 2010 (Table 3), sapwood area was derived from each tree in every year (Table 6). Table 6 showed that sapwood area changed from tree growth in near 7 years, the difference between original and data of 2016 ranged from 4 to 34 cm^2, and averaged was 14 cm^2. Taking transpiration in 2015 for example, the transpiration estimation from "original" one and "consider tree growth" one were shown in Figure 22. Yearly stand transpiration estimation from original one was 106.11 mm, while stand transpiration estimation considered tree growth was 109.41 mm. The difference between these two was only about 3.3 mm per year. It suggested that the effect of tree growth maybe could be neglected in this study, because the tree growth in this Japanese cedar plantation was small (averaged 14 cm^2) in these 6 years in this site. Therefore, for stand scale transpiration estimation from Sep 2010 to Mar 2017 in this study, tree growth was not considered.

doi:10.6342/NTU201702787

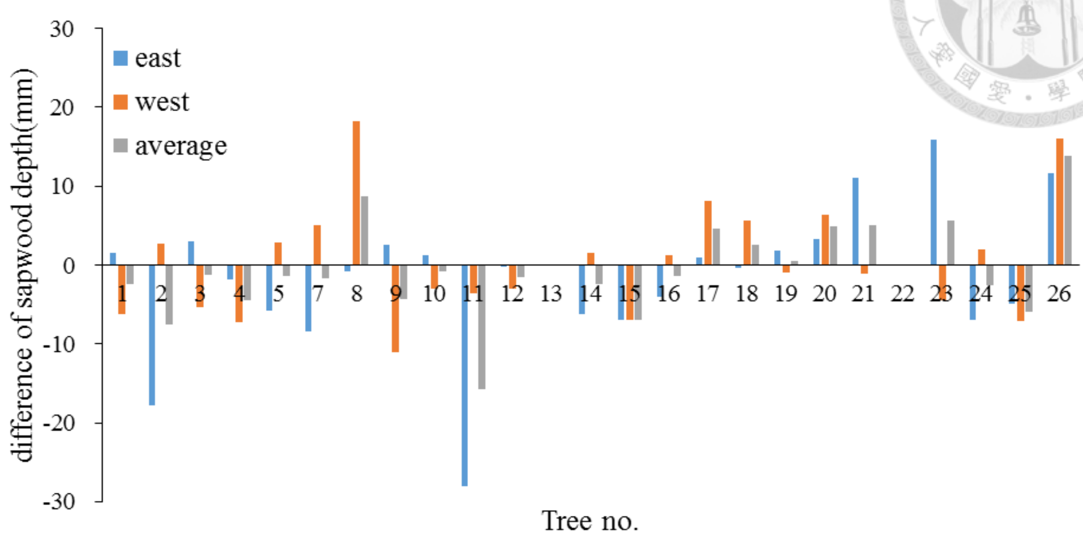


Fig.16 Difference of sapwood depth between 2010 and 2016 for each tree in east and west sides and averaged sapwood depth.

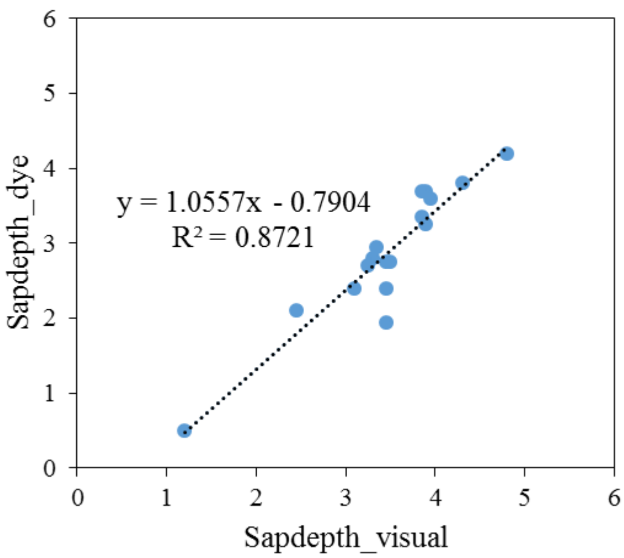


Fig. 17 Regression of two kinds of sapwood depth. Sapdepth_visual represents sapwood depth that determined by visual; sapdepth_dye represents sapwood depth that determined by color from dye experiment.

doi:10.6342/NTU201702787

Table 3 Original sapwood depth and new sapwood depth that calculated from the formula of regression line in Fig. 17.

Tree No.	2010 sapwood depth (cm)			new sapwood depth_dye		
	east	west	average	east	west	average
1	2.80	3.12	2.96	2.17	2.50	2.33
2	3.68	3.38	3.53	3.09	2.77	2.93
3	4.60	4.74	4.67	4.07	4.21	4.14
4	4.28	4.52	4.40	3.73	3.98	3.85
5	4.17	4.01	4.09	3.61	3.45	3.53
7	3.70	3.99	3.85	3.11	3.43	3.27
8	3.48	1.98	2.73	2.88	1.30	2.09
9	3.00	4.70	3.85	2.38	4.17	3.27
10	3.47	4.10	3.79	2.87	3.54	3.21
11	3.50	2.35	2.93	2.90	1.69	2.30
12	3.51	3.40	3.45	2.91	2.80	2.85
13	3.00	3.20	3.10	2.37	2.59	2.48
14	3.78	3.05	3.41	3.20	2.43	2.81
15	3.50	3.70	3.60	2.90	3.12	3.01
16	2.95	3.07	3.01	2.32	2.45	2.39
17	2.80	1.62	2.21	2.17	0.92	1.54
18	3.04	2.44	2.74	2.42	1.79	2.10
19	3.21	3.10	3.15	2.60	2.48	2.54
20	4.06	3.46	3.76	3.50	2.86	3.18
21	1.94	3.30	2.62	1.26	2.70	1.98
22	4.03	4.10	4.06	3.46	3.54	3.50
23	3.01	4.55	3.78	2.39	4.02	3.20
24	3.90	1.80	2.85	3.33	1.11	2.22
25	3.68	3.80	3.74	3.10	3.22	3.16
26	2.74	3.00	2.87	2.10	2.38	2.24
average	3.43	3.38	3.41	2.83	2.78	2.81

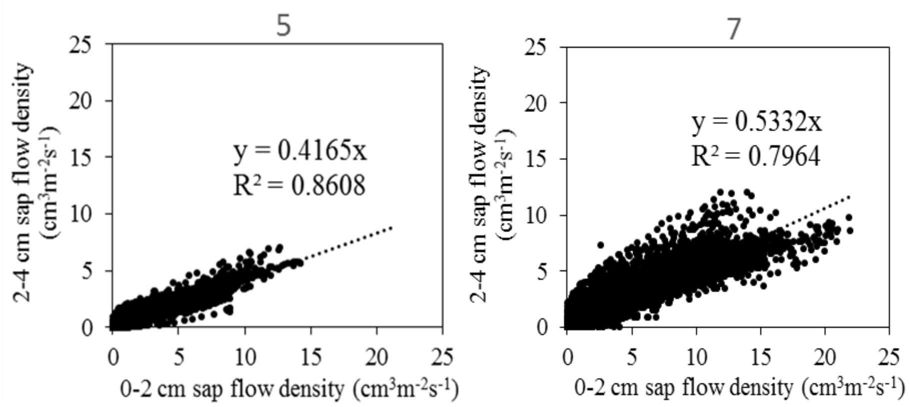


Fig. 18 Comparison of sap flow density between 0-2 cm and 2-4 cm calculated without Clearwater formula in trees No. 5 and No. 7 in the period of 2010/08/10 to 2011/02/10.

doi:10.6342/NTU201702787

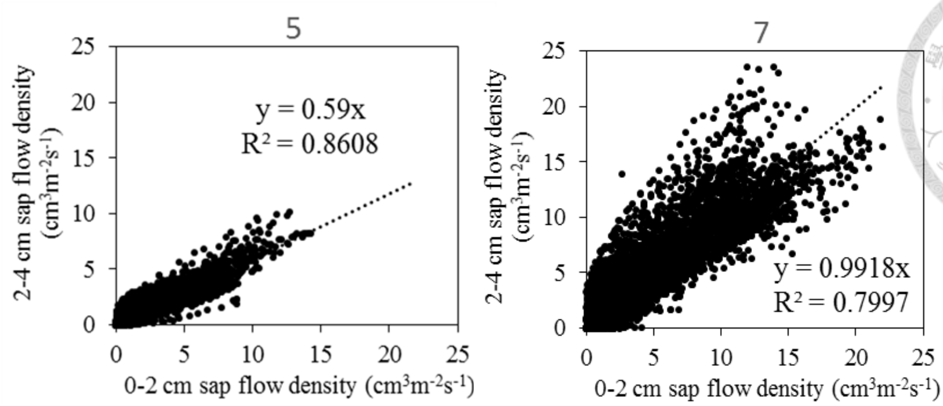


Fig. 19 Comparison of sap flow density between 0-2 cm and 2-4 cm calculated with Clearwater formula in trees No. 5 and No. 7 in the period of 2010/08/10 to 2011/02/10.

Table 4 Sapwood area calculated by new sapwood depth (Table 3) and original DBH (obtained in 2010). “0-2 cm” means sapwood area at the ranged from 0-2 cm. “2-4 cm” means total sapwood area at the ranged 2-4cm and over 4cm. “total” means total sapwood area for each tree.

Tree	Sapwood area (cm^2)		
NO.	0-2 cm	2-4 cm	total
1	192	30	222
2	229	98	327
3	209	196	405
4	257	216	473
5	308	218	526
7	246	143	390
8	212	9	220
9	194	110	304
10	204	111	315
11	145	20	165
12	218	86	304
13	180	40	220
14	261	99	360
15	184	83	268
16	308	57	364
17	126	0	126
18	183	9	191
19	178	44	222
20	333	185	518
21	174	0	174
22	207	139	345
23	278	155	434
24	198	20	218
25	242	129	371
26	254	28	283
average	221	89	310

doi:10.6342/NTU201702787

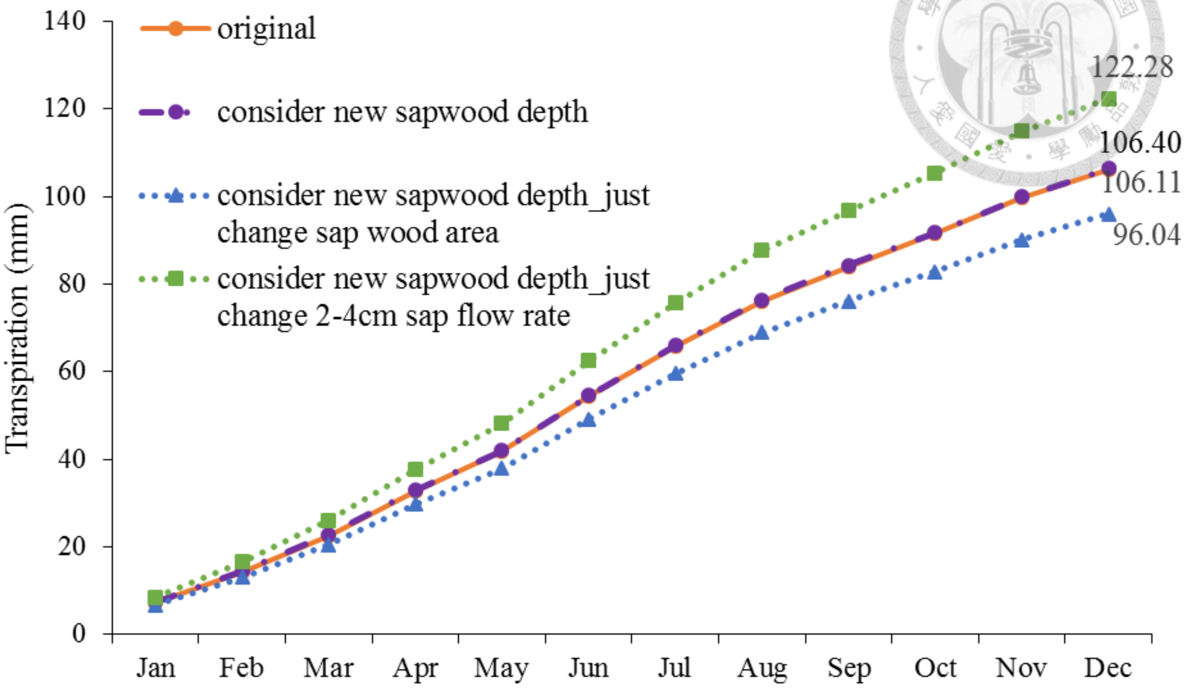


Fig. 20 Accumulation of monthly stand scale transpiration in 2015. Orange curve is the "original" one; purple dotted line with circle is the one that "consider new sapwood depth"; while green dotted line with square is that consider new sapwood depth but just change 2-4 cm sap flow rate; blue dotted line with triangle is that consider new sapwood depth but just change sapwood area.

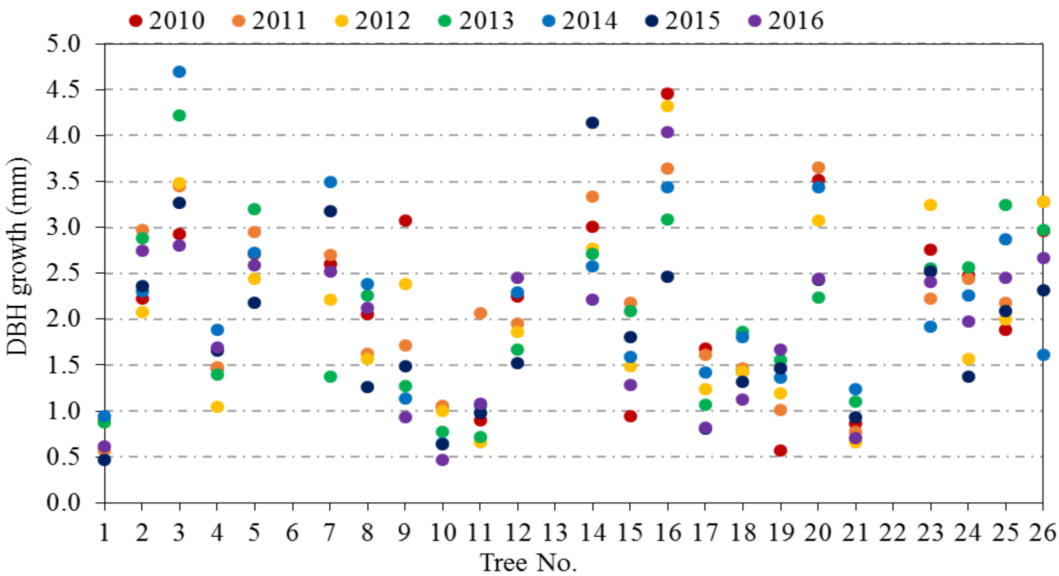


Fig. 21 DBH growth for each tree from 2010 to 2016.

doi:10.6342/NTU201702787

Table 5 DBH for each tree from 2010 to 2016. Difference represents difference between 2016 and original.

Tree No.	DBH (cm)								
	original	2010	2011	2012	2013	2014	2015	2016	Difference
1	32.6	32.6	32.7	32.8	32.9	33.0	33.0	33.1	0.5
2	38.4	38.5	38.8	39.0	39.3	39.5	39.8	40.0	1.6
3	35.3	35.4	35.8	36.1	36.6	37.0	37.4	37.6	2.3
4	42.9	43.0	43.1	43.2	43.4	43.6	43.7	43.9	1.0
5	51.0	51.1	51.4	51.7	52.0	52.3	52.5	52.7	1.7
7	41.2	41.3	41.6	41.8	42.0	42.3	42.6	42.9	1.7
8	35.7	35.8	36.0	36.1	36.3	36.6	36.7	36.9	1.2
9	32.8	33.0	33.1	33.4	33.5	33.6	33.8	33.8	1.0
10	34.5	34.6	34.7	34.8	34.8	34.9	35.0	35.0	0.5
11	25.1	25.1	25.4	25.4	25.5	25.6	25.7	25.8	0.7
12	36.7	36.8	37.0	37.2	37.4	37.6	37.7	38.0	1.3
13	30.7	30.7	30.7	30.7	30.7	30.7	30.7	30.7	0.0
14	43.6	43.8	44.1	44.4	44.6	44.9	45.3	45.5	1.9
15	31.3	31.3	31.6	31.7	31.9	32.1	32.3	32.4	1.1
16	51.0	51.2	51.6	52.0	52.3	52.7	52.9	53.3	2.3
17	27.6	27.7	27.8	28.0	28.1	28.2	28.3	28.4	0.8
18	31.1	31.2	31.3	31.5	31.6	31.8	32.0	32.1	1.0
19	30.4	30.4	30.5	30.7	30.8	30.9	31.1	31.3	0.9
20	55.0	55.2	55.5	55.8	56.1	56.4	56.7	56.9	1.9
21	30.0	30.0	30.1	30.2	30.3	30.4	30.5	30.6	0.6
22	34.9	34.9	34.9	34.9	34.9	34.9	34.9	34.9	0.0
23	46.3	46.4	46.7	47.0	47.2	47.4	47.7	47.9	1.6
24	33.5	33.6	33.9	34.0	34.3	34.5	34.6	34.8	1.3
25	40.5	40.6	40.8	41.0	41.3	41.6	41.8	42.1	1.6
26	42.5	42.6	43.0	43.3	43.6	43.8	44.0	44.3	1.8
Average	37.4	37.5	37.7	37.9	38.1	38.3	38.4	38.6	1.2

Table 6 Sapwood area calculated by DBH (Table 5) and sapwood depth obtained in 2010 (Table 3). "0-2 cm" means sapwood area at the ranged from 0-2 cm. "2-4 cm" means total sapwood area at the ranged 2-4cm and over 4cm. "total" means total sapwood area for each tree.

