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

利用樹液流法測量溪頭柳杉人工林之蒸散狀況及變異

Transpiration Estimates and Spatial and Temporal Variability of Sap Flow in a Japanese Cedar Plantation in Sitou, Central Taiwan

曾涵

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中華民國 100 年 8 月

August, 2011

致謝

首先我要感謝我的父母。感謝你們生我養我送我上學，讓我有機會寫這本論文。

接著我想要感謝在這本論文逐漸成型的過程中幫助我的人。

感謝幫忙收集整理資料的研究室成員們。

感謝給我建議幫助我找到研究方向的老師教授們。

感謝無時無刻監視我催促我並不時提供笑料的戰隊隊友們。

作業で疲れた時、一緒に食べたり飲んだり、慰めて励ましてくれる日本人の友達に感謝します。

挫折して落ち込んでいる時、会った事もないのに話しかけてくれるツイッターのフォロワーさん達に感謝します。

一人夜更かしをしている時、ネット回線を通って、素晴らしい曲と歌で元気と癒しと勢いを届いてくれる鋼兵さんとボカロＰ達に感謝します。

そして最後、久米先生に感謝します。初めてオフィスに行った時、研究のことについて何一つ知らなかった私がこの論文を完成させたのは、全て先生のお陰です。

ありがとう。そして、ありがとう。

摘要

在森林生態系中，蒸散作用是水文循環中一個重要的過程。在森林中，樹液流測量法是一個測量單株樹木個體尺度蒸散量的可靠方法。雖然已有研究報告指出樹液流在個體內有顯著的空間分布差異，並在估算個體樹木蒸散時造成困難，但卻很少有研究詳細檢視這些空間分布差異在季節上的變化。因此，本研究在位於台灣中部的台大溪頭實驗林的柳杉人工林中實施樹液流測量，試圖釐清樹木個體之內在空間與時間上的變異。本研究使用 Granier 的熱擴散探針法，在兩顆較小、三棵中等、三棵較大的柳杉上進行測量。測量期間為 2010 年七月到 2011 年一月。所得的樹液流資料經過處理，分析樹液流流速與生物計量參數如胸高直徑（DBH）、樹高、邊材厚度及邊材面積之間的關係，並且分析於不同深度及方向所測得的樹液流流速之間的相關性。

研究結果，在樹液流徑向分布變異的分析中，可以得知在整個測量期間當中，於深度 2–4 cm 處所測得的樹液流流速，約為深度 0–2 cm 處所測得樹液流流速的 50–60 %。而在樹液流的方位分布變異的分析則顯示，在不同方位之間樹液流流速有顯著的差異，一個方位的樹液流流速可能為另一方位的 50–200 %。樹液流流速與方向並沒有相關性。但在不同方位所測得的流速，他們之間的關係在整個測量期間中大致上是固定的。另外，藉由一個簡單的計算過程和比較，可以得知樹液

流在徑向分布變異與方位分布變異的季節性改變，有可能在估算個體樹木尺度的蒸散量時造成不顯著的影響。總體而言，本研究探討適當的設計，來測量柳杉的個體蒸散量。

關鍵字：蒸發散、蒸散、樹液流測量、尺度放大、樹液流個體內變異

Abstract

Transpiration is an important process in water cycle of forested ecosystem. To measure transpiration in forests, sap flow measurement method can be robust technique for individual tree-scale measurements. Although it have been reported that significant spatial variations in sap flow within-tree, which makes difficult to estimated individual tree-scale transpiration estimates, few studies have examined their seasonal change characteristics. Thus, this study was conducted to clarify within-tree special and temporal variations in sap flow in a Japanese cypress forest, Sitou NTU experimental forest located in Central Taiwan. In this study Granier's thermal dissipation technique is applied to two smaller sized, three middle sized and three larger sized trees, respectively. The measurement was carried out through 2010 July to 2011 January. Sap flow data is analyzed for the relationships between sap flux density and some biometric parameters such as DBH, tree height, sapwood thickness and sapwood area, and the correlation between sap flux density at different depth and azimuthal aspects.

Consequently, in radial profile analysis, we found inner sap flow velocities measured at depth of 2–4 cm was approximately 50–60 % of the outermost sap flux density measured at depth of 0–2 cm through the measurement period. In azimuthal variations analysis, we found significant azimuthal variations in sap flux density, and one aspect showed 50–200 % of other aspects. Dependency of sap flux density on direction cannot be found. However, the relationships between one aspect and the other aspects are mostly fairly consistent through the measurement period. We also showed seasonal change of the radial and azimuthal variations in sap flow could have insignificant impacts on accuracy of individual tree-scale transpiration estimates based on a simple numerical exercise. Overall, this study discussed appropriate design for individual-tree scale transpiration estimates for Japanese cypress trees.

Keywords: *evapotranspiration, transpiration, sap flow measurement, scaling up, sap flow within tree variability*

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Chapter 1

Introduction

Evapotranspiration is an important process in the ecosystem, and has being taken seriously in a wild range of disciplines, including ecology, hydrology and meteorology. Transpiration in the forest not only takes a big part on forest water cycle, but also has a close relationship with metabolism and water use in forest plants. However, regardless of its importance and the many aspects being affected, it is not easy to get to know the amount of transpiration of a forest. Because of its multidisciplinary focus, a number of methodologies have been developed based on a variety of theories. A various techniques provide different tools to measure and estimate evapotranspiration or its components like transpiration, directly or indirectly. From all these techniques researchers can chose to best suit their purpose.

Measuring and estimating transpiration

Because each of the evapotranspiration estimate techniques introduces a unique set of assumptions, technical difficulties, measurement errors and biases (Wilson et al. 2001), each of the techniques has its own pros and cons, and each has its specific range of application.

The measuring techniques cover a wide range of scale through both space and time from individual leaf or to the entire watershed, and from minutes to months or years. However, each of them is representative only within a particular spatial and temporal scale. At the scale of leaf or branch there are rapid weighing, steady-state porometer and photosynthesis system; at single tree level there are whole-tree potometer, ventilated chamber, weighting potted-plant, sap flow measurement; at stand level and above, there are lysimeter, eddy covariance, catchment water balance, energy balance, Penman-Monteith equation (邓东周 et al. 2008).

Techniques which measure transpiration directly, for example rapid weighing method and whole-tree photometer, often apply to smaller spatial scale. Many of these techniques require damaging the plant, like cutting off branches or even the whole plant. The intrusive damages of the plant often cause leaf water potential and physiological mechanisms of the plant to change, making the results not representative to the natural conditions (Wullschleger et al. 1998; 邓东周 et al. 2008) Also, these approaches often take their measurements inside a chamber, making them less applicable to larger trees. Other techniques such as measuring stomatal conductance on plant leaves with a porometer can be also measure the plant's transpiration rate directly. However, the process of calculating the transpiration rates and aggregating the result over a canopy can be very difficult because of the variation of transpiration rate among different leaf age, radiation intensity and boundary layer conductance (Smith and Allen 1996; 邓东周 et al. 2008).

Small scale transpiration measuring techniques are usually not very useful when studying transpiration in a forest. At a large spatial scale level, evapotranspiration of a stand or a catchment can be estimated indirectly by equations of water or energy balance. Catchment water balance method, eddy-covariance method, Bowen ratio or Penman-Monteith equation are some of the methods widely used to estimate large spatial scale transpiration. However, applicability of many micrometeorological techniques is often limited by canopy heterogeneity, topography and horizontal extension of the forest, making them hard to apply in mountains with sloped or heterogeneous terrains (Granier 1987; Schume et al. 2005; Smith and Allen 1996; Wilson et al. 2001; 邓东周 et al. 2008; 陳信雄 2006) Also, because of the estimations of these techniques are often based on other environmental conditions, they can be affected by errors in all of the other measurements (Wilson et al. 2001; Wullschleger et al. 1998; 陳信雄 2006). And since these micrometeorological techniques can only estimates transpiration indirectly, they cannot be related to the physical condition of the plants. These techniques also have the problem of being expensive and logistically difficult to implement because they often require special equipment (Wullschleger et al. 1998).

In some previous studies, a few of the commonly used transpiration measuring or estimating methods when studying forest transpiration, including soil water budget, sap flow measurement, eddy covariance and catchment water balance, were tested and compared with one or more of the others (Ford et al. 2007; Gong et al. 2007; Hogg et al. 1997; Williams et al. 2004; Wilson et al. 2001).

Sap flow measurement

The methodology of sap flow measurement is based on the idea that through the measurement of sap flux moving from root systems to leaves inside a tree and the cross-section area of water conducting xylem of sapwood, the amount of whole-tree water use can be calculated, and thus transpiration can be estimated.

To measure water flowing through stem of a tree, some kind of tracer is required to mark the sap inside xylem, and one of the most commonly used tracers is heat. There are four techniques which use heat as tracers to measure sap flow, stem heat balance methods, trunk sector heat balance methods, heat-pulse method, and thermal dissipation technique. The four techniques are fundamentally different in operating principles, therefore, selecting the one appropriate to application and taking precautions to potential sources of error, sampling strategy and scaling method is important (Smith and Allen 1996).

Stem heat balance and trunk sector heat balance methods are based on the heat balance principle. Stem or a sector of the stem is heated from outside or inside the trunk, and the heat balance is solved for the amount of heat taken up by the moving sap stream, which is then used to calculate the sap flow in the stem (Smith and Allen 1996). These two techniques are simple and reliable, but the size of tree can limit their application as the equipment had to match up with the tree and can be hard to set up sometimes (邓东周 et al. 2008). On the other hand, heat pulse method and thermal dissipation technique measure sap flow by sets of needle-like sensing probes implanted into the tree trunk. Both techniques measure the temperature difference between the two sensors, but in heat pulse method short pulses of heat is applied by the probes and in thermal dissipation technique continuous heating is used. A problem of heat-pulse method is that there can be large errors if the locations of probes on the trunk are not in a line (邓东周 et al. 2008). It has also been reported that heat-pulse method is not accurate under low sap flow (Granier 1987).

Granier's thermal dissipation technique

Among the many techniques of sap flow measurement, the thermal dissipation technique proposed by Granier at 1985 is one of the commonly used methods. In thermal dissipation technique there are two thermocouple probes in one set of sensor, one continuously-powered heater sensor and one receive sensor placed about 10 cm apart below the heater sensor. The set of sensor probes is implanted into sapwood of the tree trunk to measure the temperature differences between the two probes. The sap flow density can then be calculated empirically from the difference of temperature between probes, and finally transpiration of the tree can be calculated according to the sap flow density and the sapwood cross-sectional area (Granier 1987; Smith and Allen 1996; 邓东周 et al. 2008).

Although sap flow measurement was reported by Granier (1987) that rarely have been used to estimate transpiration of an entire stand, it is a useful tool for investigation forest transpiration (Granier 1987; Oishi et al. 2008; Tsuruta et al. 2010) and has become one of the most widely used methods to measure transpiration in forest. Sap flow measurement, especially heat dissipation technique, has the advantages of easy application, simple calculation, and needs no expensive equipment (Granier et al. 1996; Wilson et al. 2001; Wullschleger et al. 1998; 邓东周 et al. 2008). Most importantly, sap flow measurement overcomes the limitations of many micrometeorological techniques. It is not limited by the complex terrain and spatial heterogeneity, and can be used even on steep slopes (Granier et al. 1996; Wilson et al. 2001; 邓东周 et al. 2008). Also, because this method measures sap flow of trees directly, it is free from errors of other environmental measurements (Wullschleger et al. 1998).

Sap flow measurement provides data at whole plant or branch level in a fairly high time resolution (Wilson et al. 2001). Sap flow measurement measures water use of an individual tree. Therefore it can be used to divide transpiration estimates among components of the forest such as different species or tree ages, or can be used to partition evapotranspiration between plant transpiration and other evaporation components when combined with other evapotranspiration measurement (Granier et al. 1996; Smith and Allen 1996; Wilson et al. 2001).

Techniques estimating whole-tree water use not only provide physiological insights into control of water transport and storage, but also the fundamental biology underlies water resource management in more detail (Wullschleger et al. 1998). Sap flow measurement gives details on physiological and environmental controls of transpiration (Wilson et al. 2001), and provide tools to better understand rates and control of leaf and crown transpiration (Wullschleger et al. 1998). On the physiological aspects, for example, by measuring the value of transpiration and productivity of plants we can know the growing condition, and therefore develop the growing season of the forest. With combination of leaf, branch, and whole plant measurement, estimates of whole-tree water use can contribute to the understanding of several properties of trees, including stomatal and boundary layer conductance, whole-tree hydraulic conductance, vapor and liquid phase water transport, sapwood water storage, and whole-plant vulnerability of water transport to cavitation

(Wullschleger et al. 1998). On the hydrological aspect, whole-tree water use estimating techniques help describe forest water balance and improve the ability of assessing forest water utilization in water resources management (Wullschleger et al. 1998).

Sources of uncertainty common to sap flow measurements include: probe length, necrosis of surrounding tissue, sap flux axial and azimuthal variations, scaling to tree or stand transpiration, cross-sectional area and sensor length (Clearwater et al. 1999; Oliveras and Llorens 2001; Smith and Allen 1996).

Scaling up

To determine the transpiration of forest stands, the best way is to measure the water use of every tree in a plot large enough to be free of edge effects (Wullschleger et al. 1998), although it is rarely achieved considering the cost and feasibility. And so, to estimated transpiration in larger spatial levels using sap slow measurement, one must rely on scaling up water use obtained from a limited number of sample trees.

The principle of up-scaling is to extrapolate water use of small scales to higher spatial level based on a scalar. Scalars are biometric parameters which can characterize the size of the sample trees (Čermák et al. 2004). Water use is first measured in a sample of trees that span the range of values for the scalar, then transpiration of the entire stand is determined using the relationships between whole-tree water use and the scalar (Wullschleger et al. 1998). These scalars are measured directly in the field, and are usually easy to survey at stand level (Wullschleger et al. 1998). Suitability of each of these scalars depend largely on site (Wullschleger et al. 1998), and some of the commonly used scalars include DBH, basal area, leaf area, sapwood area, and others like tree girth, timber volume, tree domain, and solar equivalent leaf area (Čermák et al. 2004; Wullschleger et al. 1998).

While scaling up the result of sap flow measurement to obtain the bottom-up estimates of catchment transpiration, three spatial levels are traversed: from within-tree to tree, from tree to stand, and from stand to catchment or landscape (Ford et al. 2007; Kume et al. 2009; Tsuruta et al. 2010). At each spatial scale level, variability within the level can lead to considerable errors (Tsuruta et al. 2010). Within individual, there is variability in sap flow distribution and in the area of water conducting sapwood. At stand and catchment-level, the variability is caused by species, size and age differences in the composition of forest. These heterogeneity can lead to potential error when extrapolate data obtained from a sample not big enough to represent the variability. Variability in the subject should be considered carefully while sampling, for it can affects accuracy of the results of extrapolation.

Variability of sapwood and sap flow

Sap flow amount in a tree is a function of the mean sap flux density and the sapwood cross-sectional area (Granier 1987). Therefore, there are two sources of variability which may lead to error in the result: one is the variability of cross-sectional area of sapwood, and the other one is the variability of sap flux density across the stem cross-section.

Sapwood variability

Sapwood is the physiologically active part of xylem in the tree stem that function as water storage or conduction (Adu-Bredu and Hagihara 1996). It is reported that differences in total sap flow amount within tree classes were much greater than flux density differences (Granier 1987), which indicates the importance of sapwood area.

The cross-sectional area of sapwood, or its thickness, is strongly correlated to diameter at breast height (DBH) of the tree (常建国 et al. 2009; 熊伟 et al. 2008; 藤山洋介 et al. 2005), and differ marked among tree crown classes (Granier 1987). The variability in sapwood thickness also increases with tree size (Čermák et al. 2004; Delzon et al. 2004). It is reported that in some stands, sapwood width inside tree stem can vary with directions because of stand characteristics, environmental conditions, or side branches (常建国 et al. 2009). Although they also report that this variation of the amount of sapwood and heartwood is more significant between individuals and stands than within a single tree. Thickness of sapwood at eastern and southern sides of stems is larger than that of western and northern sides, and in different stands, azimuthal variations in sapwood thickness are different (常建国 et al. 2009).

Another study shows that sap flow can increase without an increase of sap flow rate at the main part of sapwood, which means that the sap flow conducting sapwood area might be able to enlarge its cross-section area to supplement the lack of water flow in xylem (Yoshikawa et al. 2000).

Sap flow variability

It is often reported and well known that sap flux density can vary across sapwood (Čermák et al. 2004; Delzon et al. 2004; Ford et al. 2007; Granier 1987; Oishi et al. 2008; Tateishi et al. 2008; Wilson et al. 2001; 瀧澤英紀 et al. 1996). Variation of sap flux spatial distribution may be a result of hydraulic conductivity differences across sapwood caused by tracheid diameter and density variation (Tsuruta et al. 2010). Variations also change with environmental conditions like soil water and atmosphere (Tateishi et al. 2008).

Because one cannot know the variation within the tree stem, it is not easy to tell that if error is the result of sapwood variation or measurement, which is important in estimating whole-tree sap flow (Čermák et al. 2004). Spatial variation introduces significant error when estimating whole-tree water use, especially when using the needle-like probes of sap flow measurement, for they can represent only a small fraction of the whole stem cross-section (Čermák et al. 2004; Tateishi et al. 2008).

Whole-tree sap flow estimates made base on measurement of one single sensor, which ignores sap flow distribution, are vulnerable to errors (Cohen et al. 2008; Tateishi et al. 2008). Using multi-sensor, installed in radial or azimuthal directions to measure at several points in the sapwood cross-section, we can investigate spatial variation of sap slow distribution within the tree trunk. It has been reported that differences of single-point measurement relative to multi-point measurement can be up to 154% in daily water use estimations (Nadezhdina et al. 2007). Considering radial and azimuthal variations of sap flow carefully through multi-point sap flow measurement, the accuracy in tree and stand transpiration estimations can be improved.

Radial variability of sap flow

Sap flow radial variation is an important source of uncertainty in scaling process, however, often over-looked (Wullschleger and King 2000). It has been extensively studied and is wildly known that measuring the radial variation of sap flux is required (Oliveras and Llorens 2001; Tateishi et al. 2008). Radial variation of sap flow is marked and introduces significant error if ignored when estimating whole-tree transpiration (Lu et al. 2000; Tateishi et al. 2008). Assuming uniform sap flow at all depth in sapwood can cause 90–300% errors, and up to 47% overestimates in daily transpiration (Delzon et al. 2004; Nadezhdina et al. 2007).

Using more than one single sensor, one can assess radial patterns base on sap flux measured simultaneously at multiple depths across the sapwood (Oishi et al. 2008). Many have reported that in all sizes or ages, sap flux density is higher in the outer part and declines as depth into the sapwood increases (Delzon et al. 2004; Granier et al. 1994; Schiller et al. 2007; Tateishi et al. 2008; Tsuruta et al. 2010; Wullschleger and King 2000). Although there are also studies that report another type of sap flow radial distribution pattern that the highest flow is not in the outer most part of sapwood (Cohen et al. 2008; Nadezhdina et al. 2007; 瀧澤英紀 et al. 1996).

Radial pattern of sap flux can vary among different species. There are two kinds of water conducting structures: tracheae and tracheids. In most broadleaf tree species there are tracheae in xylem and they are called porous species, and those with only tracheids and no tracheae, including conifer and some of the broadleaf tree species, are called non-porous species. Porous species can be further divided into two kinds of ring-porous species and diffuse-porous; in ring-porous species caliber of tracheae in earlywood is larger than in latewood and big tracheae arrayed along the growth rings, on the other hand, in diffuse-porous species tracheae distribute evenly across the stem cross-section there is no difference in calibers between earlywood and latewood. In diffuse-porous species radial pattern is not obvious. It has been reported that there is no radial pattern in diffuse-porous species, and one can assume it being uniform across the sapwood cross-section (Oishi et al. 2008). On the other hand, in ring-porous species radial pattern can affect sap flux measurement significantly because of the annual ring related sharp decreases over small interval shift within sapwood (Čermák et al. 2004; Clearwater et al. 1999; Oishi et al. 2008), and there may be also flow beyond visually determined sapwood (Oishi et al. 2008).

Radial variation should be assessed in non-porous, diffuse-porous and ring-porous trees (Wullschleger and King 2000). In ring-porous individuals there can be larger variation and require more replicates to obtain the same accuracy compare to other species (Oishi et al. 2008).

Other than species, there are many other factors affecting sap flow radial distribution. Radial profile can change with time (Delzon et al. 2004),water stress (Lu et al. 2000; Nadezhdina et al. 2008; Nadezhdina et al. 2007), tree size or age (Delzon et al. 2004), transpiration of leaves which link to different annual rings (瀧澤英紀 et al. 1996), and aspects within a tree (Lu et al. 2000).

Azimuthal variability of sap flow

Compared to studies of sap flow radial variation, report about sap flow variation in azimuthal directions is few, and have been considered to be irrelevant in many previous studies (Granier 1987; Oliveras and Llorens 2001; Tateishi et al. 2008; Tsuruta et al. 2010). However, it has been proved that there is considerable azimuthal variation in sap flow among the four aspects (Lu et al. 2000; Oliveras and Llorens

2001; Tateishi et al. 2008; Tsuruta et al. 2010; 赵平 et al. 2005). Azimuthal variation is larger at the base of stem and tends to homogenize upwards along tree trunk (Delzon et al. 2004; Oliveras and Llorens 2001). It has the most impact in the outer layer of sapwood, because there is the largest fraction of cross-sectional area and often there the highest flow occur (Delzon et al. 2004; Tateishi et al. 2008). These characteristic of azimuthal variation can considerably affect the measurement of needle-like probes, so several sets of sensors around the stem at different direction are need to obtain enough accuracy.

Sources of error

In the process of estimating and extrapolating measurement of sap flow to transpiration of stands or catchments, each step of the process contains considerable amount of variation which can lead to error in the final result (Ford et al. 2007).

Many studies suggest the main source of error in estimating stand transpiration being the variability within individual trees, as a result of sap flux variation across the cross-section of sapwood (Čermák et al. 2004; Kume et al. 2009; Wullschleger and King 2000; Wullschleger et al. 1998). Radial profile of sap flow is reported to introduce bias ranged from 5% of young stands, to 47% of old stands (Delzon et al. 2004). On the other hand, scaling steps become important while estimating transpiration of catchments or landscapes, and plot-to-plot variability of stand density and sapwood area variation is the most influential which can cause the greatest scaling errors (Ford et al. 2007). The effect of among tree variability of the same species is suggested to be larger than radial pattern across stem cross-section and without incorporating radial profile variability deny scaly process caused 28% of total error (Ford et al. 2007).

Optimal sample size

The optimal sample size and potential error change in respond of environment condition such as topographic position and inner-annual rainfall variability (Kume et al. 2009). One report (Kume et al. 2009) studied about sample size and potential error in even-aged, single-species forest with high water availability. They compare the optimal sample size and potential error of say flux and sapwood area of the stand, and suggest that in most cases both optimal sample sizes and potential errors of stand sap flux are larger than that of stand sapwood area. In even-aged single-species catchments a sample size of over 20 trees is necessary to capture tree-to-tree variability (Ford et al. 2007). In mixed-species forest it is recommended that at least 6 trees of each species are needed for random variation (Oishi et al. 2008).

The goal of this study

In this study we investigated spatial distribution variability of sap flow among the cross-section of sapwood, tried to estimate transpiration of individual tree, and examined the effect of sap flow variation to the result in scaling process. To reach this goal, 3 subjects were set to help clarify the problem:1) How sap flow varied across sapwood in radial and azimuthal directions; 2) is there seasonal change in radial and azimuthal variations; 3) do these variations have any impact on estimating transpiration.

To answer these 3 questions, the methodology of sap flow measurement was applied to the trees in the plantation in Sitou in central Taiwan, using thermal dissipating technique which was proposed in 1987 by Granier. First, through multi-point sap flow measurement at different part of sapwood, radial and azimuthal profiles of sap flux density can be established. The standard deviation and coefficient of variation of sap flow at different parts of sapwood is then checked for seasonal changes, and whole transpiration is estimated based on individual radial or azimuthal profiles. Finally, we examined the accuracy of these transpiration estimates to see if the spatial distribution variation of sap flow had any impact on estimating whole tree transpiration through sap flow measurement method.

Chapter 2

Material & Method

Site

Sitou is located in the county of Nantou in central Taiwan (Fig. 1), surrounded by mountains in three sides. The sea level of major area is 800–2000 m, and the highest mountain is Lingtou Mountain in the south with the altitude of 2,025 m. It extends to north and meets Fenghuang Mountain Range, forming the east boundary. Also Lingtou Mountain extends west to Nesupi Mountain Range, and forms the south and west boundaries. The streams flow between the mountain range then flow out through the exit in the north. The Fenghuang Mountain is composed of thick sandstone. The thick sandstone on the precipice of the mountain is the essential factor for fallen of huge rocks. According to the data from Sitou observation station, the average temperature of the month of Sitou is 11.0–20.8℃, and the average annual temperature is 16.6℃. The average annual rainfall is 2635.18 mm.

Experiment Plot and sample size

The measurement took place in a Japanese cedar plantation near the old meteorological tower in the third compartment of Sitou NTU Experiment Forest (Fig. 1). The experiment plot was 20×20m, and divided into 4 subplots sized 10×10m. There were 26 trees inside the plot numbered from one to 26, in which tree number 6 was dead and we excluded it from all experiment.

Biometric parameters measurement

Some biometric parameters were investigated. DBH and height of all trees in the plot were measured. Samples of wood on both east and west side of tree trunk were taken at breast height by increment borer, and the samples were brought back to dried and measured for thickness of sapwood.

Sap flow measurement

For studying radial and azimuthal variation within sapwood cross-section, a total of 60 sets Granier type sensors were installed on 19 trees in the experiment plot. Based on the installing location, sensor sets were divided into 5 different kinds, each placed at a different part on the sapwood cross-section in radial or azimuthal directions (Table 1).

Three groups of trees (DBH-S, DBH-M, and DBH-L) were selected according to DBH distribution of all trees in the plot to represent three levels of tree size. As lined up in Table 2, on the two DBH-S trees, 4 sets sensors were installed at 4 aspects of North, South, East and West, at the depth of 0–2 cm below surface of sapwood. In DBH-M and DBH-L, which has 3 trees respectively, 4 sets of sensors were installed on the 4 aspects at 0–2 cm deep, and one set of sensor at 2–4 cm deep on a randomly selected aspect, roughly 5cm apart from the 0–2 cm deep sensors. Additional to these 8 trees, another 11 trees of all levels of DBH were selected and 2 sets of sensors were installed on 2 aspects of East and West at 0–20 cm deep.

The sensor sets were handmade, each set includes a pair of thermocouple probes, one called heater sensor which contains a heating device and the other one with no heating device is called receive sensor. To install the sensors, part of the tree bark was removed to reveal the sapwood underneath. Then, sensor sets were inserted into the sapwood at breast height, heat sensor placed about 15 cm vertically above the receive sensor. The heater sensor is given 0.2W heating energy by electricity, and the deference between the two probes is measured and recorded. The sensor sets were connected to a data logger, which records the temperature differences every 30 seconds and calculates mean value every 30 minutes. After the installation completed, the sensor sets were covered by aluminum foil trays fixed on the tree and sealed with silicone on top, right and left sides for protection against rain. The measuring period is from 2010 July 21 to 2011 January 31.