Tree NO.	Sap wood area (cm^2)																								
	original			2010			2011			2012			2013			2014			2015			2016			difference:
	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	0-2 cm	2-4 cm	total	2016-original
1	192	83	276	193	84	276	193	84	277	193	84	277	194	84	278	195	85	279	195	85	280	195	85	280	4
2	229	158	387	229	158	388	231	160	391	233	161	393	234	162	397	236	163	399	237	164	402	239	166	405	18
3	209	240	449	210	241	452	212	244	457	215	247	462	217	251	468	220	255	475	222	257	480	224	260	484	34
4	257	275	532	257	276	533	258	277	535	259	278	537	260	279	539	261	280	541	262	281	544	263	283	546	14
5	308	295	603	309	296	605	311	298	609	312	300	612	314	302	616	316	303	619	317	305	622	319	307	625	22
7	246	205	451	247	206	453	249	207	456	250	209	459	251	209	460	253	211	465	255	213	469	257	215	472	20
8	212	71	282	212	71	283	213	71	285	214	72	286	216	72	288	217	73	290	218	73	291	219	73	293	10
9	194	157	350	194	158	352	196	159	354	197	160	357	198	161	359	199	161	360	200	162	362	200	163	363	13
10	204	161	365	205	161	366	205	162	367	206	162	368	206	163	369	207	163	370	207	164	371	207	164	371	6
11	145	59	204	145	59	204	147	59	206	147	60	207	148	60	207	148	60	208	149	60	209	150	61	210	6
12	218	143	361	219	143	362	220	144	364	221	145	366	222	146	368	224	147	370	225	147	372	226	149	375	14
13	180	88	269	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	261	170	431	262	170	433	264	172	436	266	173	439	268	174	442	269	175	445	272	177	449	273	178	452	21
15	184	129	313	184	129	314	186	131	316	187	131	318	188	132	320	189	133	322	190	134	324	191	135	326	12
16	308	146	454	309	147	456	312	148	460	314	150	464	316	151	467	318	152	470	320	152	472	322	154	476	22
17	161	16	176	161	16	177	162	16	178	163	16	179	164	16	180	165	16	181	165	16	181	166	16	182	5
18	183	61	244	183	61	245	184	62	246	185	62	247	186	63	249	187	63	250	188	63	251	189	64	252	8
19	178	91	270	179	92	270	179	92	271	180	92	272	181	93	274	182	93	275	183	94	277	184	95	278	8
20	333	272	605	334	273	608	336	275	612	338	277	616	340	278	618	342	280	622	343	282	625	345	283	628	22
21	176	50	226	176	50	226	177	50	227	177	50	227	178	50	228	179	50	229	179	51	230	180	51	230	5
22	207	187	394	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	278	227	505	279	228	507	281	229	509	283	231	513	284	232	516	285	233	519	287	235	522	289	236	524	19
24	198	76	274	199	77	275	200	77	278	201	78	279	203	78	281	204	79	283	205	79	284	206	80	286	12
25	242	190	432	242	191	433	244	192	436	245	193	438	247	195	442	249	196	445	250	198	448	252	199	451	19
26	254	103	357	255	103	358	257	104	361	260	105	364	261	106	367	262	106	368	264	107	370	266	107	373	16
average	222	146.1	368	225	147	373	227	148	375	228	149	377	229	150	380	231	151	382	232	152	384	233	153	386	14

doi:10.6342/NTU201702787

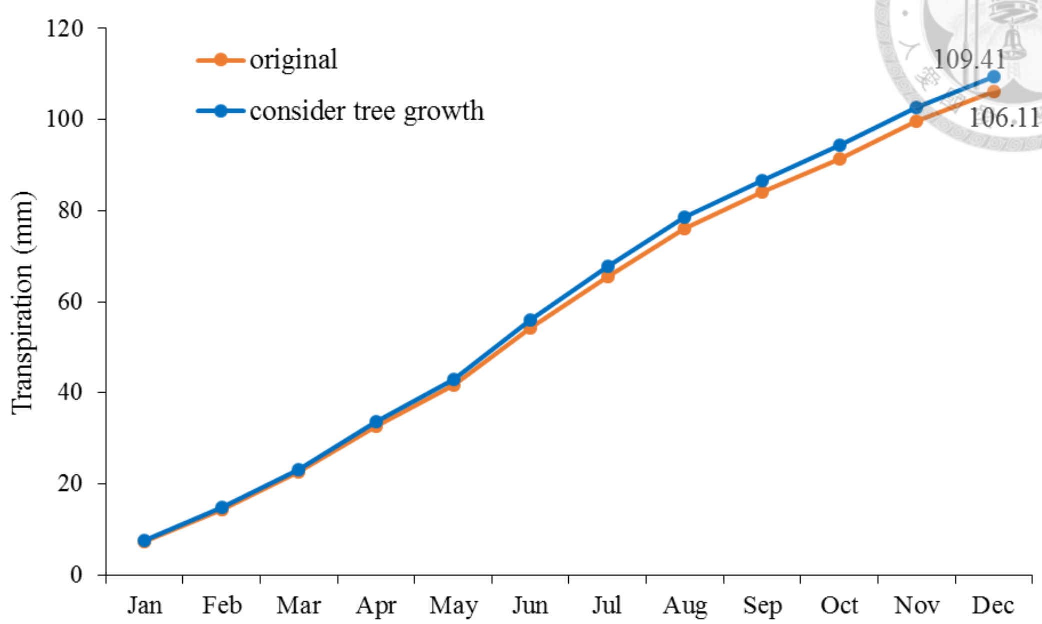


Fig. 22 Accumulation of monthly stand scale transpiration in 2015. Blue curve is the "consider tree growth" one. While orange curve is the "original" one.

doi:10.6342/NTU201702787

3-3 Application of indoor-calibration experiment results to field sap flow data

The calibration experiments in this study suggested that the original Granier formula cannot be directly used in Japanese cedar trees in Taiwan because it may underestimate sap flow density about 30 % (Fig. 15). Based on this result, five methods were applied to field data (Fig. 23 and 24) as following:

1) y=ax: all data were applied to this corrected formula y=0.73x.

2) y=ax+b: all data were applied to this corrected formula y=0.93x-7.91.

3) y=ax+b & y=ax: when y less than 2.13, the data were applied y=0.20x corrected formula; while y larger than 2.13, the data were applied y=0.93x-7.91 corrected formula.

4) y=ax+b & non: when y less than 2.13, the data were not applied any corrected formula; while y larger than 2.13 the data were applied y=0.93x-7.91 corrected formula.

where y represented sap flow density that calculated by Granier method with Clearwater formula (formula 1, 2 and 3) (Fd_Granier_CW); x represented sap flow density calculated by real water uptake (formula 4) (Fd_actual)(Fig. 23).

5) $y=az^{b}$, all data were applied to this formula $y=75.42z^{0.5634}$, where y sap flow density calculated by real water uptake (formula 4) (Fd_actual), and z represented K (formula 2)(Fig. 24).

Also, taking stand transpiration estimation in 2015 for instance (the stand transpiration estimation was performed consideration with both tree growth and new

doi:10.6342/NTU201702787

sapwood depth), and the daily curve of sap flow density in 10 days (2015/1/11-2015/1/20) was shown in Figure 25. The daily curve of method 2 was unreasonable because the sap flow density at night was too high (Fig. 25). It suggested that method 2 is not a suitable method that it maybe overestimate real transpiration. Other methods seemed without any strange of the daily curve except for method 5 which sap flow density at night was also high (Fig. 25).

The accumulation of monthly stand transpiration showed that the yearly stand scale transpiration estimation calculated from the 5 methods was extremely different (Fig. 26). The amount of yearly transpiration calculated from method 2 was 611 mm, which was the biggest one and maybe overestimated. The yearly transpiration estimation in method 5 was 473 mm, and that in method 3 was 314 mm which was about 3 times of original one; while that in method 4 and method 1 was 235 and 150, which was about 2 times and 1.5 times of original one, respectively. Except for method 2 which was overestimated, the stand transpiration estimation in other 4 methods was different largely. For these 4 methods, it is difficult to decide which one is the best method depending on the daily sap flow density curve. In addition to daily sap flow density curve, we calculated potential evaporation (Thomthwaite and Hamon) to compare with stand transpiration (Fig. 26). In figure 26 (a), we can see that transpirations of method 5 in 9 months were higher than potential evaporation (Thomthwaite and Hamon), so we assumed that method 5 maybe

doi:10.6342/NTU201702787

overestimated transpiration. For method 3, although transpirations in 3 months were higher than potential evaporation (Thomthwaite), and in 1 months were higher than potential evaporation (Hamon), the monthly transpiration were mostly lower than evaporation and the yearly transpiration was less than both potential evaporation. So we assumed that transpiration estimated from method 3 was the upper bound.

On the other hand, we applied the different formula to calibration experiment data, too (Fig. 27). Because the value of Fd_Granier_CW data in calibration experiment all > 2.13, in these five methods, the effect of No 2, No 3 and No 4 was the same for calibration experiment data. Therefore, three formula were applied. First, y=ax: all data were applied to this corrected formula y=0.73x (Fig. 27 a); second, y=ax+b: all data were applied to this corrected formula y=0.93x-7.91 (Fig. 27 b); third, $y=ax^b$, all data were applied to this formula $y=75.42z^{0.5634}$ (Fig. 27 c). First one showed that when sap flow density < 30 $cm^3m^{-2}s^{-1}$, Fd_Granier_CW still underestimated Fd_actual; when sap flow density > 30 $cm^3m^{-2}s^{-1}$, Fd_Granier_CW in some dots were underestimated and some were overestimated; when sap flow density > 40 $cm^3m^{-2}s^{-1}$, Fd_Granier_CW was overestimated (Fig. 27 a). Second one showed that Fd_Granier_CW could welly estimate Fd_actual (Fig. 27 b). Third one showed that when sap flow density < 30 $cm^3m^{-2}s^{-1}$, Fd_Granier_CW overestimated Fd_actual; while sap flow density > 40 $cm^3m^{-2}s^{-1}$, Fd_Granier_CW was understimated (Fig. 27 c), which was reversed with first one. In

doi:10.6342/NTU201702787

field sap flow data, most data of sap flow density were under 30 $cm^3m^{-2}s^{-1}$, only few data were over 30 $cm^3m^{-2}s^{-1}$. Therefore, results in Fig. 27 suggested that in the five methods (Fig. 23 and 24), method 1 used to field data may be underestimated, and method 5 may be overestimated. Consequently, we assumed that transpiration estimated from method 1 was lower bound, and that from method 3 was upper bound.

The treatments for low sap flow rate data in the relationship between Fd_actual and Fd_Granier_CW strongly affected application to the field data. The five different methods were resulted from the lack of low flow rate data in the calibration experiments; the five methods showed significantly different stand transpiration in contrast to our expectation: the yearly transpiration ranged from 150 mm (No. 1) to 611 mm (No. 2). It suggested that the data of low flow rate cannot be ignored, and it substantially affect stand scale transpiration in Xitou because of the sap flow rate in Japanese cedar in Xitou was low. Therefore, to obtained the data from low flow rate, maybe branch materials could be used to calibration experiment (Table 2). The application of calibration experiment results to field data was still few, this study used five different methods to corrected field data and showed a big difference suggested that the formula may affect transpiration estimation a lot and the estimation of transpiration can have uncertainty. Through this experiment, we found the upper bond and lower bond of stand transpiration, which was about 1.5 to 3 times higher than the original estimation. Although this study could not conclude out

doi:10.6342/NTU201702787

which was the best way to estimate stand transpiration and the estimates still have uncertainty, it can be said that the original estimation underestimated the stand transpiration in this site and that applying the calibration experiment the field data improved the accuracy of estimation.

For long-term stand transpiration estimation, tree growth, radial variation and calibration experiment should be concerned that can improve the accuracy considerably. In this study, tree growth was too small so that can be neglected; and though transpiration estimation calculated from new sapwood depth was not changed a lot, the accurate sapwood depth was essential because it affect both sapwood area and inner sap flow rate estimates. Finally, for the application of calibration experiment, depending on daily sap flow density curve, potential evaporation and applied to calibration data, we suggested that method 1, 3 and 4 were more likely to close real transpiration, and the stand transpiration estimation should be described using a range rather than a value.

doi:10.6342/NTU201702787

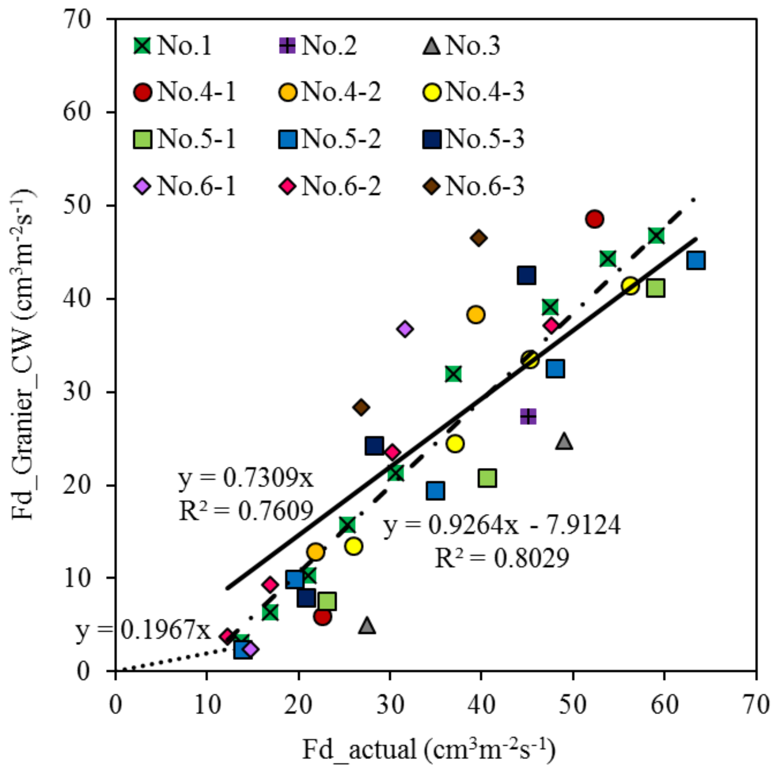


Fig. 23 Comparison of sap flow densities calculated by real water uptakes and measured by Granier probes with applying corrected formula from Clearwater in all sample segments (sap flow density ranged from 0 to 50 $cm^3m^{-2}s^{-1}$). Every dot is averaged from four azimuths in each segment. The black solid line is y=ax in method 1. The black dotted line is y=ax+b in method 2, 3 and 4. The short black dotted line is y=ax line in method 3.

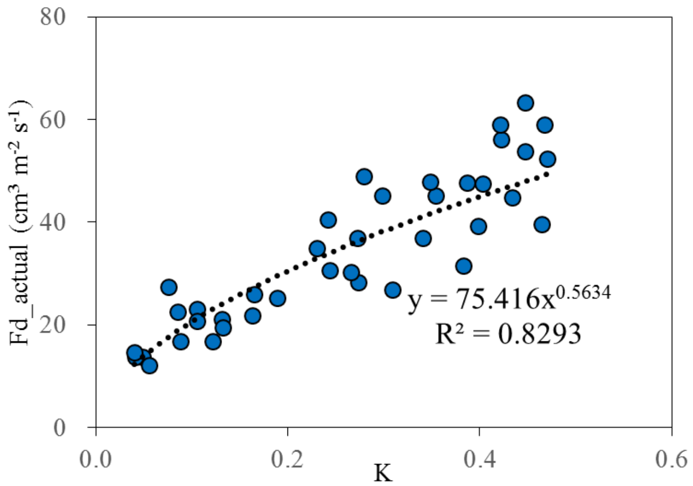


Fig. 24 Regression of K and sap flow density calculated by real water uptakes of 12 segments (method 5) (sap flow density ranged from 0 to 50 $cm^3m^{-2}s^{-1}$).

doi:10.6342/NTU201702787

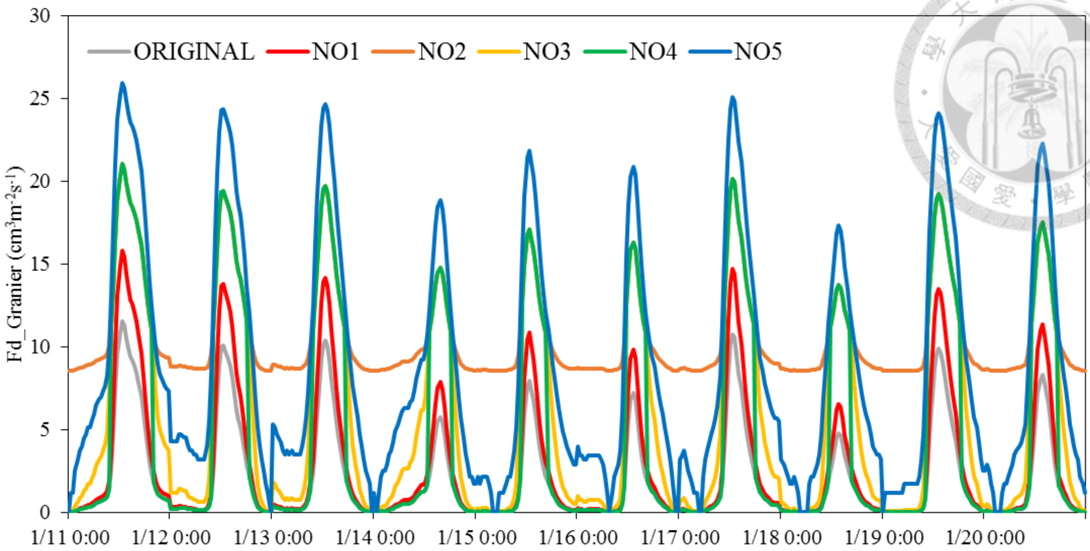


Fig. 25 Daily curve of sap flow density of north side in tree No. 9 from 2015/1/11 to 2015/1/20 that applied 5 methods from calibration experiment. Method 1 is that y=0.73x; method 2 is that y=0.93x-7.91; method 3 is that y=0.20x (y<2.13) and y=0.93x-7.91 (y>=2.13); method 4 is that y=0.93x-7.91 (y>=2.13) and no change (y<2.13); method 5 is that $y=75.42z^{0.5634}$.

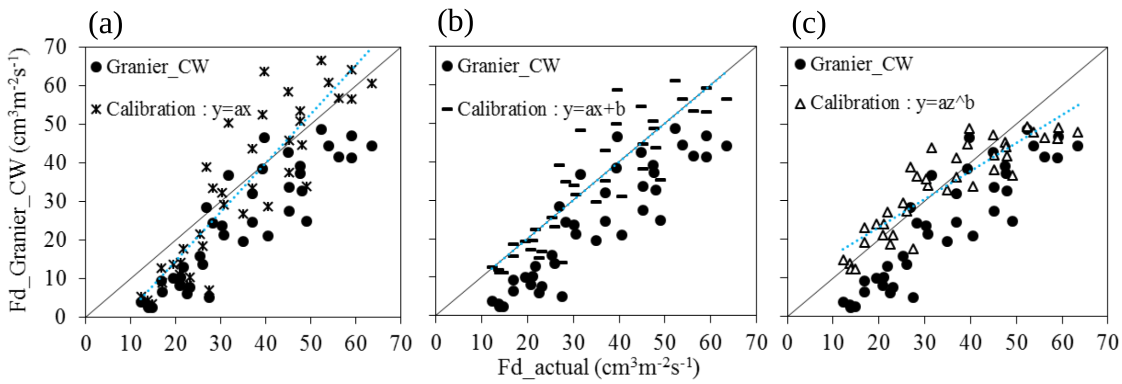


Fig. 27 Comparisons of sap flow densities calculated by real water uptakes (Fd_actual), sap flow densities measured by Granier probes with applying corrected formula from Clearwater (Fd_Granier_CW) and Fd_Granier_CW with three formula that derived from calibration experiment (a): y=ax; (b): y=ax+b; (c): $y=az^b$ in all sample segments (Fd_Granier_CW ranged from 0 to 50 $cm^3m^{-2}s^{-1}$). Every dot is averaged from four azimuths in each segment. Black solid bold line is one by one line.

doi:10.6342/NTU201702787

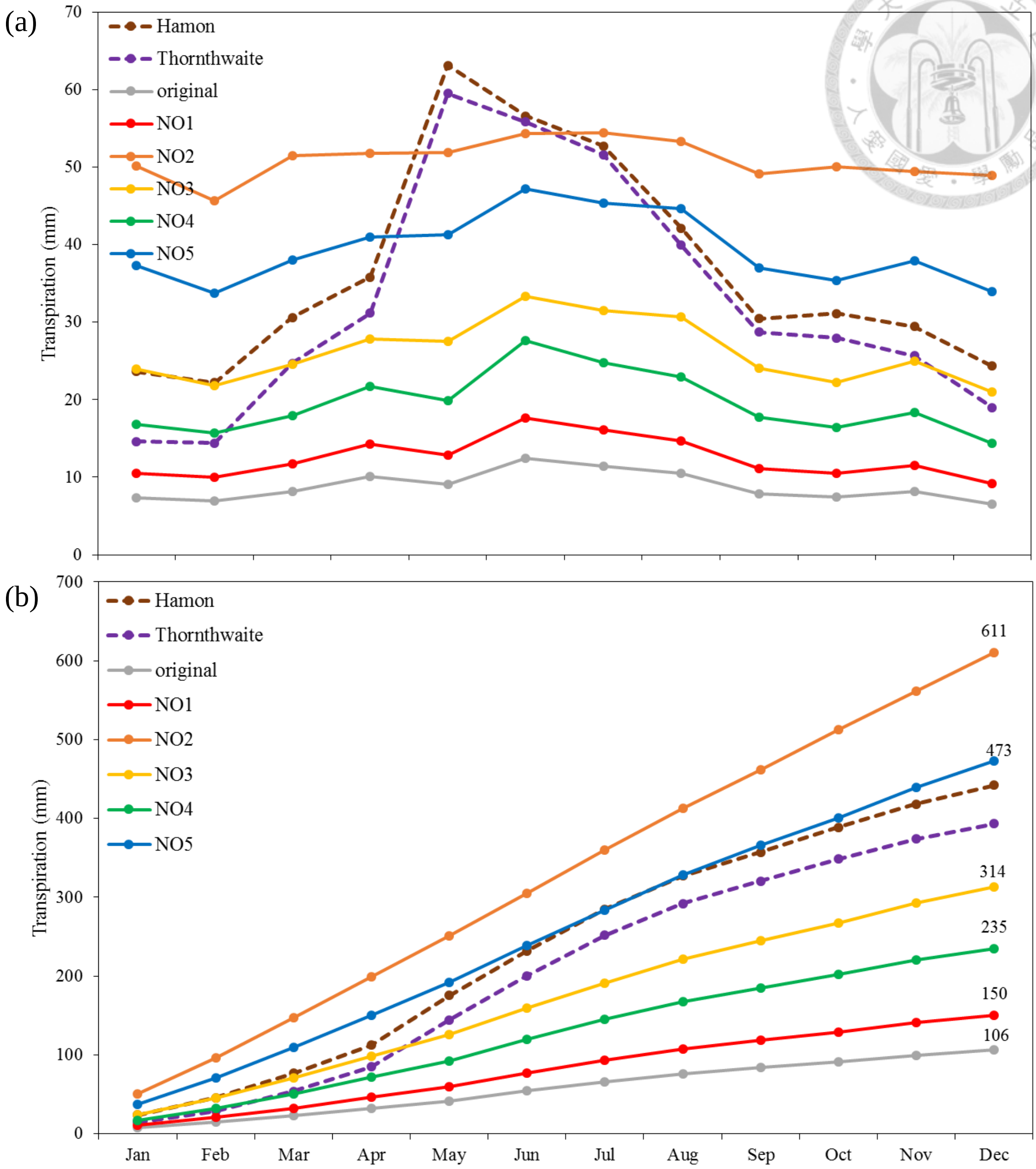


Fig. 26 Stand scale transpiration applied with 5 methods and potential evaporations in 2015. (a) Accumulation of monthly transpiration. (b) Monthly transpiration. No. 1 is that y=0.73x; No. 2 is that y=0.93x-7.91; No. 3 is that y=0.20x (y<2.13) and y=0.93x-7.91 (y>=2.13); No. 4 is that y=0.93x-7.91 (y>=2.13) and no change (y<2.13); No. 5 is that $y=75.42z^{0.5634}$. Thornthwaite and Hamon are two kinds of potential evaporation.

doi:10.6342/NTU201702787

3-4 Inter-annual variations in stand transpiration

3-4-1 Meteorological factors and stand scale transpiration from Sep 2010 to Mar 2017

Meteorological factors and stand scale transpiration from Sep 2010 to Mar 2017 were shown in Figure 28. We can see that precipitation had seasonal variations, and it was higher in summer and lower in winter for all study period (Fig. 28). Also, it had inter-annual variation that rainfall in 2nd year was extremely higher than other years (Table 8) because typhoon (SAOLA) brought about intense rainfall in that summer; rainfall in 3rd year was higher than other years also because of typhoon. Results suggested that the main reason of inter-annual variation for rainfall was the extremely precipitation caused from typhoon. Also, in this period, rainfall in 5th year was the lowest one which was 1486 mm. Compared with the average rainfall in Xitou (2,600 mm), the average rainfall in this period was lower than that except for rainfall in 3rd year. For these years, data showed that precipitation became smaller from 3rd year to 6th year, which were all lower than averaged rainfall. But because lack of the standard deviation of rainfall in Xitou, we cannot claimed that precipitation gradually became small year by year.

Soil water content (SWC) probably changed with rainfall (Fig. 28). The SWC increased while precipitation increased and decreased while precipitation decreased. There was not distinctive seasonal variation in this studied period, but we can distinguish

doi:10.6342/NTU201702787

dry period. Most data were higher than 25% (Fig. 28). The relatively dry periods were autumn of 2012 and 2014, winter of 2012 and 2014, and spring of 2013, 2015 and 2017. Because precipitation was more in summer, dry period was not existed in summer in these study period. The annual averaged SWC showed that the inter-annual variation was small in totally (Table 8).

Air temperature, with obvious seasonal variation, was high in summer and low in winter (Fig. 28). In the studied period, the maximum temperature was about 20 ^{0}C, and it was similar in these years. The minimum temperature was relatively changed a lot, while in 2016 winter was the lowest one that close to 0 ^{0}C. However, the monthly averaged temperature shows that in the studied period the trend of temperature in a year was similar (Fig. 5). Also, the annual averaged temperature in this period was 16 ^{0}C that was not different a lot from the average temperature in Xitou (16.6 ^{0}C), and the inter-annual variation was small (Table 8).

Solar radiation, without obvious seasonal variation, seemed that it was relatively high in summer (Fig. 28). There was similar trend with vapor pressure deficit (VPD) and it did not show obvious seasonal variation, either (Fig. 28). For the value of CV, the inter-annual variation for solar radiation and VPD was small (Table 8).

Stand scale transpiration, with unclear seasonal variation, was relatively high in summer and relatively low in winter. It was obvious that the trend of S and VPD was

doi:10.6342/NTU201702787

similar with transpiration (Fig. 28). Although the ratio of 12 monthly transpirations in each year was different (see appendix 5), it seems that inter-annual variation of yearly transpiration for this studied period was small (Table 8).

The ratio of transpiration and rainfall in this 6 years was not changed a lot except for 2nd year because of extremely precipitation from typhoon. The ratio ranged from 0.10 to 0.15. The relatively dry periods were in the 3rd year and 5th year. However, the E/P ratio of these two years were 0.10 and 0.15. The E/P ratio in 3rd year was low maybe because of high rainfall, though the rainfall was lower than averaged rainfall in Xitou. The E/P ratio in 5th year was high maybe because of low rainfall and small transpiration due to dry condition.

3-4-2 Relationship between transpiration and Meteorological factors

The relationships between VPD and transpiration in each year were shown in Figure 29; and the relationships between S and transpiration in each year were shown in Figure 30. We can find that transpiration was obviously affected by VPD and S, and transpiration increased with increase of VPD and S. The effect of VPD and S to transpiration was different in each year, but there is not an increasing or decreasing trend of that. For seasonally relationship, it was obvious that transpiration increased with VPD, and transpiration tended to the plateau when VPD exceeded 0.4 kPa (Fig. 31). This condition

doi:10.6342/NTU201702787

was common in winter rather than that in summer. It seemed that there was seasonal variation in the value of plateau, that is, the values in winter was the lowest in a year for all study period (Fig. 31). Seasonally relationship between S and transpiration in the study period seemed stable although it had some seasonal variation. The slope of the regression line in each season ranged from 1.2 to 2.5, but the value was not always small in winter or high in summer (Fig. 32). It suggested that the effect of S to transpiration could not have a regular trend with change of season, because of other meteorological regulation such as VPD.

In the study period, SWC was especially low in autumn and spring of 3^{rd} year and 5^{th} year, which was lower than 25% (Fig. 28). Except for that, SWC commonly more than 25%. Therefore SWC 25% was used to identify the effect of soil water content to transpiration. When SWC $<$ 25%, the maximum value of transpiration when VPD exceeded 0.4 kPa was about 1.3; on the other hand, when SWC $>$ 25%, the maximum value of transpiration when VPD exceeded 0.4 kPa was about 1.75 (Fig. 33). The trend of regression line of this two conditions was different (Fig. 33 c). However, dry condition maybe do not make transpiration become extremely low so that we cannot identify the phenomenon lower transpiration under dry period in Fig. 28. The yearly averaged SWC in 5^{th} year was the lowest, and the E/P ratio was highest. It showed that dry period in 5^{th} year maybe cause transpiration decrease. But the dry period in 3^{rd} year maybe do not

doi:10.6342/NTU201702787

cause transpiration decrease too much, so that the E/P ratio was low. Therefore, though the dry condition may decrease transpiration, the effect of SWC to transpiration was not too distinctive in this study.

Air temperature in this study showed obvious seasonal variation (Fig. 28). To identify the effect of temperature to transpiration, winter averaged temperature in the study period (= 11.64 Celsius degree) was used to divide two conditions. When temperature was lower than winter averaged temperature, the maximum value of transpiration when VPD exceeded 0.4 kPa was about 1.5; while temperature was higher than winter averaged temperature, the maximum value of transpiration when VPD exceeded 0.4 kPa was about 1.75 (Fig. 34). Though the difference of maximum transpiration in this two conditions was smaller than that in SWC, the trend of regression line of these two conditions showed that they were different (Fig. 33 c). Transpiration when VPD exceeded 0.4 kPa was lower in the condition T < winter average T than the condition T > winter average T (Fig. 34). It suggested that low air temperature may cause transpiration decrease. Also, because of the effect of solar radiation to transpiration was not different in winter respect to other season, the reason why transpiration when VPD exceeded 0.4 kPa in winter was obviously low was probably air temperature and SWC.

doi:10.6342/NTU201702787

3-4-3 Comparison of stand scale transpiration with other cloud forests

Sap flow based stand scale transpiration estimation in other cloud forests were shown in Table 7. In northeastern Taiwan, transpiration of 11 month was 192 mm (lack of data from Jun); while in central Taiwan, transpiration of one year was about 152-307 (237 mm) (Table 7). It showed that yearly transpiration in this two places seemed similar. But for monthly, the maximum was 31.3 mm in Sep and minimum was 9.6 in Jan (northeastern Taiwan in 羅勻謙 (2004)); while maximum was 25.7 mm in Jul and minimum was 15.8 mm in Feb in this study. It showed that monthly transpiration in northeastern Taiwan changed a lot, but it was relatively stable for central Taiwan (this study).

Other cloud forest in other countries, there was obvious seasonal variation in transpiration (McJannet *et al.*, 2007). Yearly stand scale transpirations ranged from 291 to 787 mm per year (Table 7), which were higher than that in Taiwan. The mean annual temperature of other countries ranged from 13 to 16 ^{0}C, which were not too higher or lower than that in Taiwan. VPD in other countries were all higher than that in Taiwan (Table 7) and it may affect transpiration substantially. Therefore, the small value of VPD in Taiwan maybe one of the reason caused lower transpiration than other countries.