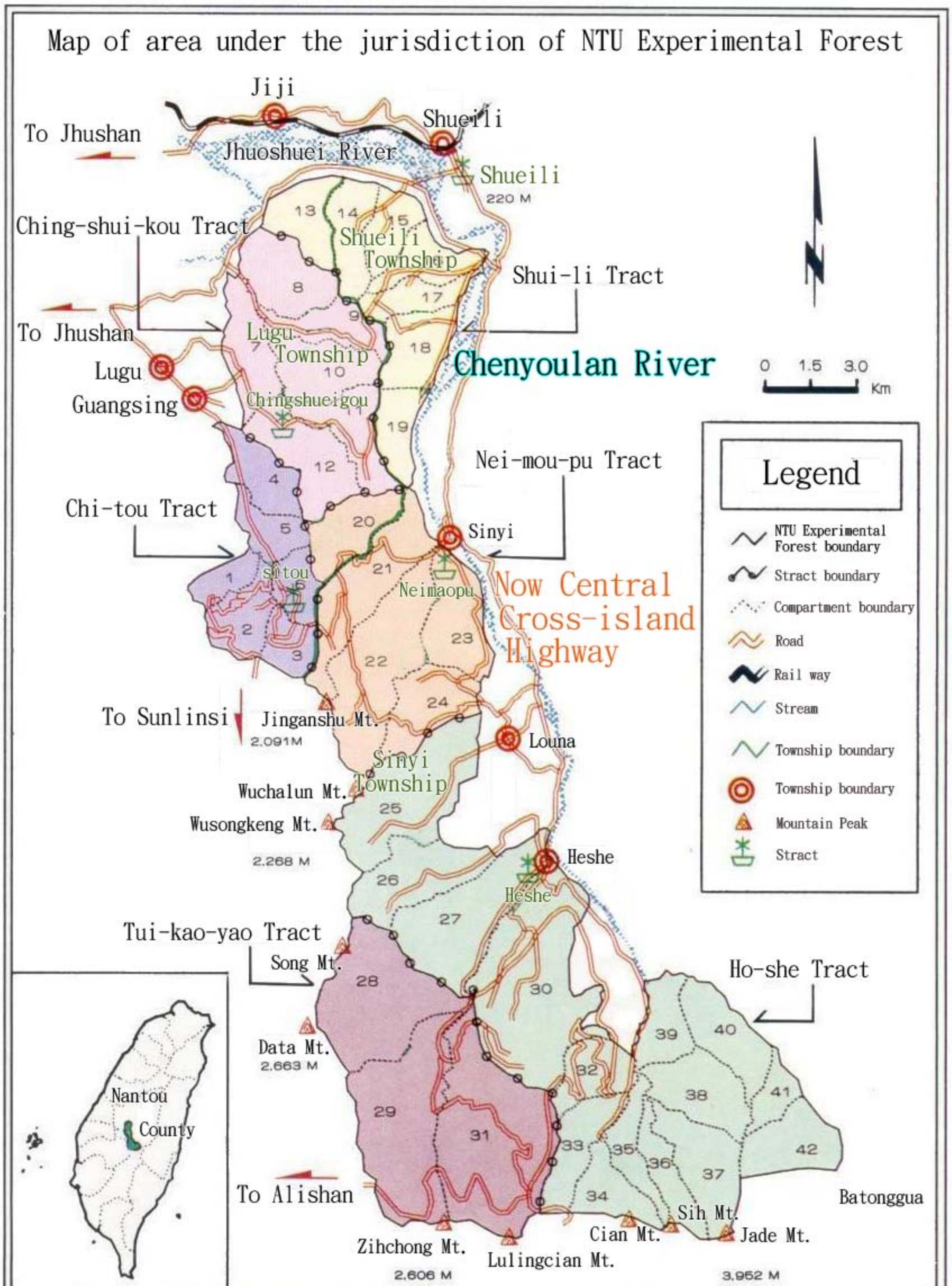
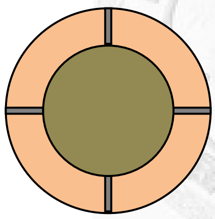
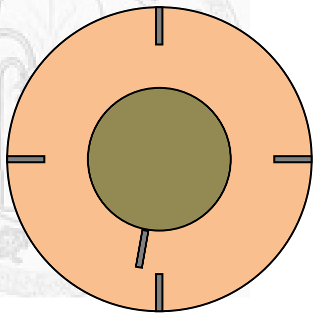
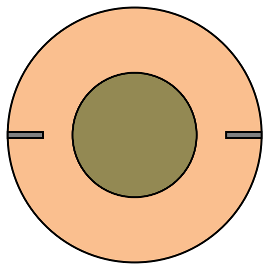


Fig. 1 The NTU Experiment Forest Map.

Table 1 The location of sensors in radial and azimuthal directions.

Sensor name	Direction	Depth
N	North	0–2 cm
S	South	0–2 cm
E	East	0–2 cm
W	West	0–2 cm
D	Random	2–4 cm

Table 2 DBH level groups and sensor arrangements of the sample trees.

Group	DBH-S	DBH-M	DBH-L	unassigned
sapwood, heartwood, sensor set				
DBH	small	medium	large	all levels
Sample size	2	3	3	11
Sensors installed	N, S, E, W	N, S, E, W, D		E, W
Directions	all 4 aspects	all 4 aspects		East and West
Depths	0–2 cm	0–2 cm, 2–4 cm		0–2 cm
Tree number	11, 17	2, 7, 25	5, 16, 20	1, 3, 4, 9, 12, 13, 14, 18, 23, 24, 26

Data processing

The raw data of temperature difference between the two probes of sensor collected by data logger was calculated according to the function Granier (1987) had proposed.

Sap flux density can be described by the equation of

$$u = 119 \times 10^{-6} \mathrm{K}^{1.231}$$

and

$$K = \frac{T_M - T}{T - T_x}$$

where u is sap flux density, T_M is the original temperature of the heated sensor when $u = 0$, T is the temperature of the heated sensor when $u > 0$, T_x is the comparative temperature of non-heated sensor. K can also be described as:

$$K = \frac{\Delta T_M - \Delta T}{\Delta T}$$

where ΔT_M is the temperature differences between the two probes when $u = 0$, and ΔT when $u > 0$.

Calculated sap flux density of each sensor was then plotted for better view of the data. Those clearly abnormal values, which may have been caused by sensor damage or power supply problems, were considered as measurement errors and were removed from the data. After these preparations, sap flow data can then be used for analysis.

Chapter 3

Results

Sample trees composition

The biometric parameters investigated of the sample trees are listed in Table 3, and relationships between DBH, height and sapwood thickness are showed in . Between DBH and sapwood thickness, and also between DBH and sapwood area the correlation is significant ($p<0.025$), and they are positively related. The correlation is not significant, but there seems to have a positive relationship between tree height and sapwood depth, however, no relationship between DBH and tree height can be seen in among these trees.

Sap flow measurement

Part of the sap flow measurement data is showed in Fig. 3, which are the sap flux speed at 0–2 cm on four aspects and one at 2–4 cm inside tree number 17, 2 and 20 during a period of 8 days in summer. It is obvious that there are similar patterns among the three trees and between different aspects and depths.

Table 3 The biometric parameters of all trees in the experiment plot.

Tree no.	DBH (cm)	Height (m)	Sapwood depth East side (mm)	Sapwood depth West side (mm)	Sapwood depth Average (cm)	Sapwood Area (cm^2)
1	32.6	31.2	28.00	31.21	2.96	275.67
2	38.4	33.1	36.79	33.77	3.53	386.51
3	35.3	36	46.00	47.40	4.67	449.38
4	42.9	26	42.82	45.18	4.40	532.19
5	51	27	41.71	40.13	4.09	603.02
7	41.2	24	36.97	39.94	3.85	451.28
8	35.7	27	34.75	19.78	2.73	282.44
9	32.8	25	30.00	47.00	3.00	280.86
10	34.5	26	34.70	41.00	3.79	365.23
11	25.1	25	35.00	23.53	2.35	168.15
12	36.7	27	35.05	34.01	3.45	360.66
13	30.7	19	29.95	32.00	3.10	268.60
14	43.6	22	37.77	30.50	3.41	430.95
15	31.3	20	35.00	37.00	3.60	313.28
16	51	21	29.48	30.77	3.01	454.16
17	27.6	21	28.00	16.24	2.21	176.43
18	31.1	21	30.37	24.42	2.74	244.08
19	30.4	26	32.12	30.95	3.15	269.93
20	55	27.5	40.63	34.60	3.76	605.49
21	30	26	19.42	33.03	2.62	225.56
22	34.9	19	40.28	41.00	4.06	393.70
23	46.3	20	30.12	45.52	3.78	505.18
24	33.5	23	39.00	17.96	2.85	274.25
25	40.5	24	36.83	38.03	3.74	432.22
26	42.5	22	27.35	30.00	2.87	357.03

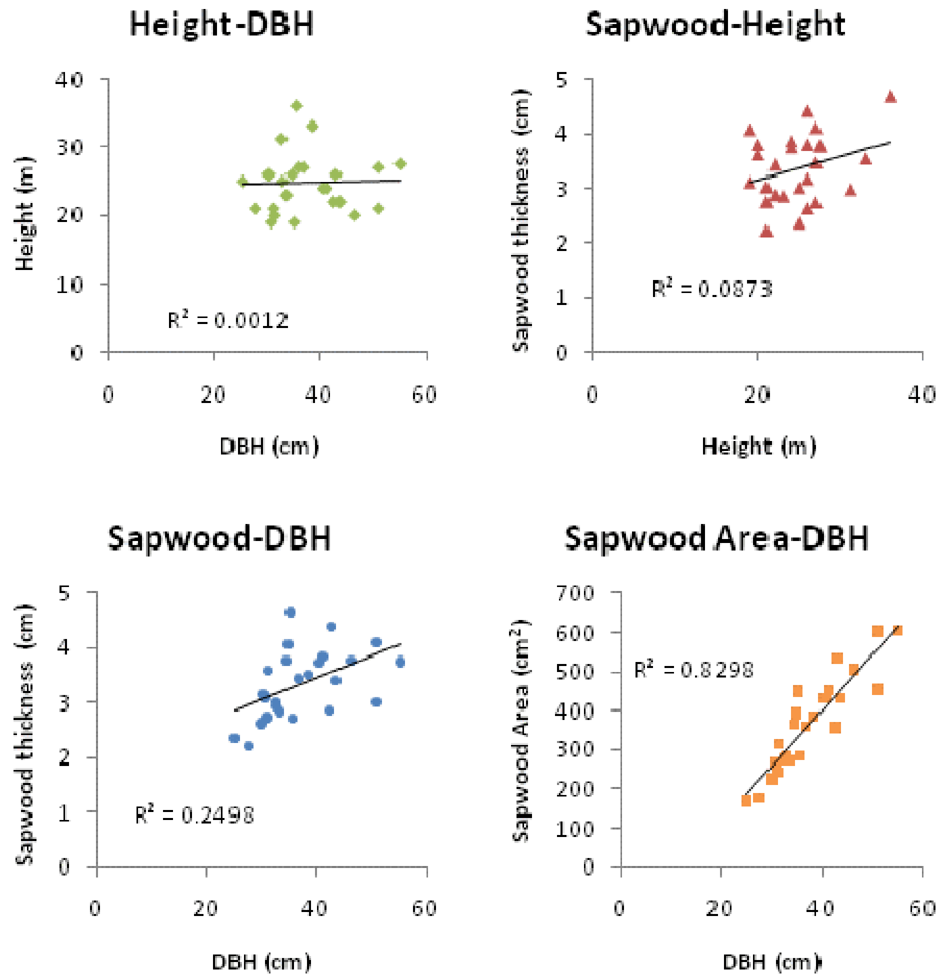


Fig. 2 The relationships between the three biometric parameters of DBH, tree height, and sapwood thickness. There is significant correlation between DBH and sapwood thickness, and also between DBH and sapwood area.