For worldwide long-term sap flow measurements, stand scale transpiration with other meteorological factors were summarized in Table 8. Compared with other long-

doi:10.6342/NTU201702787

term transpiration estimation studies, inter-annual variation of transpiration in this study was low except for that in Oishi *et al.* (2008). Also, the inter-annual variation of T and VPD in this study was lower than that in Clausnitzer *et al.* (2011). But the CV of precipitation in this study was the highest one (Table 8), and the CV of precipitation in these studies was all relatively high, which ranged from 15.8 to 23.4%. Transpiration showed a stable condition in 4 years in Oishi *et al.* (2008), which was similar with this study since the water supply was sufficient and did not face drought stress.

The main reason caused high CV of transpiration in the previous studies was soil water content (Limousin *et al.*, 2009; Wullschleger & Hanson, 2006; Zeppel *et al.*, 2008). Although precipitation in 2001 was lower than 2002, the soil water content in 2002 was low in two periods that caused transpiration decrease (Wullschleger & Hanson, 2006). There were a wet year and dry year, transpiration was low in dry year and high in wet year (Zeppel *et al.*, 2008), but the ratio of E/P in dry year was high than that in wet year. It suggested that in wet year, water except for creature use lose by run off. Especially, the transpiration in 2003 was very low because of a regular thinning of forest management in 2003; also, there was drought period in 2003 that caused transpiration decrease, and the threshold of SWC of 9.5 % was found. Also, there was heavy rainfall in two days in Aug 2012 resulted in the high precipitation in 2012 (Clausnitzer *et al.*, 2011).

doi:10.6342/NTU201702787

From previous studies, forest management and drought condition were the reason that caused inter-annual variation in transpiration. But in this study, the effect of SWC was not too much, and other meteorological factors also were relatively stable. Therefore, the inter-annual variation of transpiration was little in this study.

doi:10.6342/NTU201702787

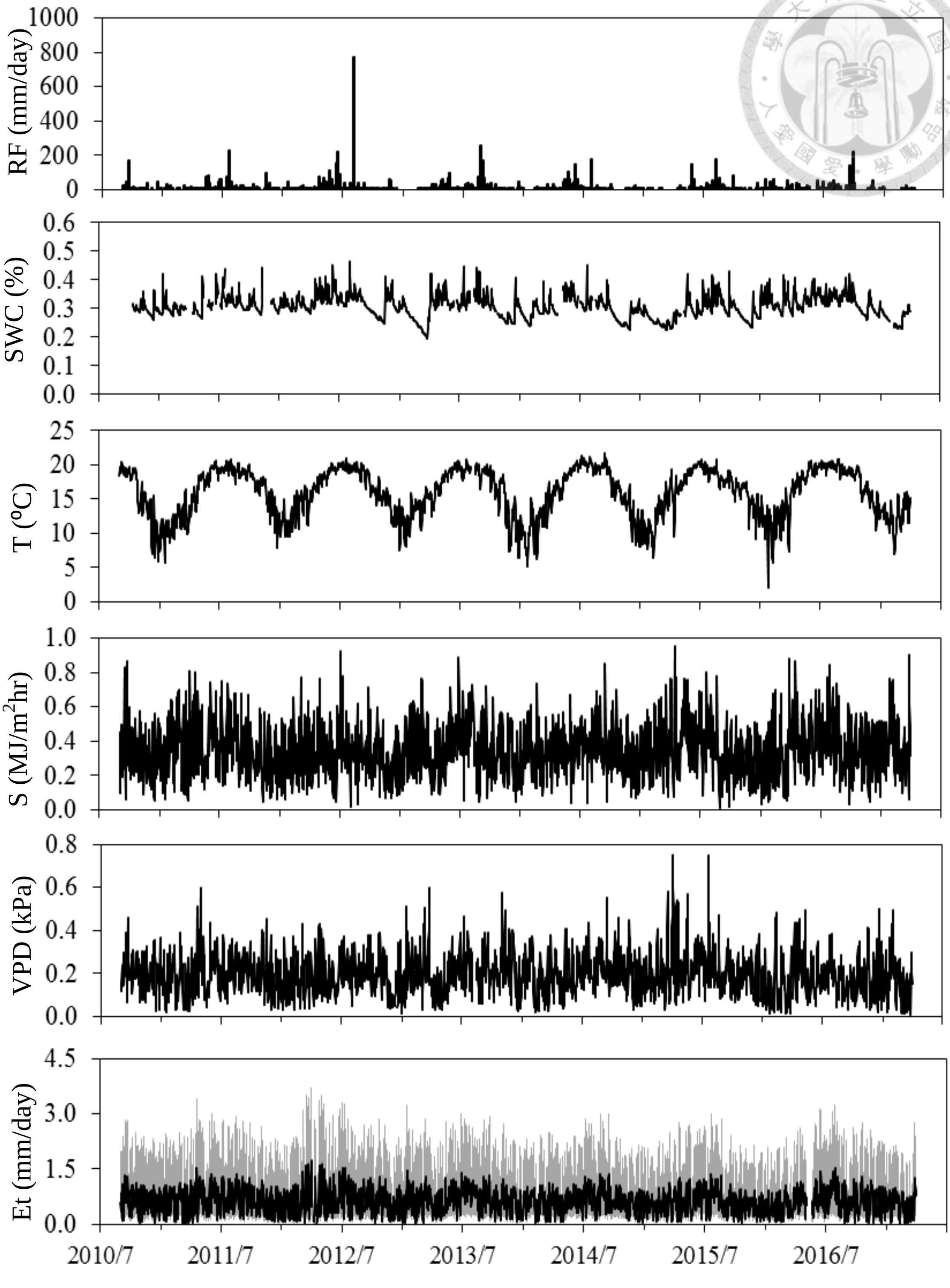
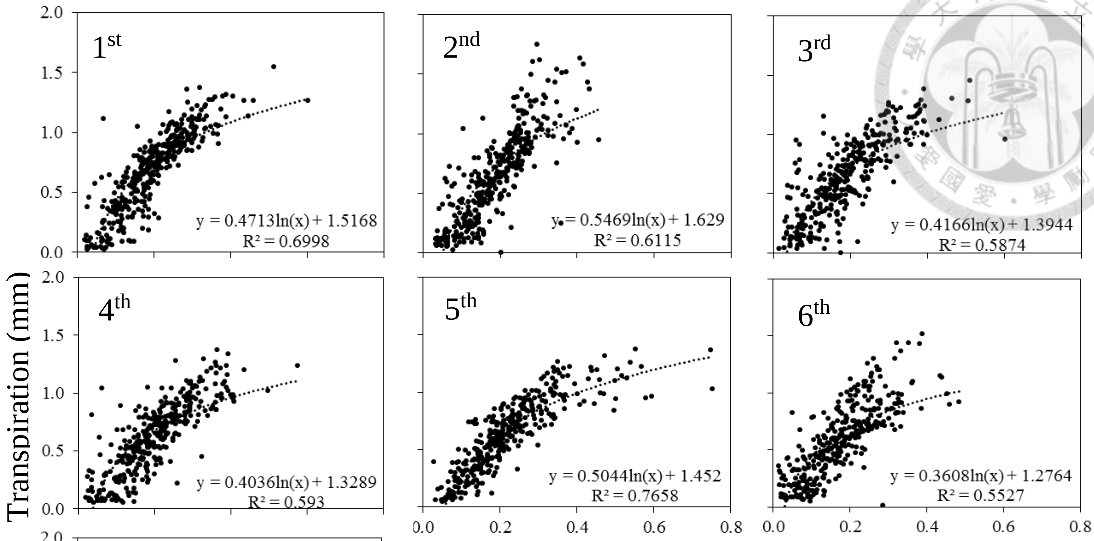


Fig. 28 Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2010 to Mar. 2017. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No1, No3 and No4), and grey line represents the value of maximum and minimum.

doi:10.6342/NTU201702787



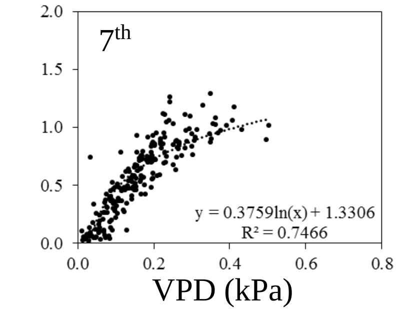
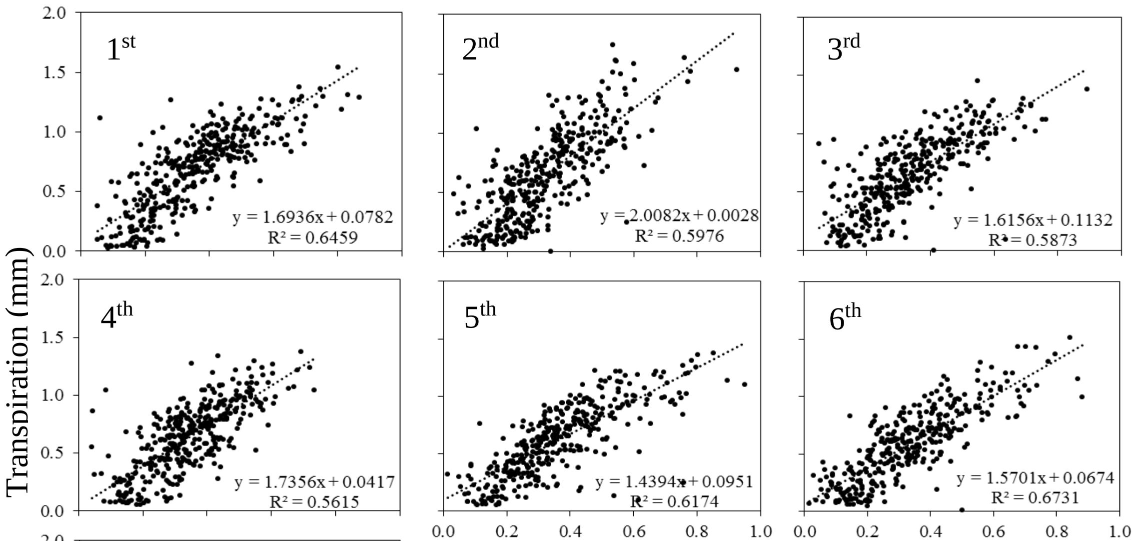


Fig. 29 Relationship between transpiration and VPD for near 7 years. 1st: Sep 2010 to Aug 2011, 2nd: Sep 2011 to Aug 2012, 3rd: Sep 2012 to Aug 2013, 4th: Sep 2013 to Aug 2014, 5th: Sep 2014 to Aug 2015, 6th: Sep 2015 to Aug 2016, 7th: Sep 2016 to Mar 2017.



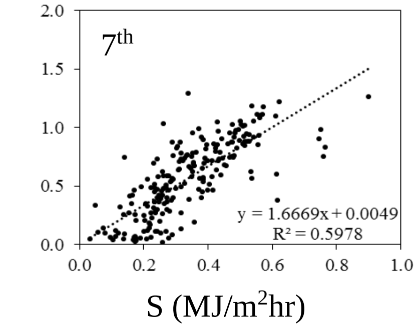


Fig. 30 Relationship between transpiration and S for near 7 years. 1st: Sep 2010 to Aug 2011, 2nd: Sep 2011 to Aug 2012, 3rd: Sep 2012 to Aug 2013, 4th: Sep 2013 to Aug 2014, 5th: Sep 2014 to Aug 2015, 6th: Sep 2015 to Aug 2016, 7th: Sep 2016 to Mar 2017.

doi:10.6342/NTU201702787

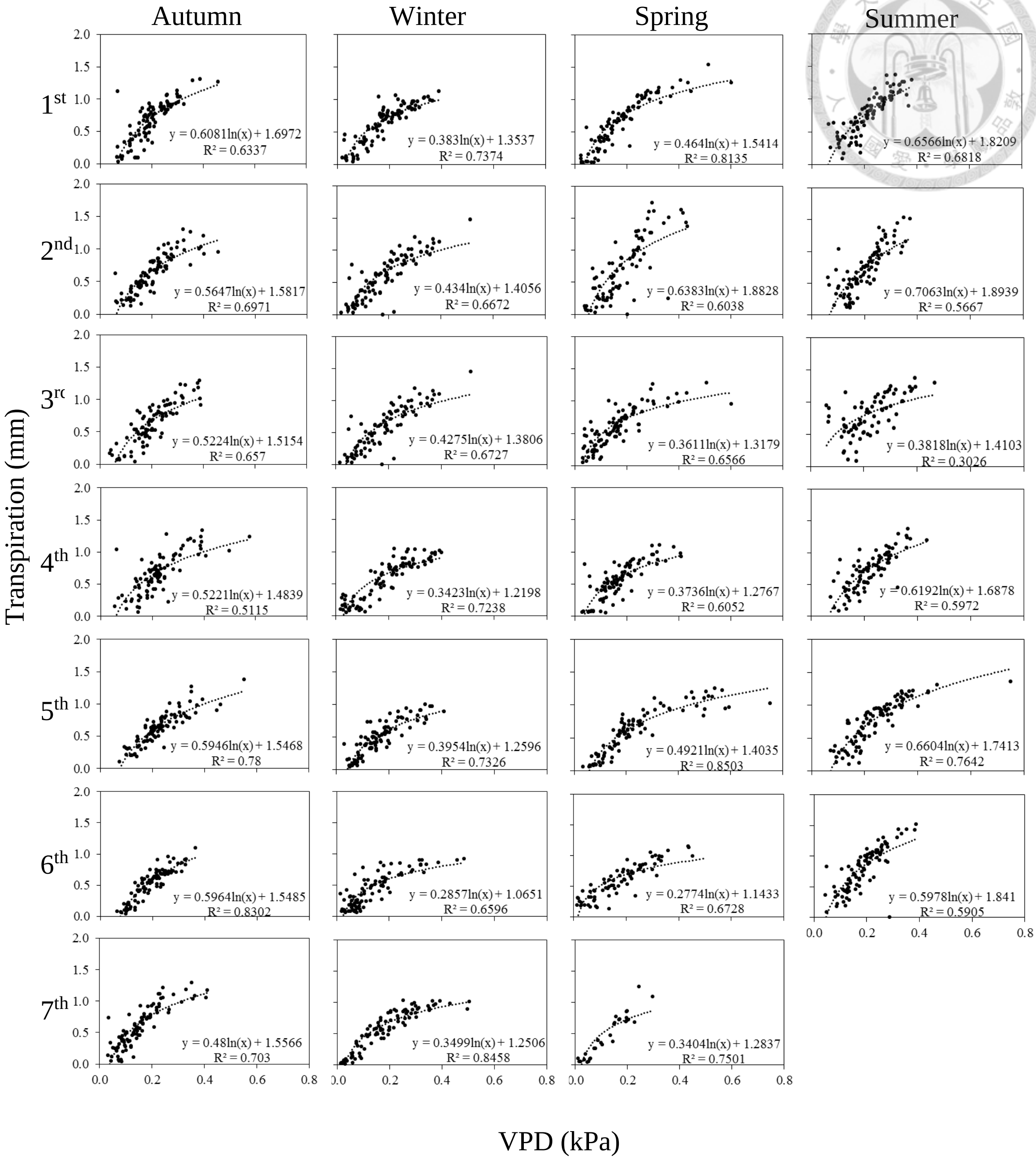


Fig. 31 Relationship between transpiration and VPD for each season in near 7 years. Autumn: Sep, Oct and Nov; Winter: Dec, Jan and Feb; Spring: Mar, Apr and May; Summer: Jun, Jul and Aug. 1st: Sep 2010 to Aug 2011, 2nd: Sep 2011 to Aug 2012, 3rd: Sep 2012 to Aug 2013, 4th: Sep 2013 to Aug 2014, 5th: Sep 2014 to Aug 2015, 6th: Sep 2015 to Aug 2016, 7th: Sep 2016 to Mar 2017.