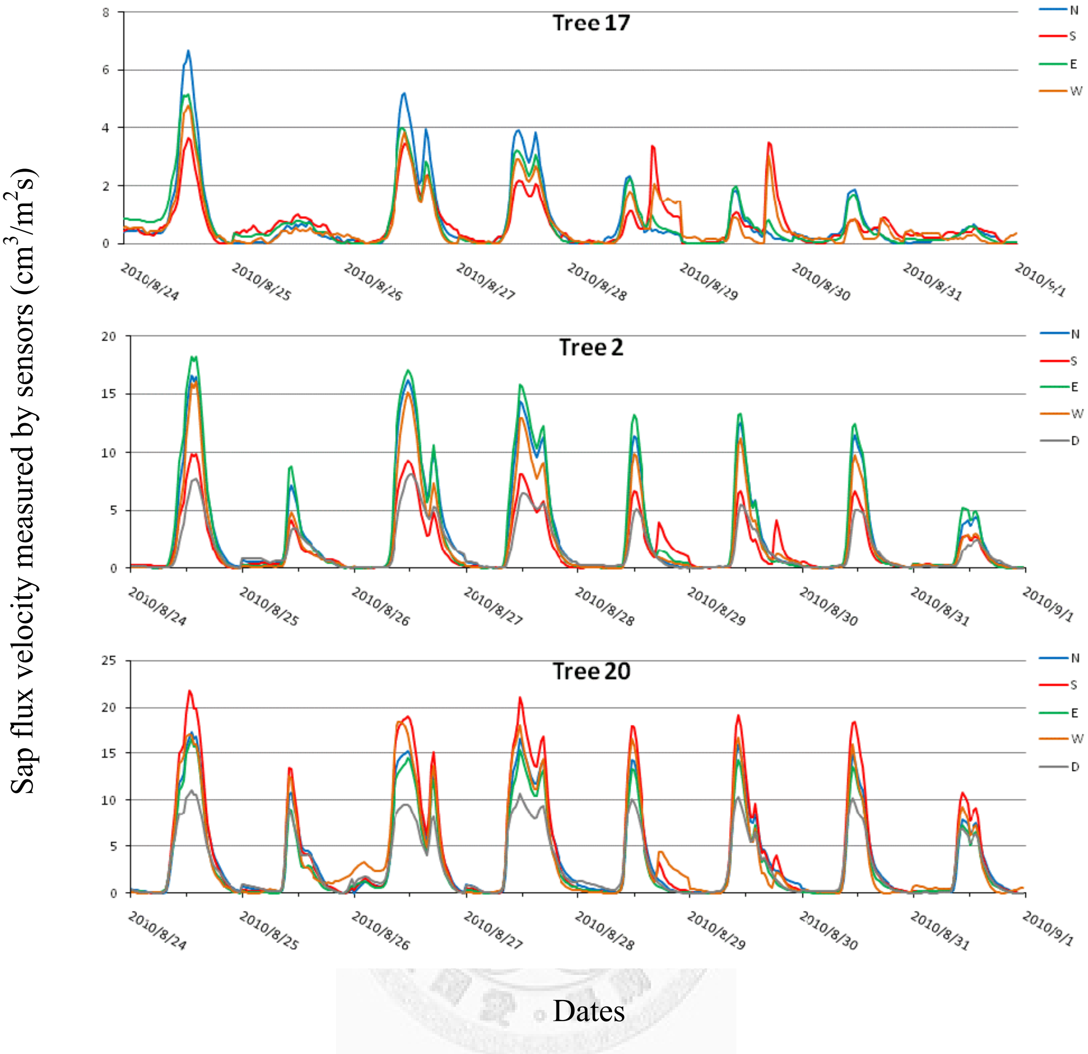


Fig. 3 A sample of sap flux density diurnal patterns during a period of 8 days in summer (2010/8/24–2010/9/1), measured in 3 sample trees from each of the 3 DBH level groups. Sap flux data measured by sensors installed in the north (sensor N), south (sensor S), east (sensor E), and west side of the trunk (sensor W) are showed in blue, red, green, and orange lines respectively. Sap flux data measured by sensors at the depth of 2–4 cm (sensor D) are showed in gray lines.

Relationships between sap flux and biometric parameters

The correlations are significant both between DBH and sap flux ($p< 0.025$), and between sapwood area and sap flux ($p<0.025$) (Fig. 4). There are positive relationships between sap flux and both of the biometric parameters. There is no significant correlation between sap flux and tree height, and sapwood thickness. These indicated that larger-sized tree can have higher sap flux density.

Radial variation

Through comparing sap flux in outer and inner layers of sapwood xylem, the radial profile can be established for each of the trees in group DBH-M and DBH-L, which have the sensor D installed in 2–4 cm deep in sapwood. To compare with sap flux density at the depth of 2–4 cm (Fd_D), which is measured at randomly selected aspects, sap flux density in the outer part of sapwood is represented by the average of sap flux density in the 0–2 cm depth on the 4 aspects (Fd_{avg}) which

$$Fd_{avg} = \frac{(Fd_N + Fd_S + Fd_E + Fd_W)}{4}$$

and Fd_N, Fd_S, Fd_E, Fd_W are sap flux density measured on the north, south, east, and west side respectively. Fd_D is compared with Fd_{avg} for the relation and correlation between them, and the ratio of outer sap flux to inner sap flux.

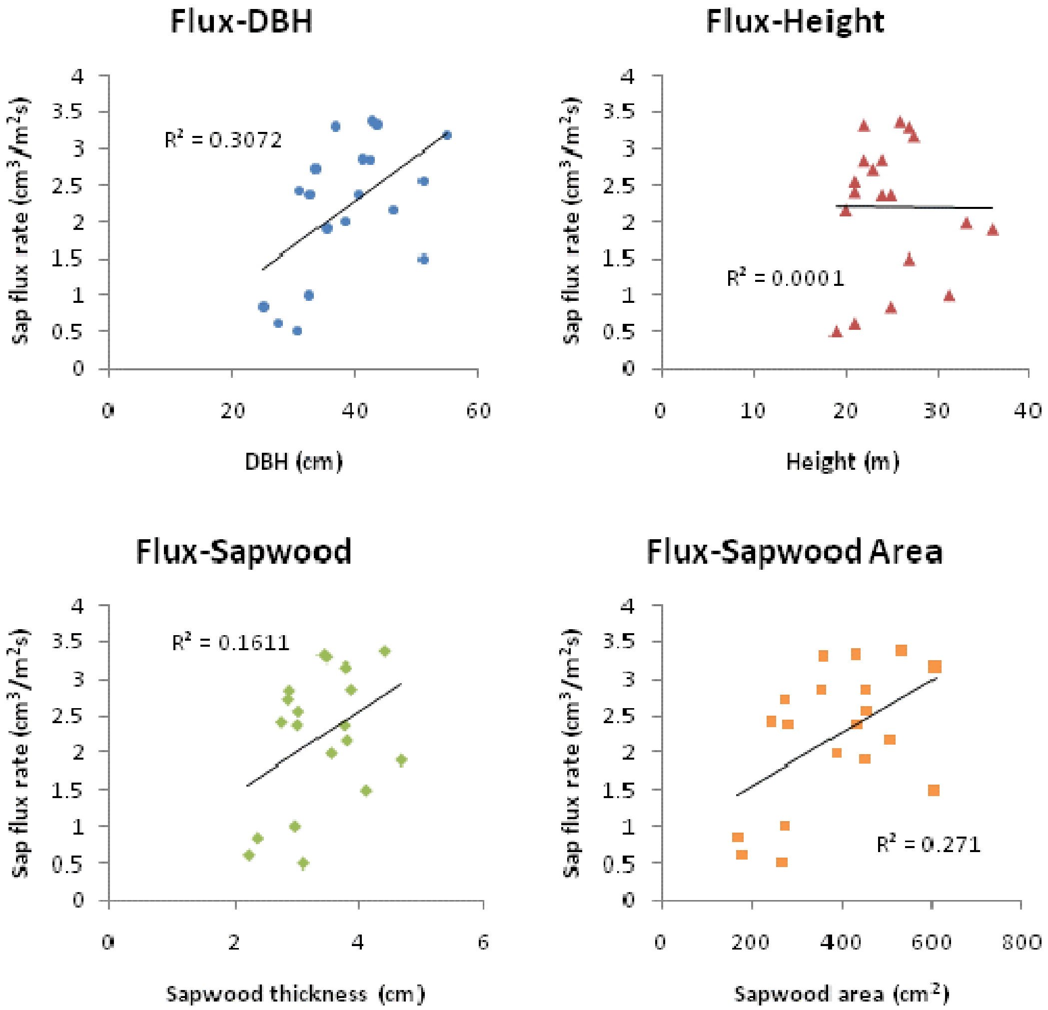


Fig. 4 The relations of biometric parameters to sap flux density of every sample trees. There are significant correlations between sap flux and both DBH and sapwood area.

The result shows that there are clearly strong correlations between the sap flux at 0–2 cm and at 2–4 cm in all of the 6 trees of group DBH-M and DBH-L (Fig. 5 and Fig. 6). Among all sample trees Fd_{avg} is always larger than Fd_D. The ratio is around 0.5 regardless of tree size, which means that at the depth of 2–4 cm in the sapwood, the sap flux density is only about half of that of the sap flux in the xylem just below the surface.

Many prior studies of radial profile of sap flow across sapwood have reported similar result that flux density decrease deeper into the sapwood (Delzon et al. 2004; Tateishi et al. 2008; Tsuruta et al. 2010; 鶴田健二 et al. 2008), and a strong correlation and linear relationship between different depths (Delzon et al. 2004; Lu et al. 2000; Oishi et al. 2008; Tateishi et al. 2008; Tsuruta et al. 2010).

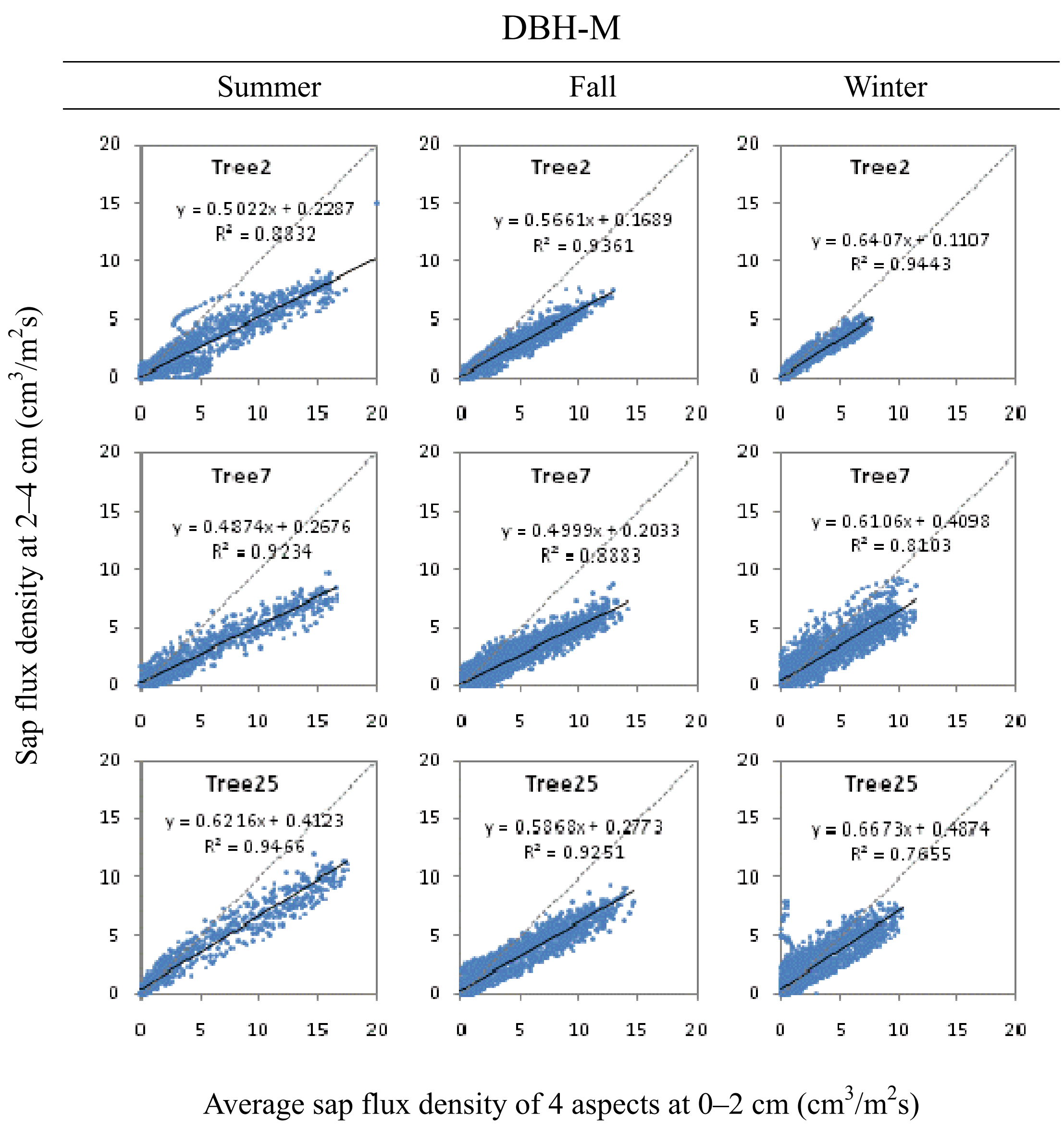


Fig. 5 The linear relationships between sap flux in outer and inner layer of sapwood xylem in group DBH-M trees. The 1：1 line is showed as ....

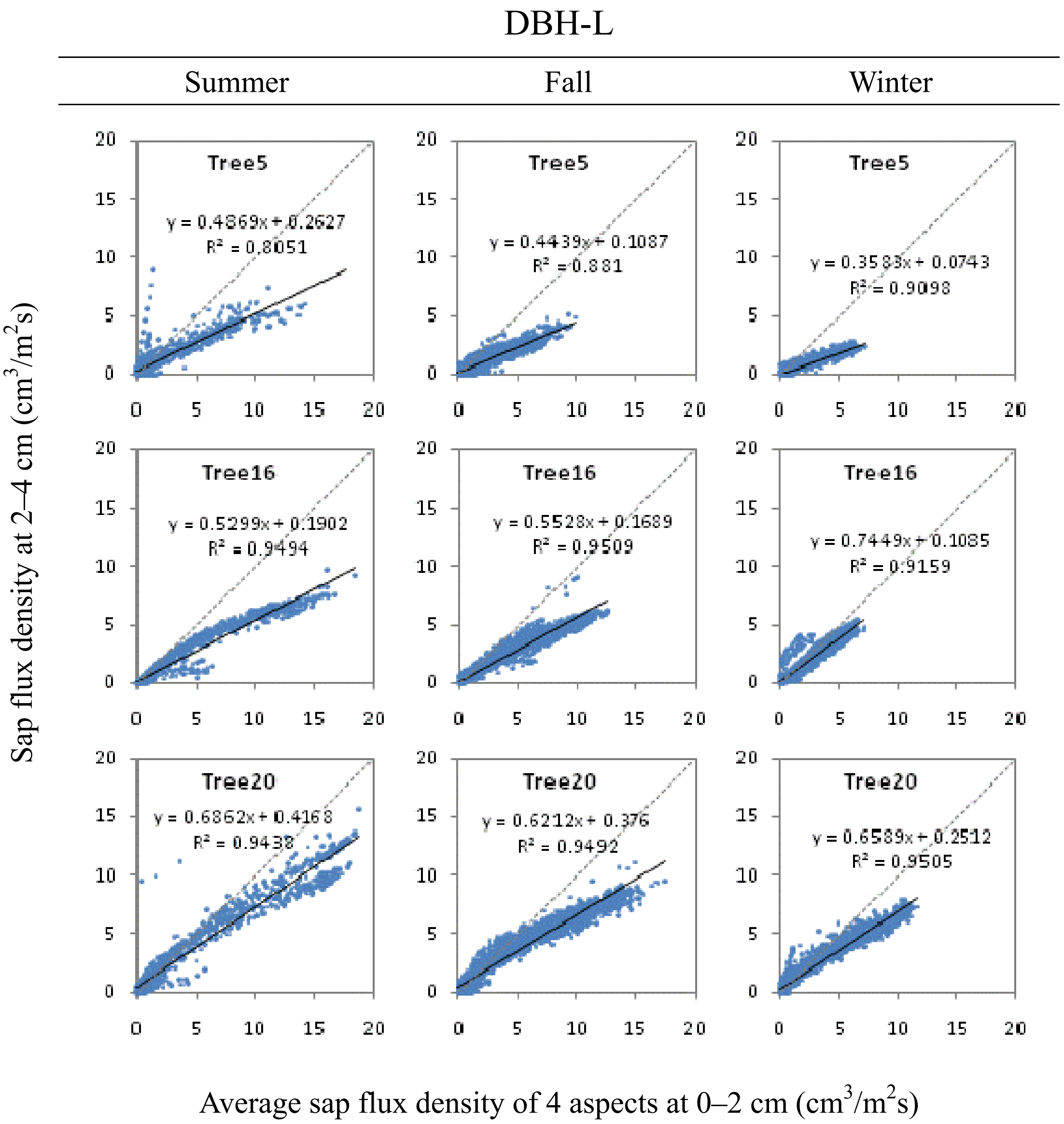


Fig. 6 The linear relationships between sap flux in outer and inner layer of sapwood xylem in group DBH-L trees. The 1：1 line is showed as ....

Azimuthal variation

All trees in group DBH-S, DBH-M, and DBH-L are investigated for sap flux density correlations between different azimuthal aspects (Fig. 7, Fig. 8 and Fig. 9). Among all trees sap flux density on different aspects are positively related to each other, but correlations between them depends. In DBH-M, and DBH-L there are relatively clear signs of linear relationships between aspects, and value of R^2 in most trees are around 0.7–0.9. However, in tree 11 and tree 17 in group DBH-S, R^2 are much smaller, which can even goes down to <0.5. The reason why these two trees have such low R^2 value is probably because tree 11 and 17 are both small in DBH and also in sap flux rate, so even minor variations can contribute relatively large errors to correlation.

Differences of sap flux density between different aspects are significant in some and not significant in others. There is not one particular aspect that always has the highest sap flux density. In most trees the ratio of one aspect to another seems constant over the 3 seasons, while, few samples (e.g., tree 11 and tree 17) suggests that relations may change over time.

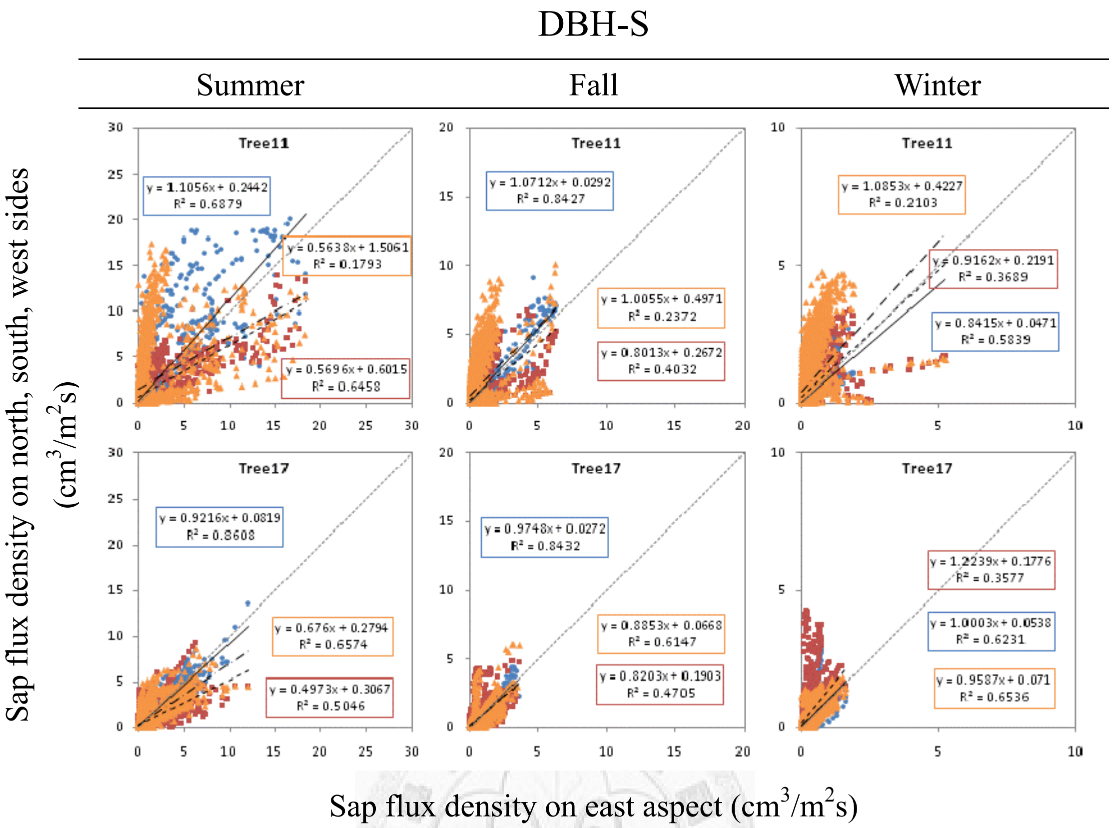


Fig. 7 The linear relationships of sap flux density between different aspects in group DBH-S trees. Sap flux density on north (●), south (■), west (▲) sides (cm^3/m^2s) The linear functions and R^2 of regression line are showed with frames of the same color with data points. The 1：1 line is showed as ....

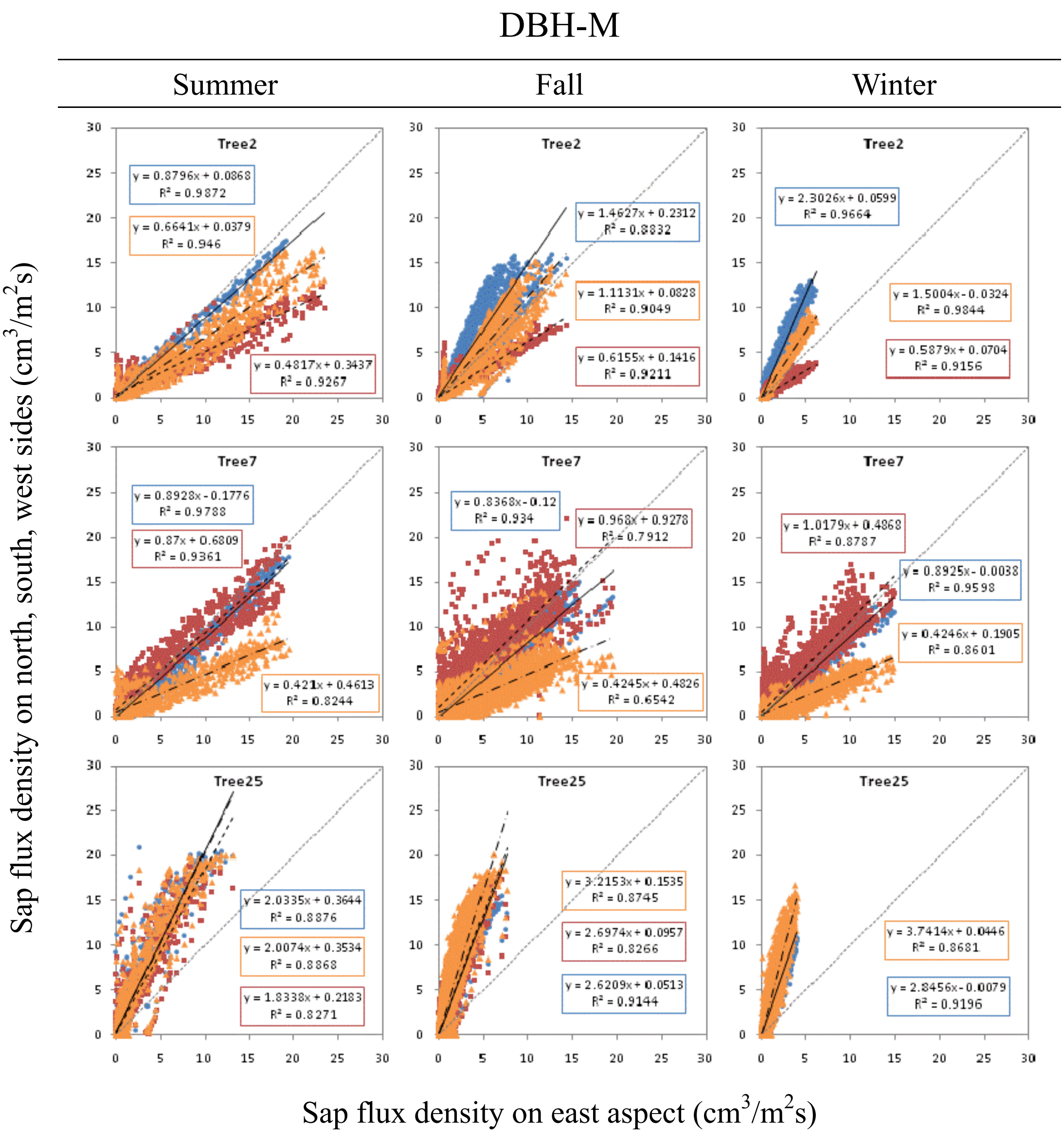


Fig. 8 The linear relationships of sap flux density between different aspects in group DBH-M trees. Sap flux density on north (●), south (■), west (▲) sides (cm^3/m^2s) The linear functions and R^2 of regression line are showed with frames of the same color with data points. The 1：1 line is showed as ....

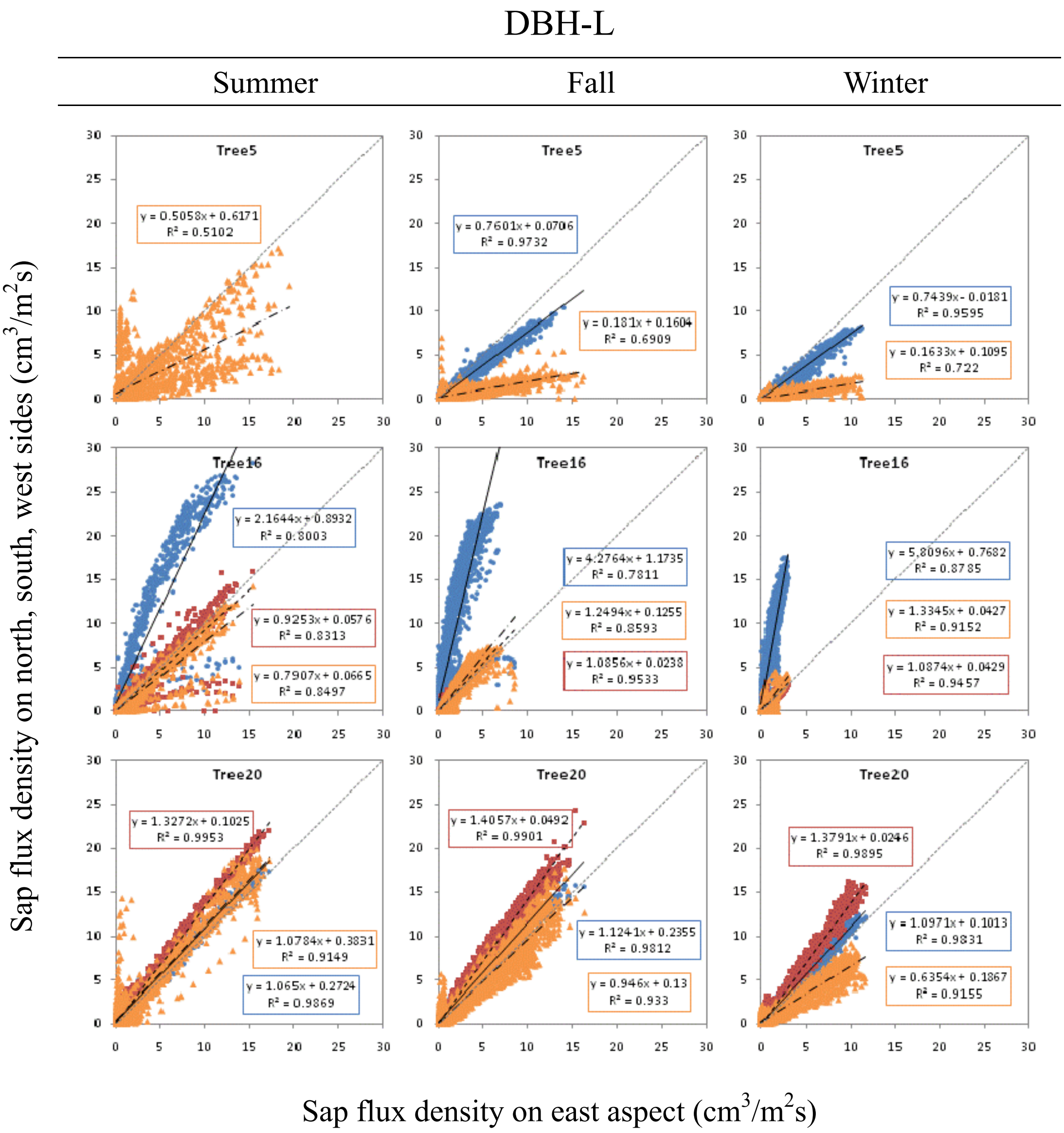


Fig. 9 The linear relationships of sap flux density between different aspects in group DBH-L trees. Sap flux density on north (●), south (■), west (▲) sides (cm^3/m^2s) The linear functions and R^2 of regression line are showed with frames of the same color with data points. The 1：1 line is showed as .... The lack of sap flux data on north and south aspects of tree 5 is the result of sensor damage.