doi:10.6342/NTU201702787

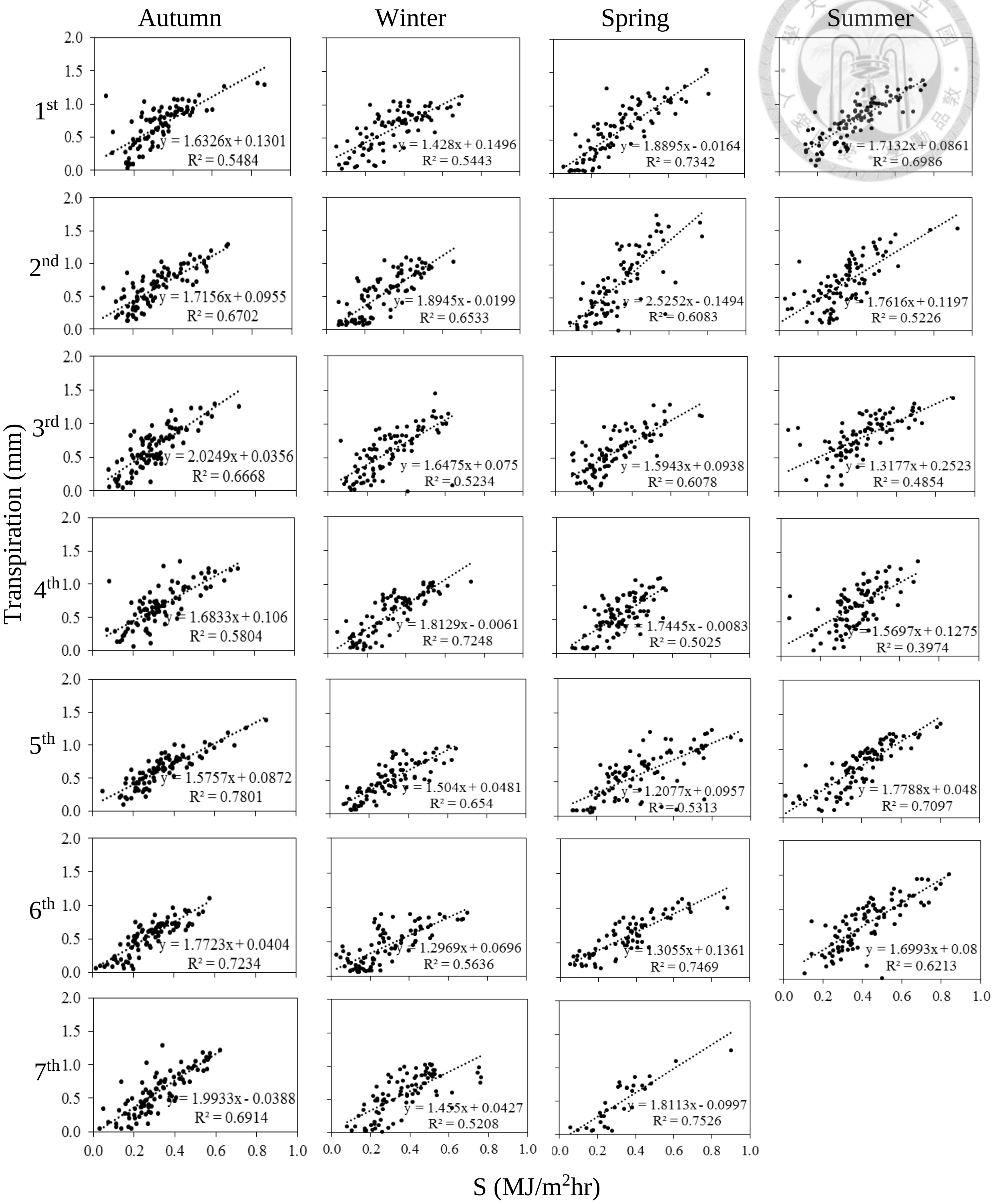


Fig. 32 Relationship between transpiration and S for each season in near 7 years. Autumn: Sep, Oct and Nov; Winter: Dec, Jan and Feb; Spring: Mar, Apr and May; Summer: Jun, Jul and Aug. 1st: Sep 2010 to Aug 2011, 2nd: Sep 2011 to Aug 2012, 3rd: Sep 2012 to Aug 2013, 4th: Sep 2013 to Aug 2014, 5th: Sep 2014 to Aug 2015, 6th: Sep 2015 to Aug 2016, 7th: Sep 2016 to Mar 2017.

doi:10.6342/NTU201702787

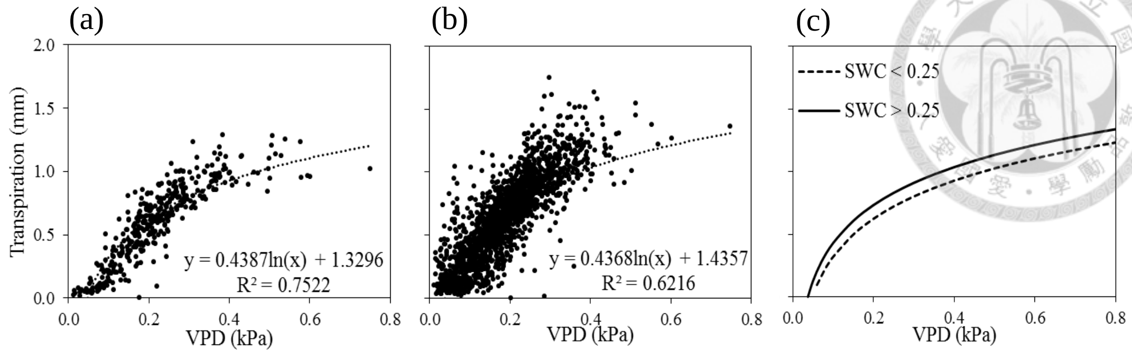


Fig. 33 Relationship between VPD and transpiration under the condition: (a) SWC < 25%, (b) SWC > 25%. And regression lines of (a) and (b) were shown in (c).

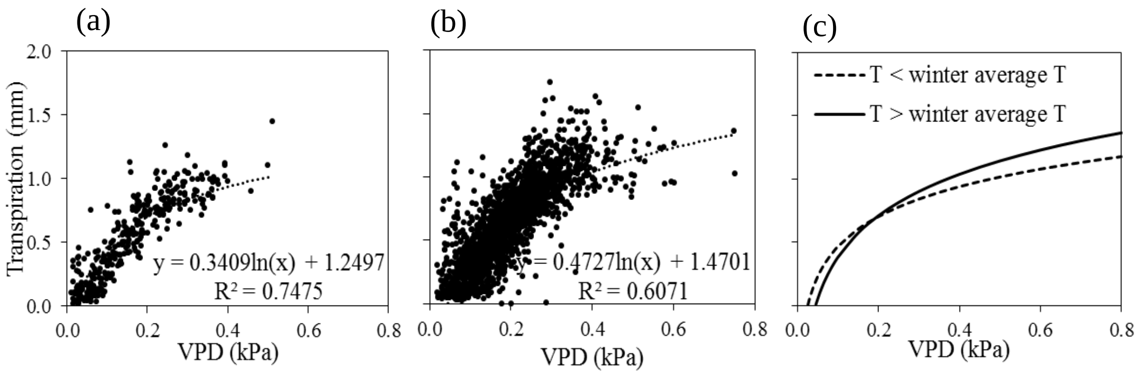


Fig. 34 Relationship between VPD and transpiration under the condition: (a) T < winter average T, (b) T > winter average T. And regression lines of (a) and (b) were shown in (c).

Table 7 Comparisons of sap flow measurement based stand transpiration in cloud forest.

Forest type	mean annual precipitation (mm)	mean annual temperature (^{0}C)	highest VPD (kPa)	Transpiration (mm)	Reference
Japanese cedar	2142	16	1.21	152-307	This study
Taiwan cypress	2780	13.4	-	192	羅勻謙 (2004)
Metrosideros polymorpha	5000	14.5	1.6	291	Santiago *et al.* (2000)
Morella faya	1660	13	4.5	416	García-Santos. (2012)
old growth cloud forest	3427	15.5	1.5	787	Muñoz-Villers *et al.* (2012)
mountain cloud forest	2983	-	2.4	591	McJannet et al. (2007)
mountain cloud forest	3040	-	1.7	589	McJannet et al. (2007)
mountain cloud forest	7471	-	2.2	353	McJannet et al. (2007)

doi:10.6342/NTU201702787

Table 8 Annual transpiration (range of transpiration estimation was shown) and meteorological factors such as precipitation (P), solar radiation (S), vapor pressure deficit (VPD), air temperature (T), soil water content (SWC) and ratio between E and P from previous studies and this study. 1st: Sep 2010 to Aug 2011, 2nd: Sep 2011 to Aug 2012, 3rd: Sep 2012 to Aug 2013, 4th: Sep 2013 to Aug 2014, 5th: Sep 2014 to Aug 2015, 6th: Sep 2015 to Aug 2016, 7th: Sep 2016 to Mar 2017 Data in 7th year in this study was not used to CV calculating because it was not full data of a year.

	year	E (mm)	P (mm)	E/P	T (^{0}C)	VPD (kPa)	SWC (%)	S (MJ/m^{2}y)	Reference
Tharande, Genmany	2001	165	938	0.18	8.3	0.36	-	-	Clausnitzer *et al.* (2011)
	2002	138	1098	0.13	9	0.38	-	-	
	2003	83	501	0.17	8.9	0.49	-	-	
	2004	171	874	0.20	8.5	0.37	-	-	
	2005	209	898	0.23	8.2	0.39	-	-	
	2006	214	776	0.28	8.9	0.43	-	-	
	2007	158	913	0.17	9.5	0.37	-	-	
	CV(%)	27.3	21.5	25.5	5.2	11.6	-	-	
North Carolina, America	2002	336.0	1092.0	3.3	-	-	-	-	Oishi *et al.* (2008)
	2003	329.0	1346.0	4.1	-	-	-	-	
	2004	346.0	992.0	2.9	-	-	-	-	
	2005	343.0	934.0	2.7	-	-	-	-	
	CV(%)	2.2	16.7	19.0	-	-	-	-	
Tennessee, America	2000	325.0	766	0.4	-	-	-	-	Wullschleger and Hanson. (2006)
	2001	309.0	539	0.6	-	-	-	-	
	2002	255.0	730	0.3	-	-	-	-	
	2003	315.0	968	0.3	-	-	-	-	
	CV(%)	10.4	23.4	26.7	-	-	-	-	
New South Wales, Australia	2003	317.0	522.0	0.6	-	-	-	-	Zeppel *et al.* (2008)
	2004	443.0	1062.0	0.4	-	-	-	-	
Montpellier, France	2004	430.0	989.0	0.4	-	-	-	-	Limousin *et al.* (2009)
	2005	364.0	835.0	0.4	-	-	-	-	
	2006	308.0	940.0	0.3	-	-	-	-	
	2007	417.0	681.0	0.6	-	-	-	-	
	CV(%)	14.7	15.8	26.1	-	-	-	-	
Nantou, Taiwan	1st	248 (169-325)	2062	0.12	15.6	0.19	0.31	3111	this study
	2nd	234 (160-306)	3232	0.07	16.4	0.19	0.33	2822	
	3rd	240 (159-318)	2433	0.10	16.1	0.19	0.31	2953	
	4th	231 (150-311)	1871	0.12	15.6	0.20	0.31	2987	
	5th	226 (141-304)	1486	0.15	15.9	0.22	0.29	3196	
	6th	218 (135-277)	1773	0.12	16.1	0.18	0.32	2948	
	7th	121 (83-157)	852	0.14	15.1	0.16	0.29	1729	
	CV(%)	5.0	28.9	23.3	2.1	7.3	4.0	4.4	

doi:10.6342/NTU201702787

Chapter 4 Conclusions

This study first aimed to determine the accuracy of thermal dissipation method-based sap flow on Japanese cedar tree in Xitou, central Taiwan. Calibration experiment results showed that under the condition in Xitou, thermal dissipation method-based sap flow may underestimate about 30 % of real water uptake. It suggested that Granier empirical formula cannot be directly used for Japanese cedar trees in central Taiwan. Also, the application of Clearwater formula in our study approved the accuracy of estimation, suggesting importance of sapwood depth estimation for sap flow measurement.

The second aim was to identify the effect of sapwood depth to stand scale transpiration, also for tree growth because of near 7-years data. The effect of new sapwood depth (from dye injection) was near 0 to stand scale transpiration in this study, because though 2-4 cm sap flow rate became high, sapwood area became small. Also, the effect of tree growth on stand transpiration estimation was not significant in this study, because Japanese cedar tree in plot were about 60 years old (60-66 years old in near 7 years), the growth of these trees was small in this 7 years.

Following, the third aim was to estimate stand scale transpiration with the consideration of results from the calibration experiments. This study found the calibration experiments should be carefully applied to the field measurements, as the five methods that applied to field data produced quite different stand transpiration estimates, mainly

doi:10.6342/NTU201702787

due to low flow rate data treatments. A lower range and upper range of stand transpiration estimation was 1.5 to 3 times larger than that from the original estimation. Although this study could not determine the best way to apply the calibration experiments, the probable range of the stand scale transpiration estimation derived in this study may be better estimates than the original estimates.

The last aim was to understand the condition of near 7-years data of stand transpiration with meteorological factors. For meteorological factors, the inter-annual variation seemed a little except for rainfall. The relationship between transpiration and meteorological factors was relatively high for vapor pressure deficit (VPD) and solar radiation (S). The effect of soil water content (SWC) to transpiration was not distinct in this study, suggested that the water supply was sufficient for trees in most time. The low air temperature in winter decreased the stand transpiration, which was one of reasons that caused seasonal variation of stand transpiration in this site. Because the inter-annual variation of meteorological factors was little, the inter-annual variation of transpiration that mainly affected by VPD and S was little, too. Consequently, from this near 7-years long-term data, the condition of transpiration and meteorological in Xitou were likely stable.

For future, because the low sap flow rate data was important, small size branch or stem maybe can be used to obtain the lack data. For more carefully measurement, the

doi:10.6342/NTU201702787

volumetric cylinder in calibration can be replace by electronic scale, and records water consumption continuously to get more accurate data. The sapwood area and DBH may have a relationship that can be used to obtained sapwood area from DBH. It may be a better way for long-term investigation. If plants transpiration and forest evaporation are known, by comparing it with the value calculated by eddy covariance method, the accuracy of the application of calibration results to field data can be identified.

doi:10.6342/NTU201702787

Chapter 5 Reference

林祐竹. (2011). 棲蘭山樣區降水對台灣扁柏樹液流影響之探討. *東華大學自然資源管理研究所碩士論文*, 1-95.

林務局第四次全國森林資源調查 (2017).

徐嘉君. (2015). 台灣山地霧林的分布型態. *林業研究專訊*, *22*(1), 5-8.

陳俐如. (2005). 鴛鴦湖地區台灣扁柏樹液流動之探討. *東華大學自然資源管理研究所碩士論文*, 1-86.

蔡孜奕. (2013). 臺灣中部塔塔加地區臺灣雲杉老熟林樹液流特性. *臺灣大學森林環境暨資源學研究所學位論文*, 1-78.

羅勻謙. (2004). 鴛鴦湖地區台灣扁柏森林生態系蒸散作用之研究. *東華大學自然資源管理研究所碩士論文*, 1-81.

Alkaeed, O., Flores, C., Jinno, K., & Tsutsumi, A. (2006). Comparison of several reference evapotranspiration methods for Itoshima Peninsula area, Fukuoka, Japan. *Memoirs of the Faculty of Engineering, Kyushu University*, *66*(1), 1-14.

Ayutthaya, I. N., Do, F. C., Pannengpetch, K., Junjittakarn, J., Maeght, J. L., Rocheteau, A., & Cochard, H. (2009). Transient thermal dissipation method of xylem sap flow measurement: multi-species calibration and field evaluation. *Tree Physiology*, *30*(1), 139.

Braun, P., & Schmid, J. (1999). Sap flow measurements in grapevines (Vitis vinifera L.) 2. Granier measurements. *Plant and Soil*, *215*(1), 47-55.

Burgess, S. S. O., & Dawson, T. E. (2004). The contribution of fog to the water relations of Sequoia sempervirens (D. Don): foliar uptake and prevention of dehydration. *Plant, Cell & Environment*, *27*(8), 1023-1034.

Bush, S. E., Hultine, K. R., Sperry, J. S., & Ehleringer, J. R. (2010). Calibration of thermal dissipation sap flow probes for ring-and diffuse-porous trees. *Tree physiology*, *30*(12), 1545-1554.

Chen, M. L. (2013). Characteristics of sap flow in a Japanese cedar plantation in Sitou, central Taiwan. *School of Forestry and Resource Conservation College of Bioresources and Agriculture, National Taiwan University Master Thesis*, 1-81.

doi:10.6342/NTU201702787

Chiu, C. W., Kume, T., Komatsu, H., Tseng, H., Wey, T. H., & Otsuki, K. (2016). Seasonal changes of azimuthal, radial, and tree-to-tree variations in sap flux affect stand transpiration estimates in a Cryptomeria japonica. *Journal of Forest Research*, *21*(4), 151-160.

Clausnitzer, F., Köstner, B., Schwärzel, K., & Bernhofer, C. (2011). Relationships between canopy transpiration, atmospheric conditions and soil water availability—Analyses of long-term sap-flow measurements in an old Norway spruce forest at the Ore Mountains/Germany. *Agricultural and forest meteorology*, *151*(8), 1023-1034.

Clearwater, M. J., Meinzer, F. C., Andrade, J. L., Goldstein, G., & Holbrook, N. M. (1999). Potential errors in measurement of nonuniform sap flow using heat dissipation probes. *Tree physiology*, *19*(10), 681-687.

Dawson, T. E. (1998). Fog in the California redwood forest: ecosystem inputs and use by plants. *Oecologia*, *117*(4), 476-485.

Delzon, S., Sartore, M., Granier, A., & Loustau, D. (2004). Radial profiles of sap flow with increasing tree size in maritime pine. *Tree Physiology*, *24*(11), 1285-1293.

Do, F., & Rocheteau, A. (2002). Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 2. Advantages and calibration of a noncontinuous heating system. *Tree physiology*, *22*(9), 649-654.

García-Santos, G. (2012). Transpiration in a sub-tropical ridge-top cloud forest. *Journal of hydrology*, *462*, 42-52.

Gebauer, T., Horna, V., & Leuschner, C. (2008). Variability in radial sap flux density patterns and sapwood area among seven co-occurring temperate broad-leaved tree species. *Tree physiology*, *28*(12), 1821-1830.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., & Sitch, S. (2004). Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. *Journal of Hydrology*, *286*(1), 249-270.

Granier, A. (1987). Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree physiology*, *3*(4), 309-320.

doi:10.6342/NTU201702787

Granier, A., Huc, R., & Barigah, S. T. (1996). Transpiration of natural rain forest and its dependence on climatic factors. *Agricultural and forest meteorology*, *78*(1-2), 19-29.

Gutiérrez, M. V., & Santiago, L. S. (2006). A comparison of sap flow measurements and potometry in two tropical lowland tree species with contrasting wood properties. *Revista de biología tropical*, *54*(1), 73-81.

Hölttä, T., Linkosalo, T., Riikonen, A., Sevanto, S., & Nikinmaa, E. (2015). An analysis of Granier sap flow method, its sensitivity to heat storage and a new approach to improve its time dynamics. *Agricultural and Forest Meteorology*, *211*, 2-12.

Hultine, K. R., Nagler, P. L., Morino, K., Bush, S. E., Burtch, K. G., Dennison, P. E. & Ehleringer, J. R. (2010). Sap flux-scaled transpiration by tamarisk (Tamarix spp.) before, during and after episodic defoliation by the saltcedar leaf beetle (Diorhabda carinulata). *Agricultural and Forest Meteorology*, *150*(11), 1467-1475.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L. & Dolman, A. J. (2010). Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature, 467*(7318), 951-954.

Klimešová, J., Středová, H., & Středa, T. (2013). Maize transpiration in response to meteorological conditions. *Contributions to Geophysics and Geodesy*, *43*(3), 225-236.

Komatsu, H., Onozawa, Y., Kume, T., Tsuruta, K., Kumagai, T. O., Shinohara, Y., & Otsuki, K. (2010). Stand-scale transpiration estimates in a Moso bamboo forest: II. Comparison with coniferous forests. *Forest Ecology and Management*, *260*(8), 1295-1302.

Köstner, B., Granier, A., & Cermák, J. (1998). Sapflow measurements in forest stands: methods and uncertainties. In *Annales des sciences forestières* (Vol. 55, No. 1-2, pp. 13-27). EDP Sciences.

Kumagai, T. O., Aoki, S., Nagasawa, H., Mabuchi, T., Kubota, K., Inoue, S. & Otsuki, K. (2005). Effects of tree-to-tree and radial variations on sap flow estimates of transpiration in Japanese cedar. *Agricultural and Forest Meteorology, 135*(1), 110-116.

doi:10.6342/NTU201702787

Kume, T., Onozawa, Y., Komatsu, H., Tsuruta, K., Shinohara, Y., Umebayashi, T., & Otsuki, K. (2010). Stand-scale transpiration estimates in a Moso bamboo forest:(I) Applicability of sap flux measurements. *Forest Ecology and Management*, *260*(8), 1287-1294.

Kume, T., Otsuki, K., Du, S., Yamanaka, N., Wang, Y. L., & Liu, G. B. (2012). Spatial variation in sap flow velocity in semiarid region trees: its impact on stand-scale transpiration estimates. *Hydrological Processes*, *26*(8), 1161-1168.

Laplace, S. (2013). Study on transpiration in a Taiwanese Moso bamboo forest using sap flow measurement. *School of Forestry and Resource Conservation College of Bioresources and Agriculture, National Taiwan University Master Thesis*, 1-92.

Limousin, J. M., Rambal, S., Ourcival, J. M., Rocheteau, A., Joffre, R., & Rodríguez-Cortina, R. (2009). Long-term transpiration change with rainfall decline in a Mediterranean Quercus ilex forest. *Global Change Biology*, *15*(9), 2163-2175.

Lin, M., Guan, D., Wang, A., Jin, C., Wu, J., & Yuan, F. (2015). Impact of leaf retained water on tree transpiration. *Canadian Journal of Forest Research*, *45*(10), 1351-1357.

Lu, P., Urban, L., & Zhao, P. (2004). Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: theory and practice. *Acta Botanica Sinica-English edition*, *46*(6), 631-646.

Lu, P., Woo, K. C., & Liu, Z. T. (2002). Estimation of whole-plant transpiration of bananas using sap flow measurements. *Journal of Experimental Botany*, *53*(375), 1771-1779.

McJannet, D., Fitch, P., Disher, M., & Wallace, J. (2007). Measurements of transpiration in four tropical rainforest types of north Queensland, Australia. *Hydrological Processes*, *21*(26), 3549-3564.

Meinzer, F. C., Goldstein, G., & Andrade, J. L. (2001). Regulation of water flux through tropical forest canopy trees: do universal rules apply? *Tree Physiology*, *21*(1), 19-26.

doi:10.6342/NTU201702787

Misson, L., Rasse, D. P., Vincke, C., Aubinet, M., & François, L. (2002). Predicting transpiration from forest stands in Belgium for the 21st century. *Agricultural and Forest Meteorology*, *111*(4), 265-282.

Muñoz-Villers, L. E., Holwerda, F., Gómez-Cárdenas, M., Equihua, M., Asbjornsen, H., Bruijnzeel, L. A. & Tobón, C. (2012). Water balances of old-growth and regenerating montane cloud forests in central Veracruz, Mexico. *Journal of Hydrology*, *462*, 53-66.

Nadezhdina, N., Cermak, J., & Ceulemans, R. (2002). Radial patterns of sap flow in woody stems of dominant and understory species: scaling errors associated with positioning of sensors. *Tree Physiology-Victoria-*, *22*(13), 907-918.

Nakada, R., Fujisawa, Y., & Hirakawa, Y. (1999). Soft X-ray observation of water distribution in the stem ofCryptomeria japonica D. Don I: General description of water distribution. *Journal of wood science*, *45*(3), 188-193.

Niu, F., Röll, A., Hardanto, A., Meijide, A., Köhler, M., & Hölscher, D. (2015). Oil palm water use: calibration of a sap flux method and a field measurement scheme. *Tree physiology*, *35*(5), 563-573.

Ohashi, H., Motegi, Y., & Yasue, M. (1985). Water distribution and water alleyway in the living stem of Cryptomeria japonica. *Res Bull Fac Agric Gifu Univ*, *50*, 111-129.

Oishi, A. C., Oren, R., & Stoy, P. C. (2008). Estimating components of forest evapotranspiration: a footprint approach for scaling sap flux measurements. *Agricultural and Forest Meteorology*, *148*(11), 1719-1732.

Okada, N., Hirakawa, Y., & Katayama, Y. (2012). Radial movement of sapwood-injected rubidium into heartwood of Japanese cedar (Cryptomeriajaponica) in the growing period. *Journal of wood science*, *58*(1), 1-8.

Pataki, D. E., & Oren, R. (2003). Species differences in stomatal control of water loss at the canopy scale in a mature bottomland deciduous forest. *Advances in Water Resources*, *26*(12), 1267-1278.

doi:10.6342/NTU201702787

Paudel, I., Kanety, T., & Cohen, S. (2013). Inactive xylem can explain differences in calibration factors for thermal dissipation probe sap flow measurements. *Tree physiology*, *33*(9).

Ritter, A., Regalado, C. M., & Aschan, G. (2009). Fog reduces transpiration in tree species of the Canarian relict heath-laurel cloud forest (Garajonay National Park, Spain). *Tree physiology*, *29*(4), 517-528.

Santiago, L. S., Goldstein, G., Meinzer, F. C., Fownes, J. H., & Mueller-Dombois, D. (2000). Transpiration and forest structure in relation to soil waterlogging in a Hawaiian montane cloud forest. *Tree Physiology*, *20*(10), 673-681.

Shen, Q., Gao, G., Fu, B., & Lü, Y. (2015). Responses of shelterbelt stand transpiration to drought and groundwater variations in an arid inland river basin of Northwest China. *Journal of Hydrology*, *531*, 738-748.

Shinohara, Y., Tsuruta, K., Ogura, A., Noto, F., Komatsu, H., Otsuki, K., & Maruyama, T. (2013). Azimuthal and radial variations in sap flux density and effects on stand-scale transpiration estimates in a Japanese cedar forest. *Tree physiology*, *33*(5).

Smith, D. M., & Allen, S. J. (1996). Measurement of sap flow in plant stems. *Journal of Experimental Botany*, *47*(12), 1833-1844.

Steppe, K., De Pauw, D. J., Doody, T. M., & Teskey, R. O. (2010). A comparison of sap flux density using thermal dissipation, heat pulse velocity and heat field deformation methods. *Agricultural and Forest Meteorology*, *150*(7), 1046-1056.

Sterling, S. M., Ducharne, A., & Polcher, J. (2013). The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change*, *3*(4), 385-390.

Sun, H., Aubrey, D. P., & Teskey, R. O. (2012). A simple calibration improved the accuracy of the thermal dissipation technique for sap flow measurements in juvenile trees of six species. *Trees*, *26*(2), 631-640.

Tseng, H. (2011).Transpiration estimates and spatial and temporal variability of sap flow in a Japanese cedar plantation in Sitou, central Taiwan. *School of Forestry and Resource Conservation College of Bioresources and Agriculture*, *National Taiwan University Master Thesis*, 1-74.

doi:10.6342/NTU201702787

Tsuruta, K., Kume, T., Komatsu, H., Higashi, N., Umebayashi, T., Kumagai, T. O., & Otsuki, K. (2010). Azimuthal variations of sap flux density within Japanese cypress xylem trunks and their effects on tree transpiration estimates. *Journal of Forest Research*, *15*(6), 398-403.

Wey, T. H., Lai, Y. J., Chang, C. S., Shen, C. W., Hong, C. Y., Wang, Y. N., & Chen, M. C. (2011). Preliminary studies on fog characteristics at Xitou region of central Taiwan. *J NTU Exp Forest, 25*, 149-160.

Wiedemann, A., Marañón-Jiménez, S., Rebmann, C., Herbst, M., & Cuntz, M. (2016). An empirical study of the wound effect on sap flux density measured with thermal dissipation probes. *Tree Physiology*.

Wilson, K. B., Hanson, P. J., Mulholland, P. J., Baldocchi, D. D., & Wullschleger, S. D. (2001). A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agricultural and forest Meteorology*, *106*(2), 153-168.

Wullschleger, S. D., & Hanson, P. J. (2006). Sensitivity of canopy transpiration to altered precipitation in an upland oak forest: Evidence from a long-term field manipulation study. *Global Change Biology*, *12*(1), 97-109.

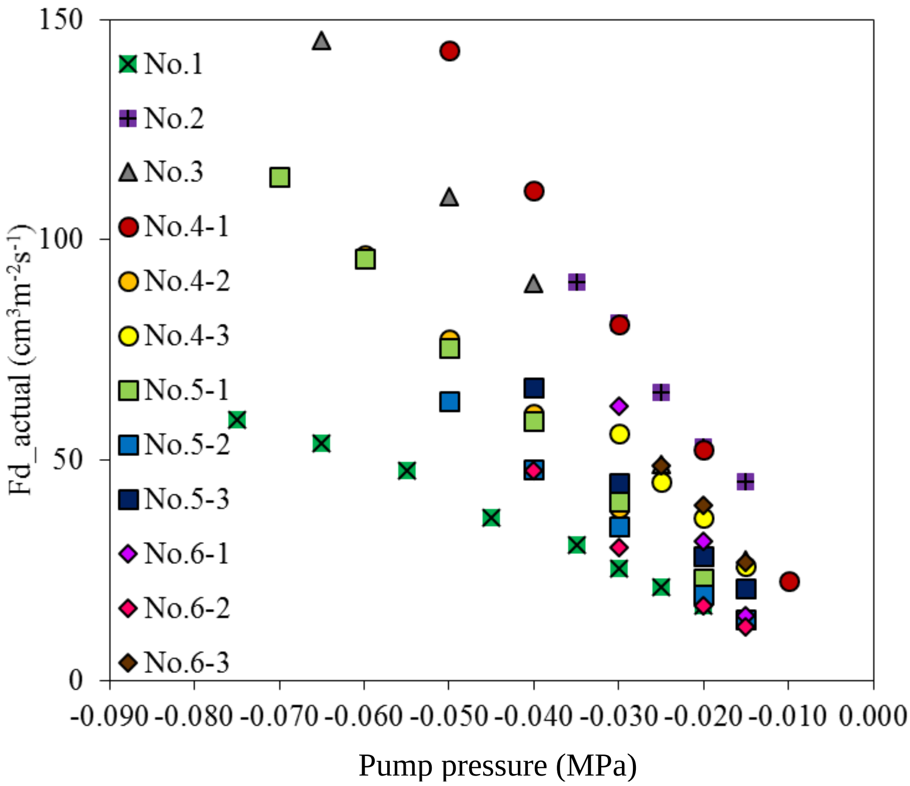
Wullschleger, S. D., Hanson, P. J., & Todd, D. E. (2001). Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. *Forest Ecology and Management*, *143*(1), 205-213.

Zeppel, M. J., Macinnis-Ng, C. M., Yunusa, I. A., Whitley, R. J., & Eamus, D. (2008). Long term trends of stand transpiration in a remnant forest during wet and dry years. *Journal of Hydrology*, *349*(1), 200-213.

doi:10.6342/NTU201702787

Appendix 1. Water conductance for 12 segments.