Seasonal changes of sap flux density variations

To better understand whether the variations between different aspects change temporally, standard deviation (SD) and coefficient of variation (CV) are calculated. To eliminate the effect of the small values of sap flux density at nighttime, only sap flux data recorded during daytime from 10:00 to 17:00 are used. Standard deviation of all sample trees, except tree 12, appears to have a trend of decrease with time (Fig. 10). This seems that azimuthal variation decrease as season shifts from summer to winter. On the other hand, in most trees coefficient of variation remains constant throughout the measuring period, with only in few trees there are trends of very slightly increase or decrease can be seen (Fig. 11). Comparing standard deviation and coefficient of variation, the smaller average sap flux rate during wintertime might be the explanation of the decreasing trends of standard deviation, and probably caused the value of coefficient of variation to increase slightly.

The averages of standard deviation and coefficient of variation for each tree are also calculated to examine their relationships with biometric parameters. There is a significant correlation between standard deviation and DBH ($p < 0.025$), but not tree height, sapwood thickness and sapwood area. It appears that SD is positively related to DBH (Fig. 12). On the other hand, correlation is not significant between coefficient of variation and any of these biometric parameters ($p = 0.08$), although it seems to be a negative relationship with sapwood thickness (Fig. 13).

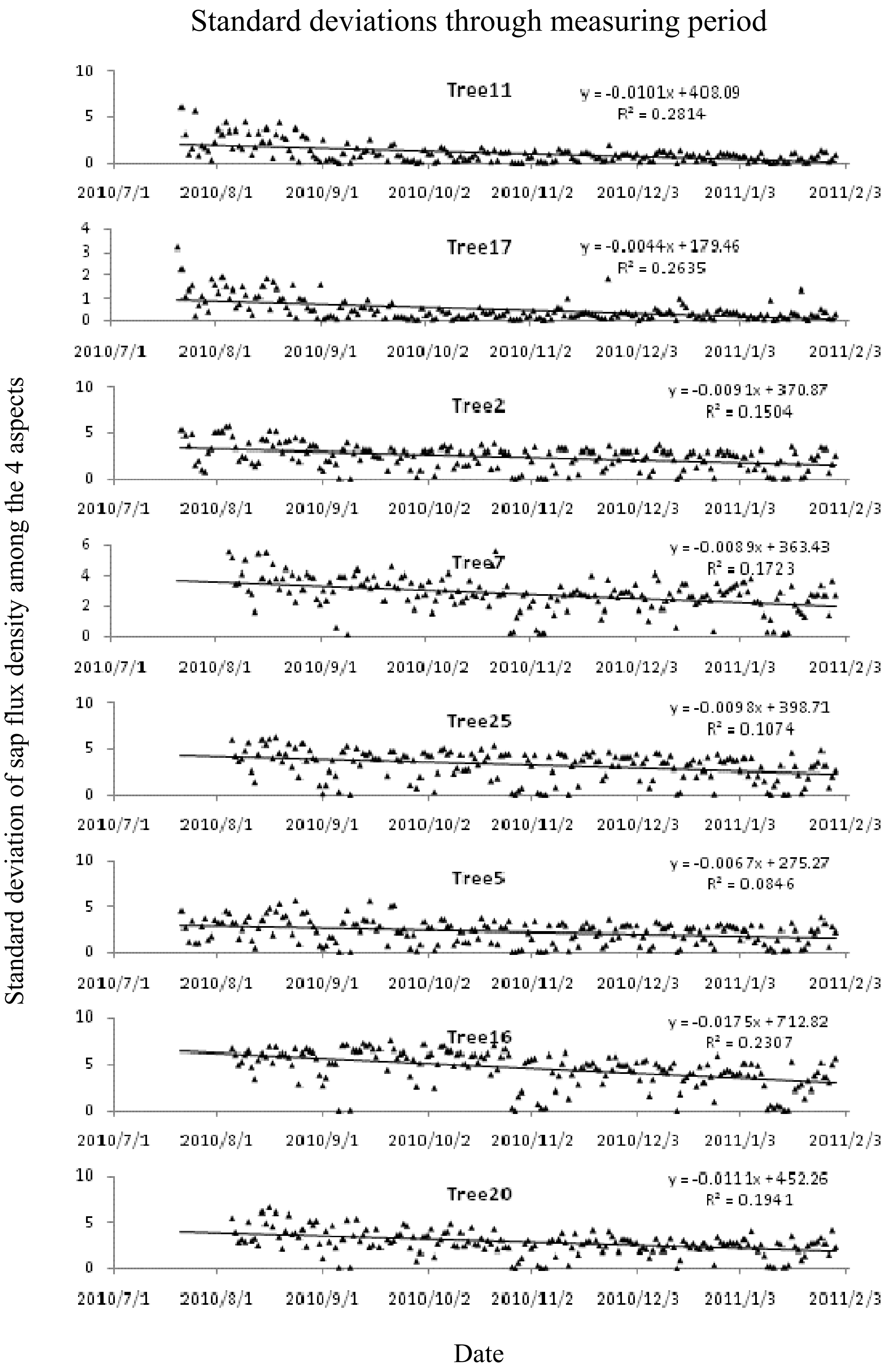


Fig. 10 The seasonal changes of standard deviation (▲) of sap flux density among the 4 different aspects.

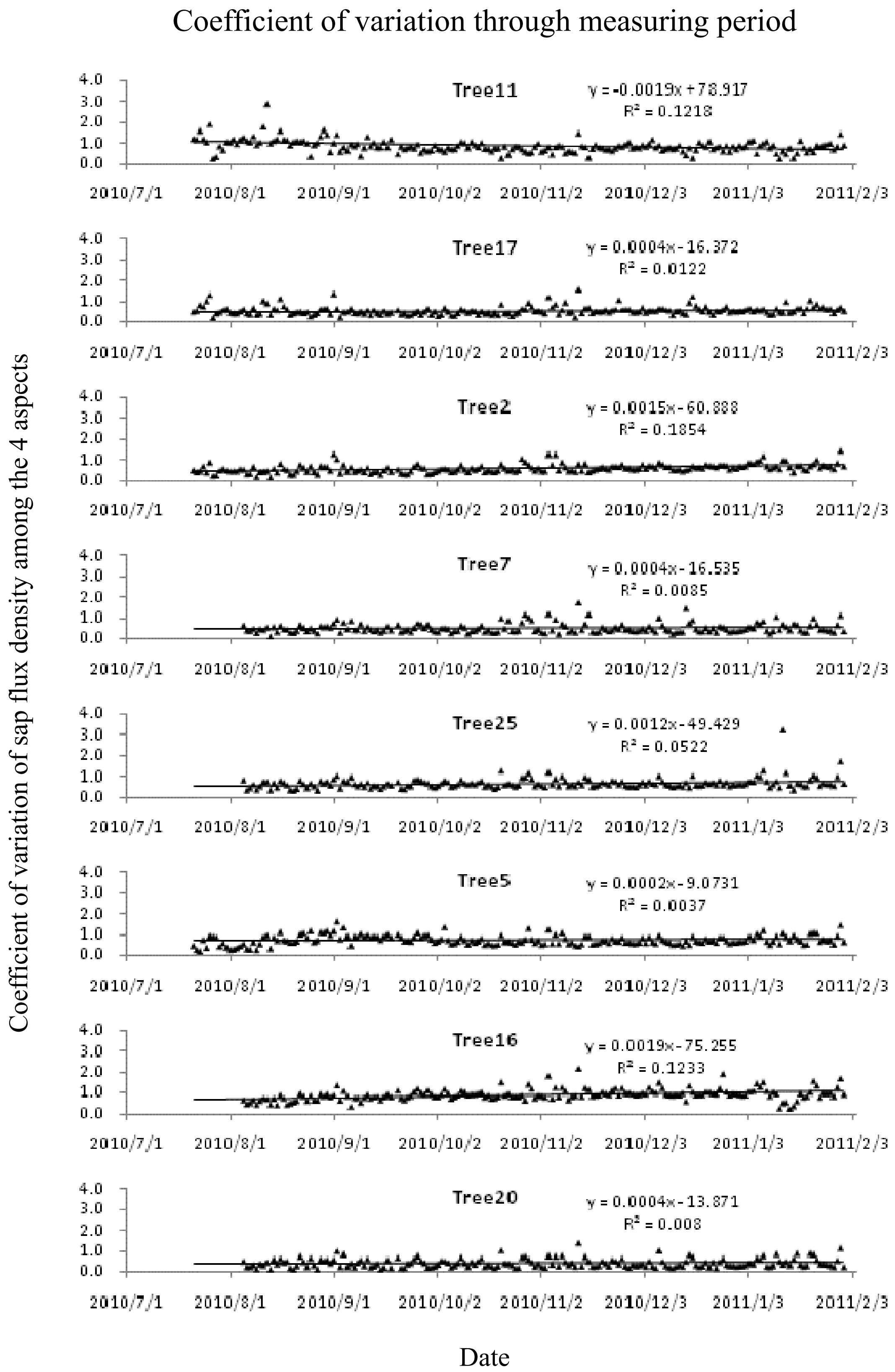


Fig. 11 The seasonal changes of coefficient of variation (▲) of sap flux density among the 4 different aspects.

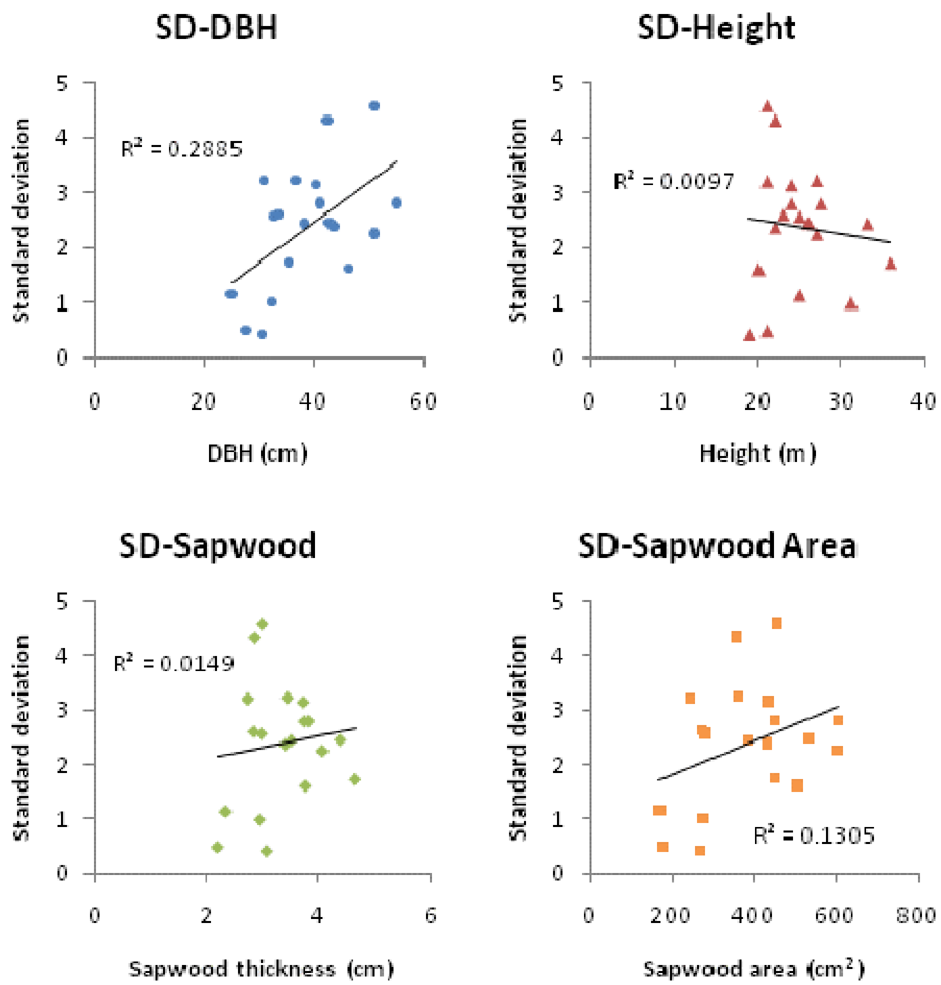


Fig. 12 The relationships between the standard deviation of sap flux density among the 4 aspects and the biometric parameters of DBH, tree height, sapwood thickness and sapwood area.

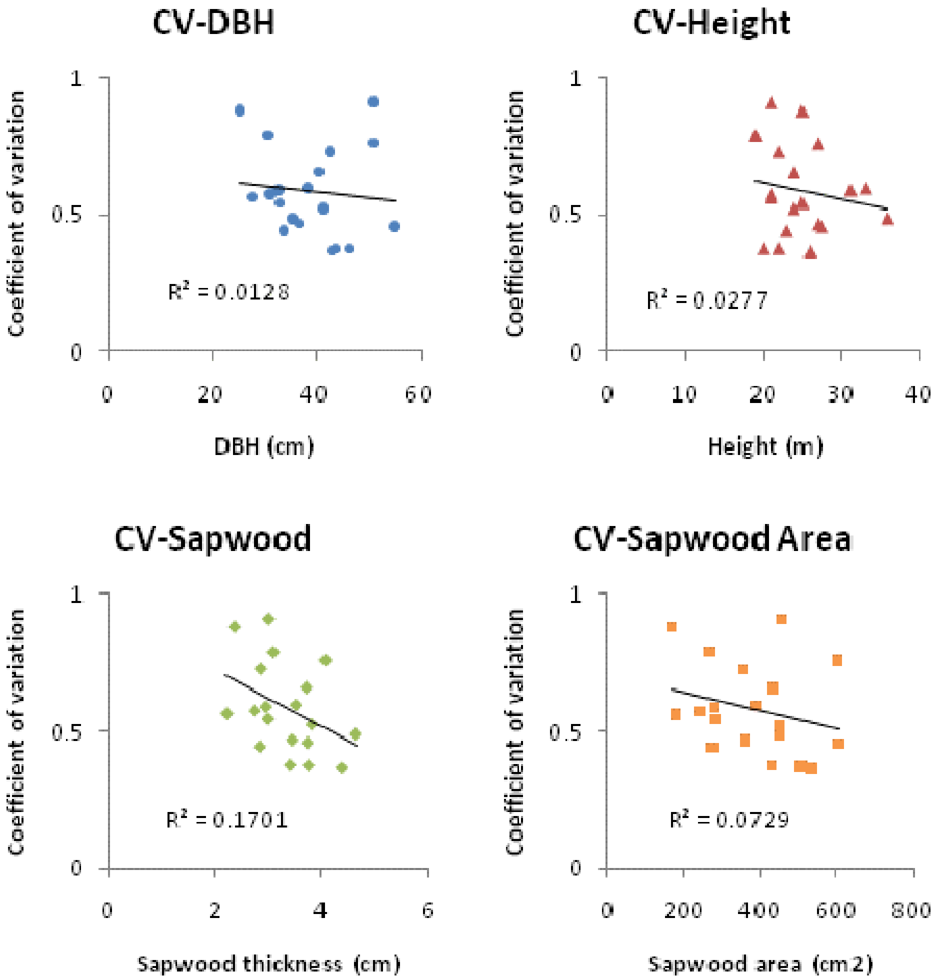


Fig. 13 The relationships between the coefficient of variation of sap flux density among the 4 aspects and the biometric parameters of DBH, tree height, sapwood thickness and sapwood area.

Seasonal changes of variation affecting transpiration estimates

With the knowledge of radial and azimuthal profiles of sap flux density across sapwood cross-section, whole tree transpiration can be estimated. And to see if the seasonal changes of radial and azimuthal variation of sap flux density had any effect on estimating single tree transpiration, first the accurate value must be acquired.

Single tree transpiration

With the knowledge of radial and azimuthal profiles of sap flux density across sapwood cross-section, whole tree transpiration can be estimated. And to see if the seasonal changes of radial and azimuthal variation of sap flux density had any effect on estimating single tree transpiration, first the accurate value must be acquired.

$$Q = \left(Fd_{avg} \times A_{0-2}\right) + \left(Fd_{D} \times A_{2-4}\right)$$

where A_{0-2} is the sapwood cross-section area of the outer ring of 0–2 cm depth, and A_{2-4} is that of the inner ring of 2–4 cm (Fig. 14). A_{0-2} and A_{2-4} are calculated as

$$A_{0-2} = \pi\left[\left(\frac{DBH}{2}\right)^2 - \left(\frac{DBH}{2} - 2\right)^2\right]$$

$$A_{2-4} = \pi\left[\left(\frac{DBH}{2} - 2\right)^2 - \left(\frac{DBH}{2} - 4\right)^2\right]$$

In the case when the sapwood thickness is less than 4 cm (Fig. 15), because sap flux density data measured by of sap flow measurement reflects average sap flux density over the whole metal part of the sensor probes, which is 2 cm long, A_{2-4}

does not change even if it reaches heartwood. Because Q is calculated directly from the accurate values of sap flux density measured in the field, it is assumed to be the best estimate value of individual transpiration.

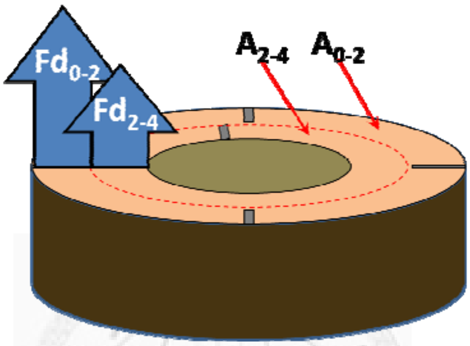


Fig. 14 The inner and outer ring of sapwood cross-section area, and sap flux density.

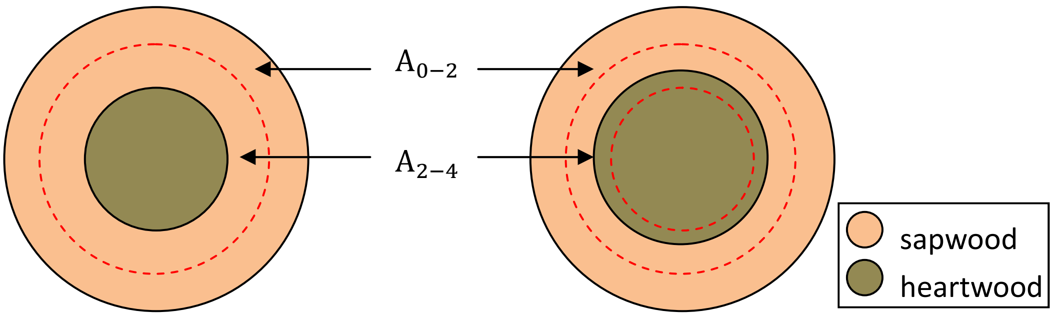


Fig. 15 The inner ring of xylem at 2–4 cm deep in the sapwood is showed as the transparent ring-shaped area bounded by - - - . It does not matter if this area includes heartwood or not.

Transpiration estimates

Transpiration estimates based on the linear correlations between sap flux density at different depth and aspects can be made and compared to the accurate value of individual transpiration which calculated earlier. The idea is that if the variation of sap flow distribution within the tree trunk does not change with season, the ratio between sap flux density measured at different point in sapwood should be constant. Then we should be able to apply the sap flux density distribution profile obtained in summer to estimate individual tree transpiration in other seasons.

Using only the sap flow data collected in the summer, ratios of inner to outer layers of xylem, and ratios between different aspects are defined as the slope of the regression lines, which is calculated for each tree. These ratios are then used to estimate individual transpiration for each tree in other season, fall and winter. Comparing these estimates to the accurate value of individual transpiration in fall and winter, the effect of seasonal charges of sap flux variation can be examined.

To simplify the question, radial and azimuthal variation is considered separately, with transpiration estimates based on sap flux radial profile, the fixed radial ratio estimates (Q_r), consider only radial variation, and transpiration estimates based on sap flux azimuthal profile, the fixed azimuthal ratio estimates (Q_a), consider only azimuthal venation. Q_r and Q_a are calculated according to the equations of:

$$Q_r = \left(Fd_{avg} \times A_{0-2}\right) + \left(Fd_{avg} \times R_D \times A_{2-4}\right)$$

and

$$Q_a = \left(Fd_E \times R_{avg} \times A_{0-2}\right) + (Fd_D \times A_{2-4})$$

$$R_{avg} = \frac{(R_N + R_S + R_E + R_W)}{4}$$

where R_D is the slope of the Fd_{avg} to Fd_D regression line, and R_N, R_S, R_E, R_W are the slopes of the regression lines of respectively Fd_N, Fd_S, Fd_E, Fd_W to Fd_E in summer.

After calculating Q_r and Q_a was compared with Q to see if there is any season change in relations of sap flux density in different parts on the sapwood cross-section.

Figure shows half hourly Q_r (Fig. 16) and Q_a (Fig. 17) with the best estimate values of transpiration on the x axis and estimates on the y axis. Q_r of all 6 trees are highly comparative to Q. The seasonal total transpiration and their estimates (Fig. 18 and Fig. 19) are also calculated and compared, and the result agrees with those of half hourly transpiration. This indicates that there is no seasonal change in radial profile of sap flux density.

On the other hand, Q_a shows lesser consistency to Q than Q_r does. The correlation between estimates and the best estimate value are less strong, especially in tree 11 and tree 17 which are smaller in size and sap flow. Also the correlations between aspects in tree 11 and tree 17 are not as clear as in other trees (Fig. 7).

Apart from lower consistency, there are also signs of potential of underestimate or overestimate in some of the trees. This indicates that there might be small seasonal changes between relationships sap flux dusty on different aspects, depend on individual trees.

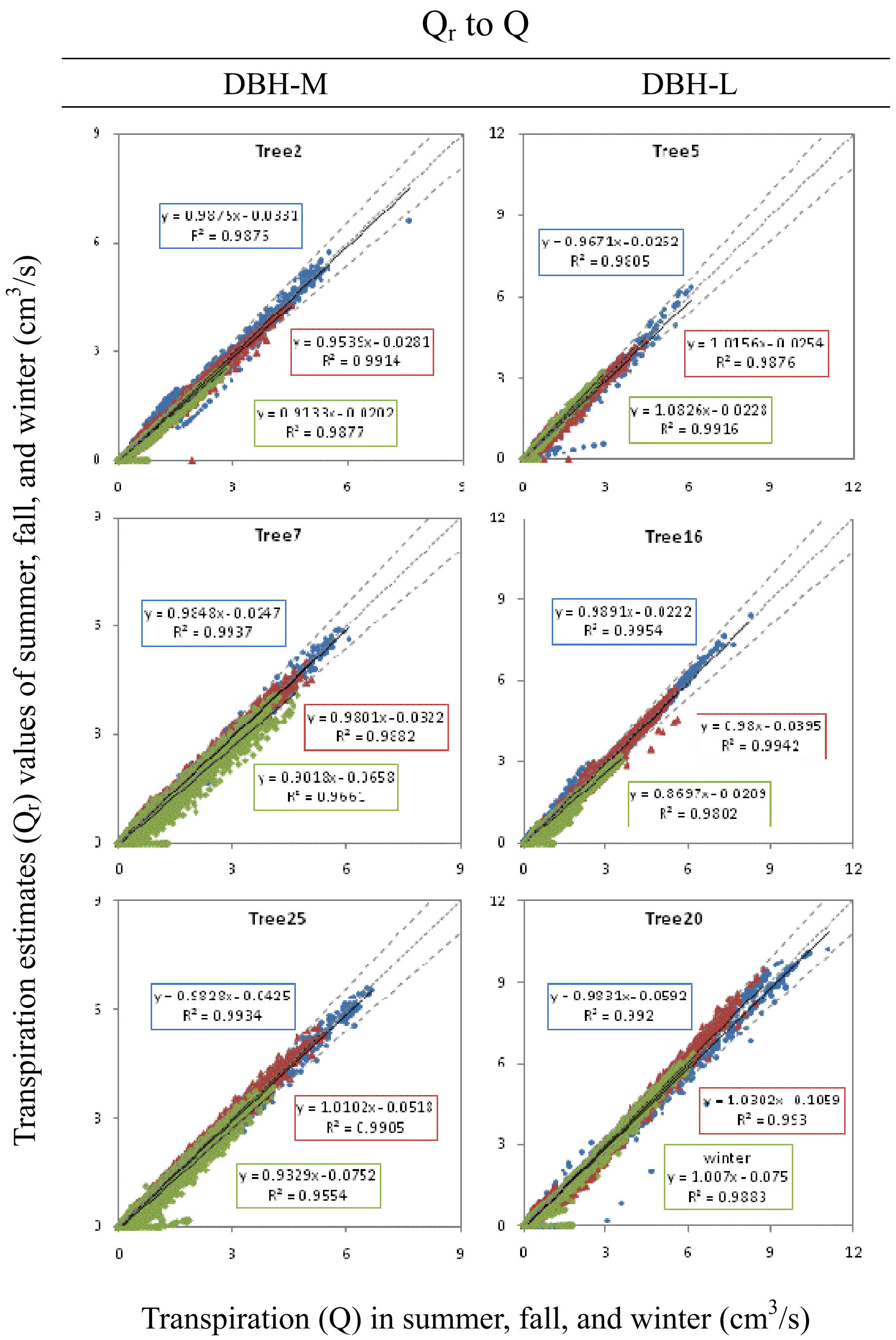


Fig. 16 Comparing half-hour transpiration estimates based on azimuthal profile (Q_r) to the best estimate transpiration (Q) in summer (●), fall (▲), and winter (■). The linear functions and R^2 of regression line are showed with frames of the same color with data points. The 1 : 1 line is showed as .... , and the 1 : 1 ± 0.1 lines as - - - .