To assure that the water conductance of each segment may affect the accuracy of sap flow density estimation or not, we use pump pressure as X and real sap flow density as Y to make figure (Fig. 9). Results show that segment No. 4-1 had the highest water conductance, and No. 1 had the lowest one (4-1, 2, 3, 6-3, 6-1, 4-3, 5-3, 5-1, 4-2, 5-2, 6-2, 1). Compared with figure 12, the more overestimated real sap flow density one was No. 2, and the more underestimated one was No. 4-3 (2, 6-3, 4-1, 6-1, 4-2, 5-3, 3, 1, 5-2, 6-2, 5-1, 4-3). So that water conductance may not affect the accuracy of sap flow density estimation.



doi:10.6342/NTU201702787

Appendix 2. Sapwood depth for each tree in east and west sides and averaged in 2010 and 2016 and the difference of sapwood depth between these two years

Tree No.	2010 sapwood depth (cm)			2016 sapwood depth (cm)			difference between 2010&2016 (cm)		
	east	west	average	east	west	average	east	west	average
1	2.80	3.12	2.96	2.95	2.50	2.73	0.15	-0.62	-0.24
2	3.68	3.38	3.53	1.90	3.65	2.78	-1.78	0.27	-0.75
3	4.60	4.74	4.67	4.90	4.20	4.55	0.30	-0.54	-0.12
4	4.28	4.52	4.40	4.10	3.80	3.95	-0.18	-0.72	-0.45
5	4.17	4.01	4.09	3.60	4.30	3.95	-0.57	0.29	-0.14
7	3.70	3.99	3.85	2.85	4.50	3.68	-0.85	0.51	-0.17
8	3.48	1.98	2.73	3.40	3.80	3.60	-0.08	1.82	0.87
9	3.00	4.70	3.85	3.25	3.60	3.43	0.25	-1.10	-0.43
10	3.47	4.10	3.79	3.60	3.80	3.70	0.13	-0.30	-0.09
11	3.50	2.35	2.93	0.70	2.00	1.35	-2.80	-0.35	-1.58
12	3.51	3.40	3.45	3.50	3.10	3.30	0.00	-0.30	-0.15
13	3.00	3.20	3.10	-	-	-	-	-	-
14	3.78	3.05	3.41	3.15	3.20	3.18	-0.63	0.15	-0.24
15	3.50	3.70	3.60	2.80	3.00	2.90	-0.70	-0.70	-0.70
16	2.95	3.07	3.01	2.55	3.20	2.88	-0.40	0.13	-0.13
17	2.80	1.62	2.21	2.90	2.43	2.67	0.10	0.81	0.46
18	3.04	2.44	2.74	3.00	3.00	3.00	-0.04	0.56	0.26
19	3.21	3.10	3.15	3.40	3.00	3.20	0.19	-0.09	0.05
20	4.06	3.46	3.76	4.40	4.10	4.25	0.34	0.64	0.49
21	1.94	3.30	2.62	3.05	3.20	3.13	1.11	-0.10	0.50
22	4.03	4.10	4.06	-	-	-	-	-	-
23	3.01	4.55	3.78	4.60	4.10	4.35	1.59	-0.45	0.57
24	3.90	1.80	2.85	3.20	2.00	2.60	-0.70	0.20	-0.25
25	3.68	3.80	3.74	3.20	3.10	3.15	-0.48	-0.70	-0.59
26	2.74	3.00	2.87	3.90	4.60	4.25	1.17	1.60	1.38
average	3.43	3.38	3.41	3.26	3.40	3.33	-0.17	0.04	-0.06

doi:10.6342/NTU201702787

Appendix 3. Sapwood depth determined by visual and dye in 17 trees

Tree No.	sapwood depth (cm)		
	visual	dye	difference
1	3.30	2.80	-0.50
2	3.45	1.95	-1.50
3	4.80	4.20	-0.60
4	3.85	3.35	-0.50
5	3.95	3.60	-0.35
7	3.45	2.40	-1.05
8	-	-	-
9	3.25	2.70	-0.55
10	-	-	-
11	1.20	0.50	-0.70
12	3.90	3.25	-0.65
13	-	-	-
14	3.45	2.75	-0.70
15	-	-	-
16	2.45	2.10	-0.35
17	3.10	2.40	-0.70
18	3.35	2.95	-0.40
19	-	-	-
20	3.50	2.75	-0.75
21	-	-	-
22	-	-	-
23	4.30	3.80	-0.50
24	3.90	3.70	-0.20
25	3.85	3.70	-0.15
26	-	-	-
average	3.47	2.88	-0.60

doi:10.6342/NTU201702787

Appendix 4. DBH growth for each tree from 2010 to 2016

Tree No.	Growth of DBH (mm)						
	2010	2011	2012	2013	2014	2015	2016
1	0.45	0.57	0.89	0.87	0.95	0.47	0.61
2	1.11	2.97	2.08	2.88	2.30	2.36	2.75
3	1.46	3.46	3.48	4.22	4.70	3.27	2.80
4	0.73	1.48	1.05	1.39	1.88	1.65	1.69
5	1.36	2.95	2.44	3.20	2.73	2.18	2.59
7	1.30	2.70	2.21	1.38	3.50	3.18	2.53
8	1.03	1.62	1.57	2.26	2.39	1.26	2.12
9	1.54	1.71	2.39	1.28	1.14	1.49	0.93
10	0.52	1.06	1.00	0.77	0.65	0.64	0.47
11	0.45	2.07	0.66	0.72	1.06	0.98	1.09
12	1.12	1.95	1.86	1.67	2.29	1.53	2.45
14	1.50	3.34	2.77	2.71	2.57	4.14	2.22
15	0.47	2.18	1.48	2.09	1.59	1.81	1.28
16	2.23	3.64	4.32	3.09	3.43	2.47	4.04
17	0.84	1.62	1.24	1.07	1.42	0.81	0.82
18	0.72	1.47	1.43	1.87	1.81	1.32	1.13
19	0.29	1.02	1.20	1.55	1.37	1.47	1.67
20	1.76	3.65	3.07	2.24	3.44	2.43	2.44
21	0.43	0.78	0.67	1.10	1.24	0.93	0.70
23	1.38	2.23	3.24	2.55	1.92	2.52	2.41
24	1.24	2.44	1.57	2.56	2.26	1.38	1.97
25	0.95	2.18	2.00	3.25	2.87	2.08	2.46
26	1.48	3.28	3.28	2.98	1.62	2.31	2.66
average	1.06	2.19	2.00	2.07	2.13	1.86	1.90

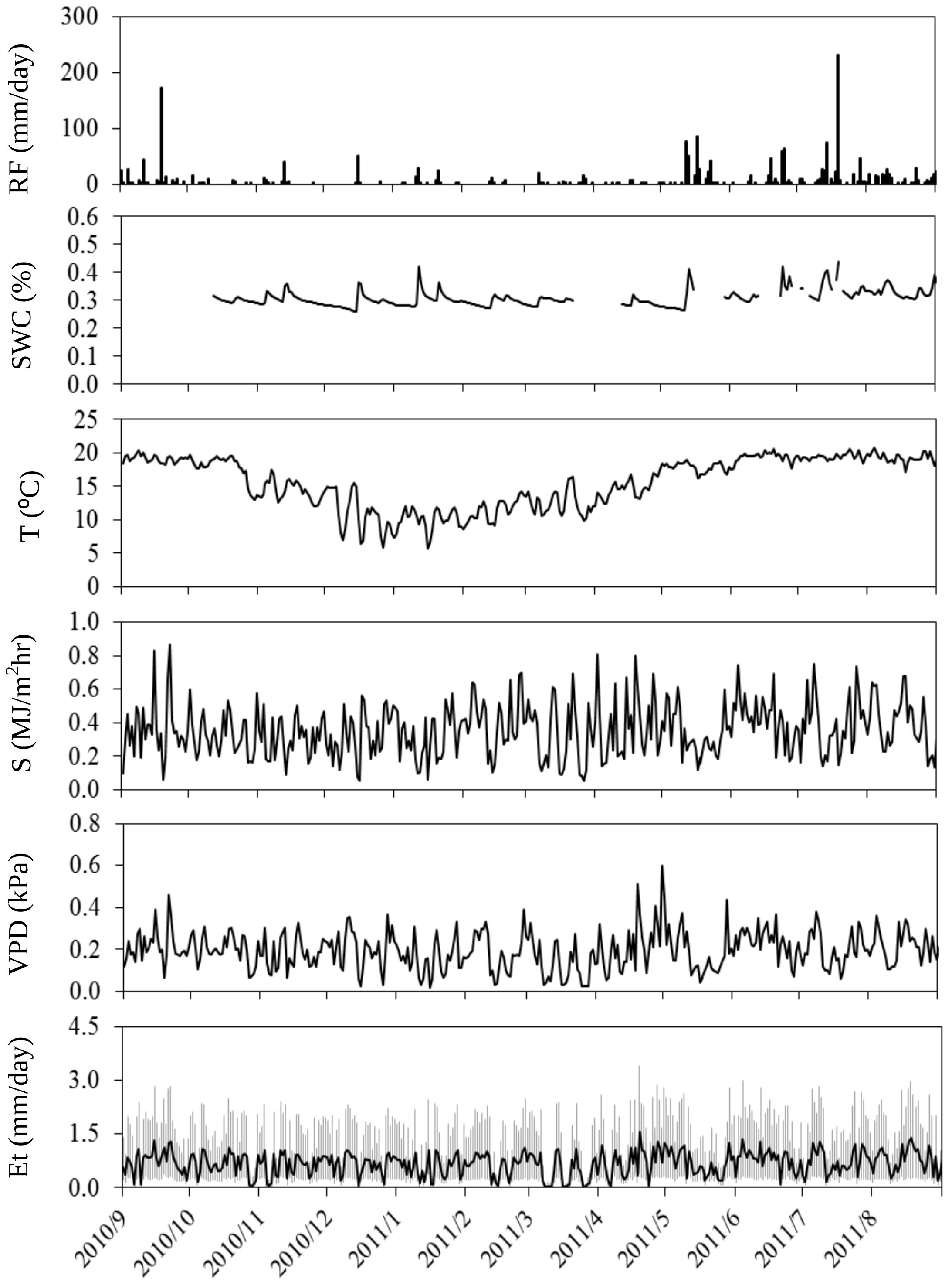
Appendix 5. Monthly stand scale transpiration estimation for near 7 years. 1st: Sep 2010 to Aug 2011, 2nd: Sep 2011 to Aug 2012, 3rd: Sep 2012 to Aug 2013, 4th: Sep 2013 to Aug 2014, 5th: Sep 2014 to Aug 2015, 6th: Sep 2015 to Aug 2016, 7th: Sep 2016 to Mar 2017.

	1st	2nd	3rd	4th	5th	6th	7th	average
Sep	21.8	21.9	20.8	22.2	20.1	16.2	14.8	19.7
Oct	20.3	18.1	19.3	18.9	21.2	15.4	21.2	19.2
Nov	19.2	18.0	17.5	19.4	15.9	17.2	18.0	17.9
Dec	20.9	16.2	15.1	15.0	13.8	13.9	19.9	16.4
Jan	17.9	16.1	20.1	22.2	16.1	13.1	19.7	17.9
Feb	18.8	16.7	18.0	15.1	14.9	12.5	12.5	15.5
Mar	14.6	25.4	21.3	16.5	17.0	16.0	15.0	18.0
Apr	22.5	13.2	14.4	16.8	20.0	21.8		18.1
May	20.8	22.8	19.0	18.3	18.9	18.4*		20.1
Jun	24.2	20.8	23.4	18.7	24.7	23.2		22.5
Jul	22.7	25.2	27.8	25.4	22.7	28.2		25.3
Aug	24.4	19.4	23.2	22.5	21.2	20.1		21.8
Total	248	234	240	231	226	218	121	232

*data coverage 45.16% (14 days), the value was calculated by ratio.

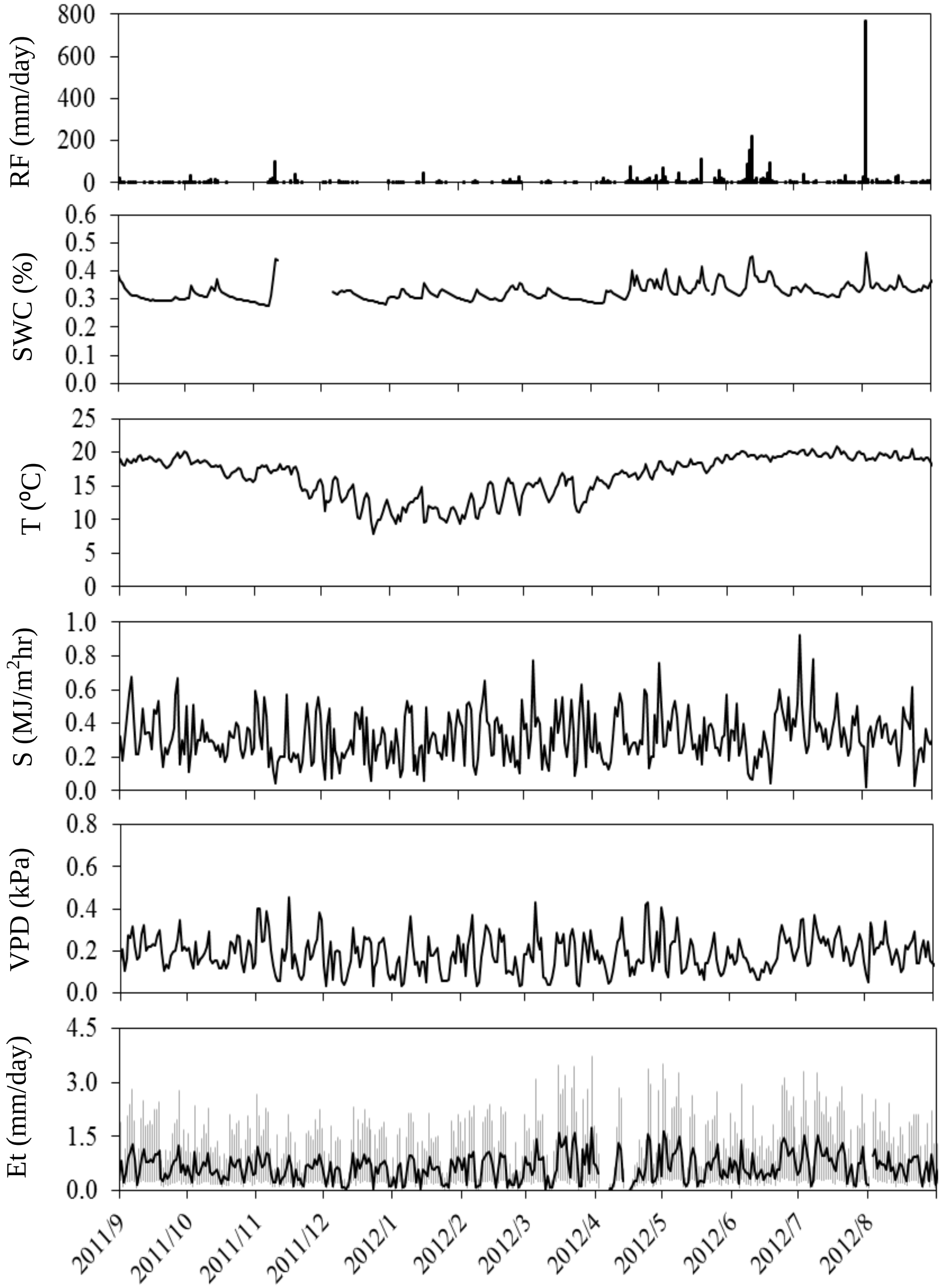
doi:10.6342/NTU201702787

Appendix 6. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2010 to Aug. 2011. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



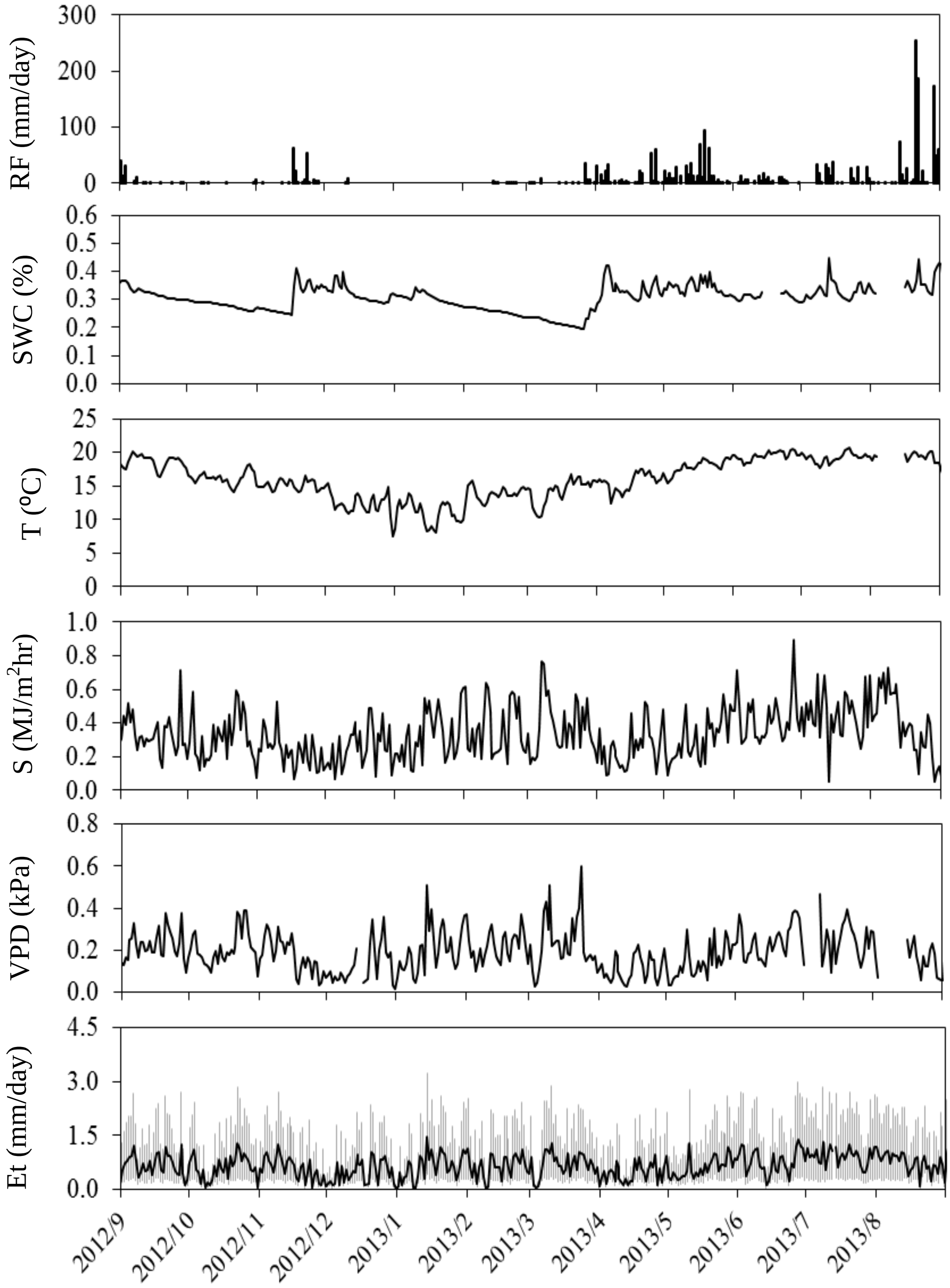
doi:10.6342/NTU201702787

Appendix 7. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2011 to Aug. 2012. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



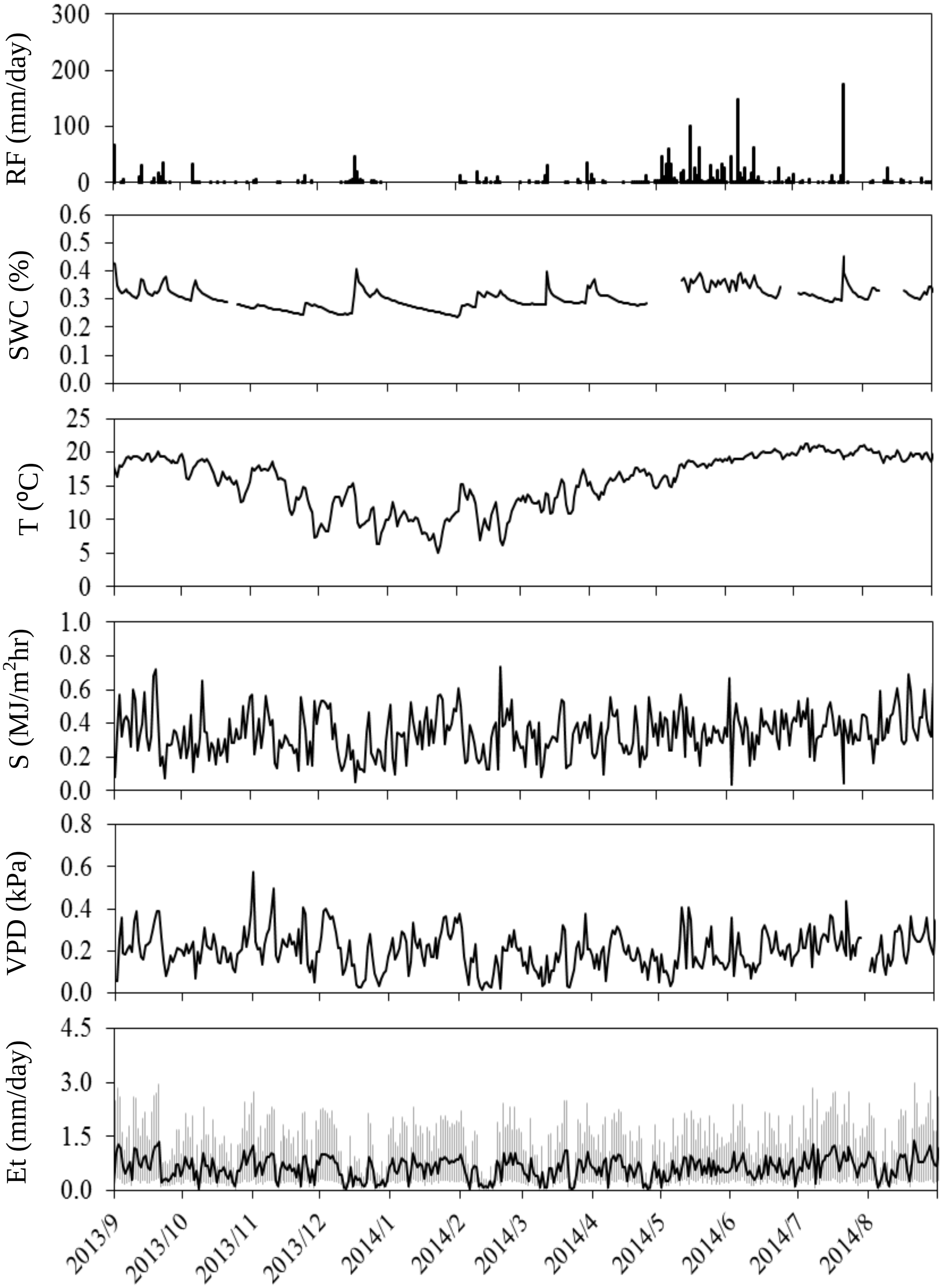
doi:10.6342/NTU201702787

Appendix 8. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2012 to Aug. 2013. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



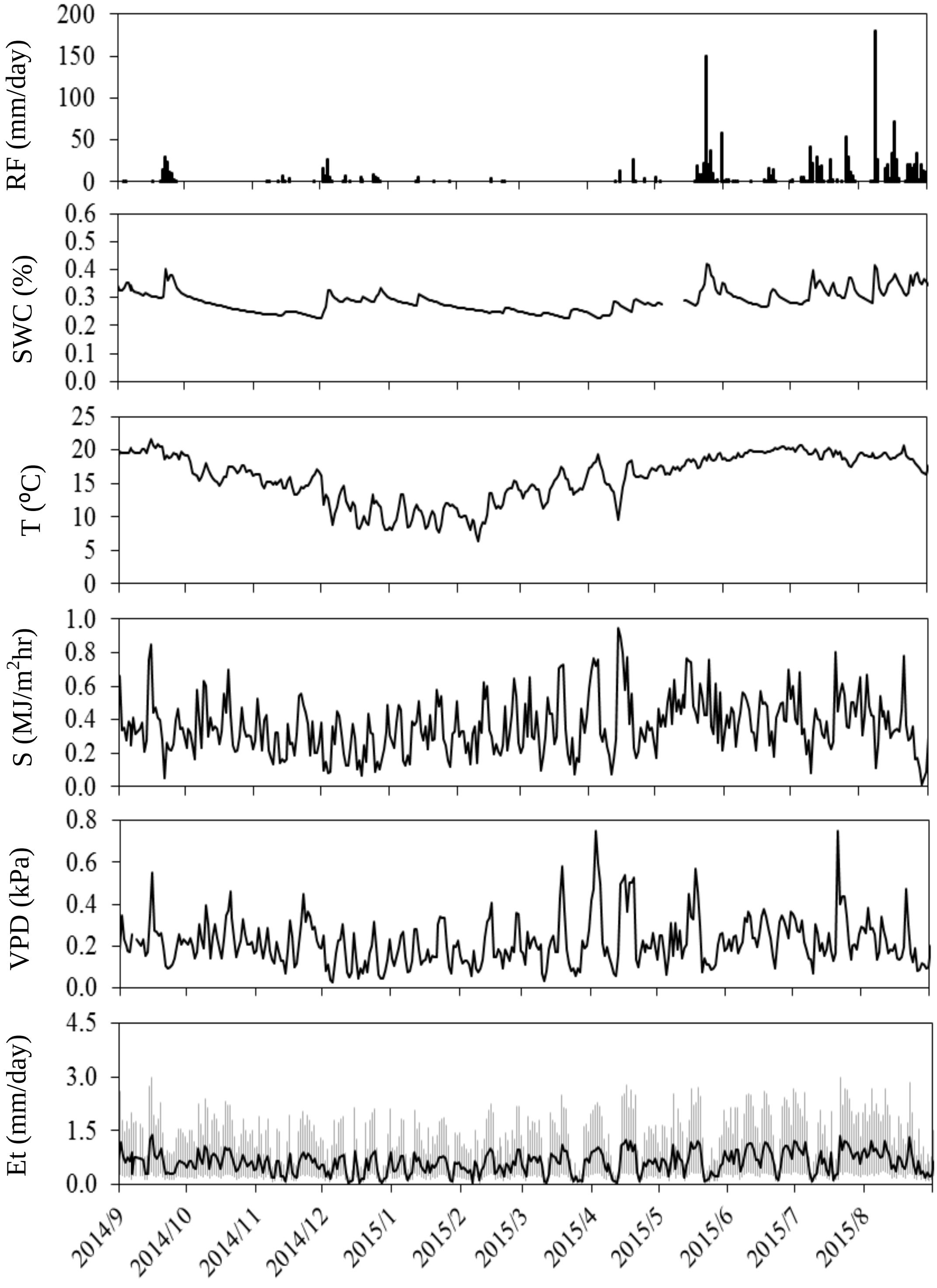
doi:10.6342/NTU201702787

Appendix 9. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2013 to Aug. 2014. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



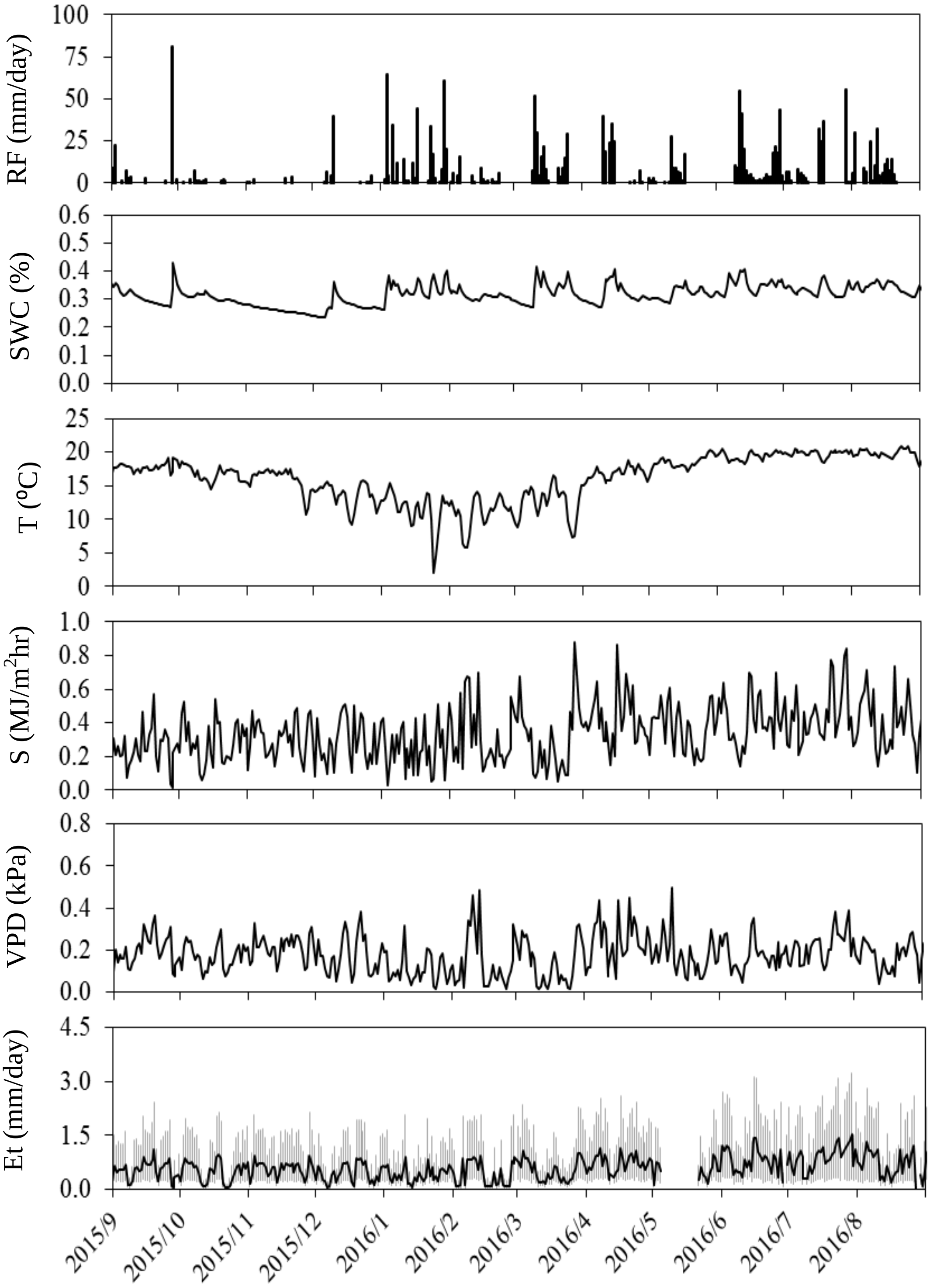
doi:10.6342/NTU201702787

Appendix 10. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2014 to Aug. 2015. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



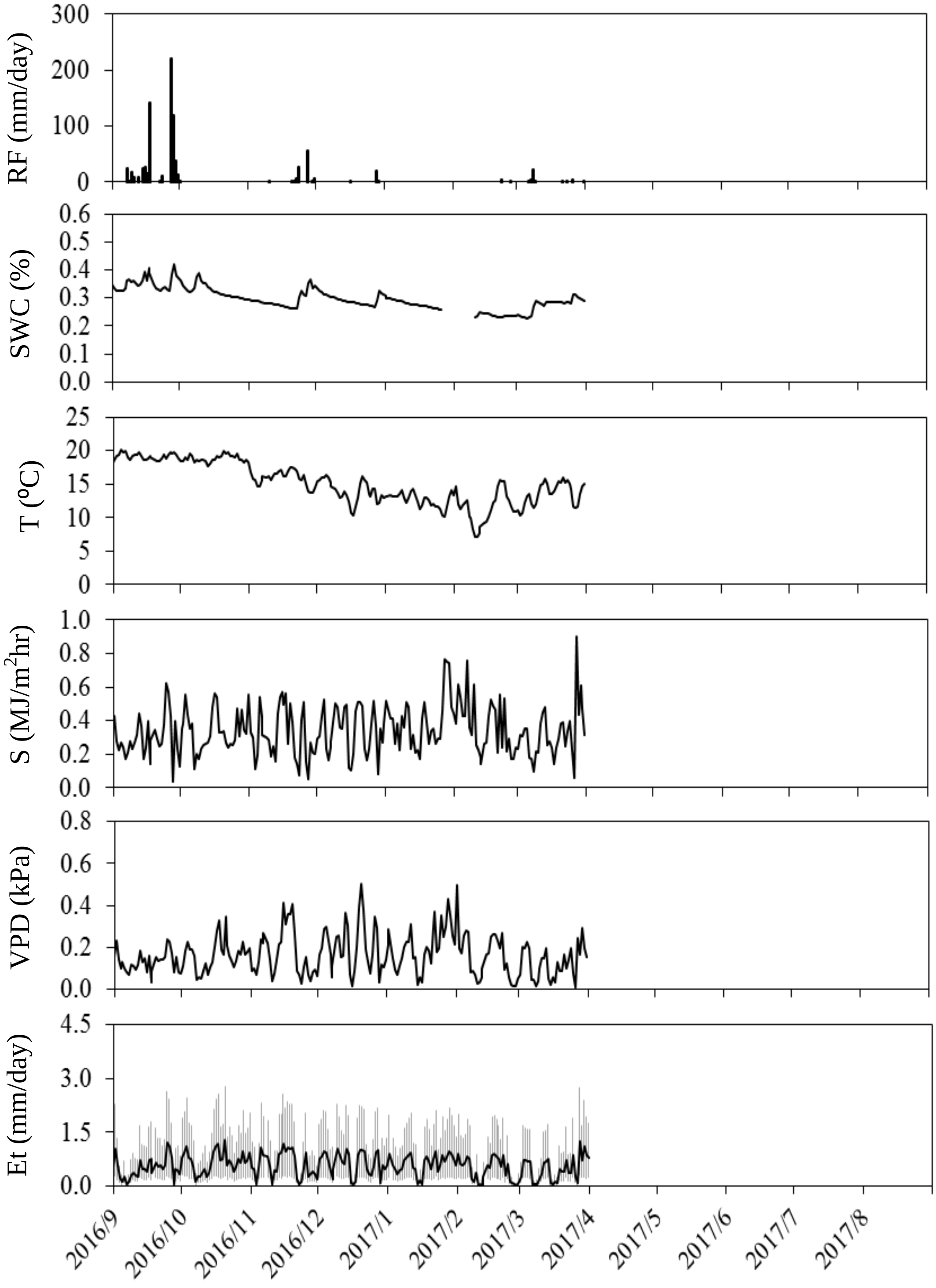
doi:10.6342/NTU201702787

Appendix 11. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2015 to Aug. 2016. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



doi:10.6342/NTU201702787

Appendix 12. Meteorological factors (daily) such as rainfall (RF), soil water content (SWC), air temperature (T), solar radiation (S) and vapor pressure deficit (VPD) and stand scale transpiration (Et) (daily) from Sep. 2016 to Mar. 2017. Black line in Et represents averaged transpiration which calculated from of 3 calibration application methods (No. 1, No. 3 and No. 4), and grey line represents the value of maximum and minimum.



doi:10.6342/NTU201702787