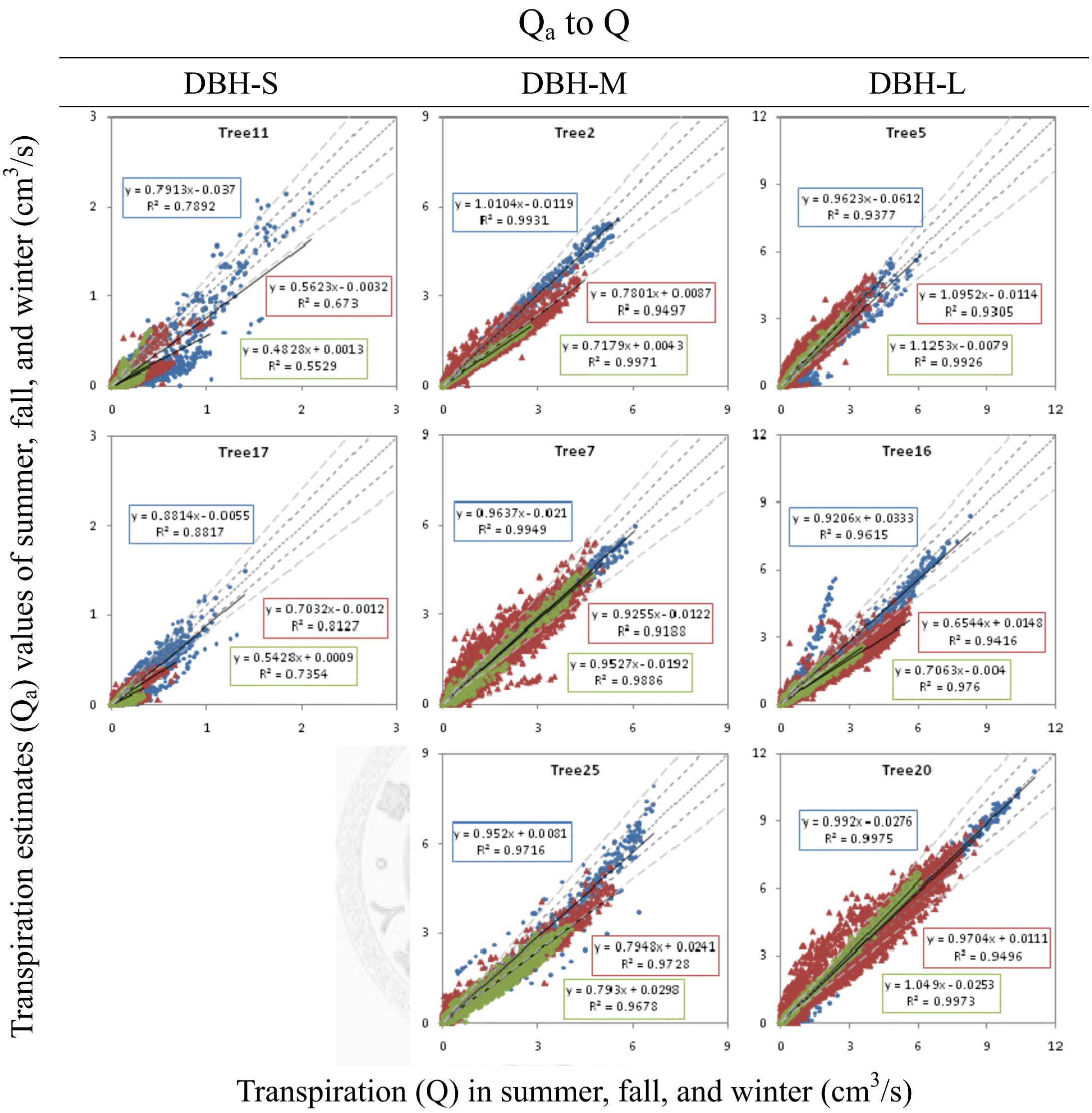


Fig. 17 Comparing half-hour transpiration estimates based on azimuthal profile (Q_a) to the best estimate transpiration (Q) in summer (●), fall (▲), and winter (■). The linear functions and R^2 of regression line are showed with frames of the same color with data points. The 1 : 1 line is showed as .... , the $1:1 \pm 0.1$ lines as - - - , and the $1:1 \pm 0.2$ lines as — —.

Q_r to Q

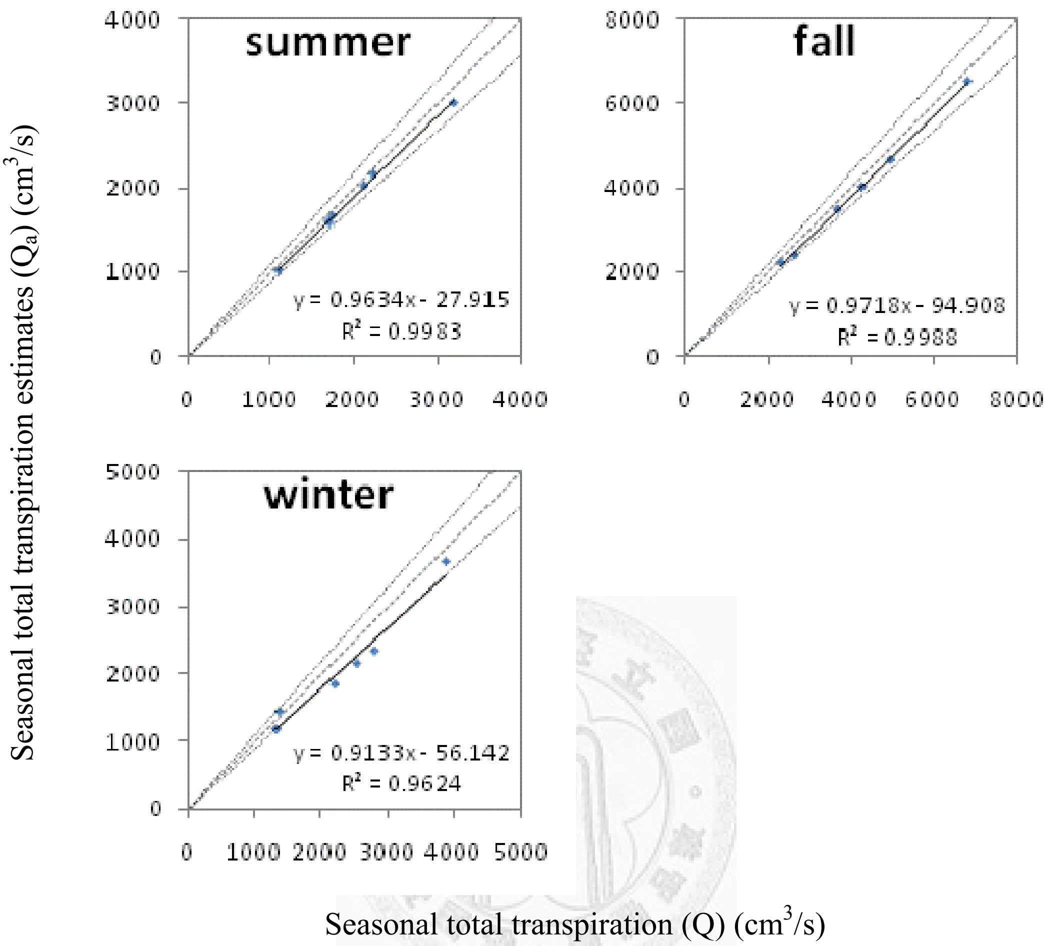


Fig. 18 Comparing the seasonal total of Q_r to Q. The 1 : 1 line is showed as .... , and the $1:1 \pm 0.1$ lines as - - - .

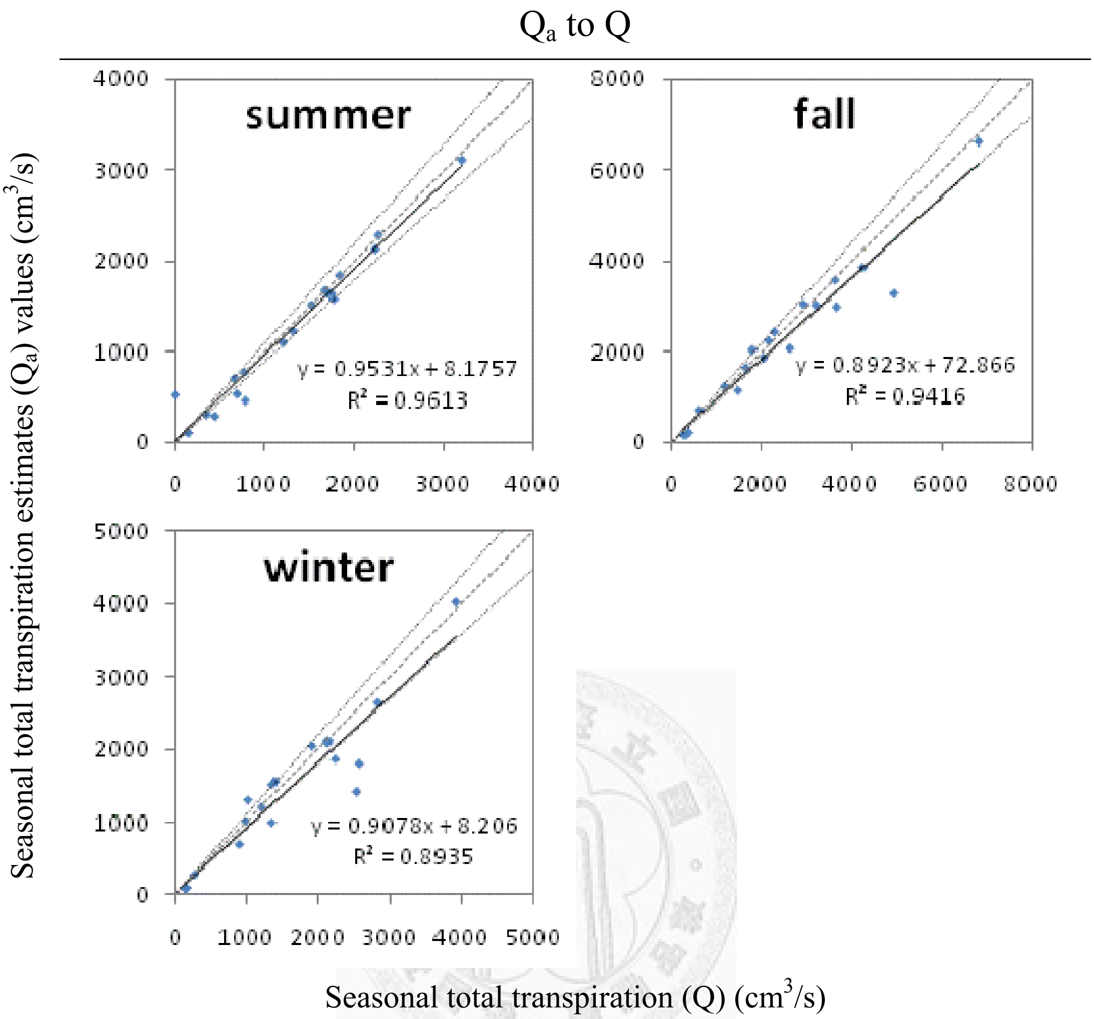


Fig. 19 Comparing the seasonal total of Q_a to Q. The 1 : 1 line is showed as .... , and the 1 : 1 ± 0.1 lines as - - - .

Chapter 4

Discussion

Through the analysis of sap flow measurement data, it is clear that both radial and azimuthal variations of sap flow exist within individual tree throughout the sapwood cross-section.

Sap flux densities in different depths of sapwood are highly correlated. Higher sap flow is observed in the outer layer of sapwood at 0–2 cm deep and sap flow at the depth of 2–4 cm is lower. Sap flux density in 2–4 cm deep in sapwood is about half as much as in 0–2 cm deep, and there appears to have linear relationships between the two depths. This result agrees with most previous reports, suggesting sap flow strongly related between any two points in different depth of sapwood and between the outer and inner sap flux density there is often a linear relationship (Delzon et al. 2004; Lu et al. 2000; Tateishi et al. 2008). Although there are also studies that report another type of sap flow radial distribution pattern that the highest flow is not in the outer most part of sapwood (Cohen et al. 2008; Nadezhdina et al. 2007; 瀧澤英紀 et al. 1996), and have polynomial relationships (Cohen et al. 2008).

Radial profile of sap flow distribution has been reported in some studies. The ratio can have a pretty wide range. Tateishi et al. (2008) have reported difference at different depth of 61–97%. Others suggest larger decreases that sap flux density can be 45–65% of the highest flux in the outer most layer of sapwood (Schiller et al. 2007; 瀧澤英紀 et al. 1996). Radial profile can change with tree size, that in small trees sap flux decrease less than 60% or no decreasing at all, and in large tree say flux can decrease dramatically at sapwood-heartwood boundary of 80% (Delzon et al. 2004). It is reported that there is little contribution made by xylem at depth greater than 60mm (Delzon et al. 2004). In our studies, because there was no sample tree that has sapwood thickness over 6 cm, we did not measure sap flow deeper than 4 cm.

The correlation and ratio between sap flux densities of different aspects in azimuthal variation depends on individual tree. Most of the sample trees with relatively larger DBH have higher correlations and more significant linear relationships between each of the different aspects, which is agreed by many of the studies examining sap flow azimuthal variation (Delzon et al. 2004; Lu et al. 2000; Tsuruta et al. 2010; 赵平 et al. 2005). On the other hand, trees with smaller DBH tend to have relatively unstable relationships in sap flow. Ratio of sap flux density between different aspects also appears to depend on individuals. Sap flux density measured at one aspect can be 50–200 % of another. Tateishi et al. (2008) reported that correlation ratio at different direction can range from 97–61%, and the variability is most considerable around noon. Another finding in sap flow azimuthal variation is that there is no particular aspect that always has the highest sap flux density among every tree. There are some reports about dependence of sap flux density to directions which gave similar results that there is no preferential orientation (Cohen et al. 2008; Lu et al. 2000). Some researchers suggest that light environment is not the primary factor to azimuthal variation in sap flow (Cohen et al. 2008; Tsuruta et al. 2010).

In azimuthal profile of sap flux density among the 4 aspects, there are slight seasonal changes of sap flux density ratios between aspects. The differences between different aspects become smaller in fall and winter when the sap flux density is low. In radial profile, changes of sap flux density differences between inner and outer sapwood through measurement period are minor.

Based on radial and azimuthal profile and the fixed ratio of sap flux density, estimates of single tree transpiration are made to compare with the best estimate value of transpiration. The result, single-tree transpiration estimates made with the assumption that no seasonal changes in sap flow radial profile is very comparable with the best estimate value. The difference is within 10%. This indicates that seasonal changes in radial variation is minor and have no significant impact on transpiration estimations. On the other hand, single-tree transpiration estimates made assuming no seasonal changes in sap flow azimuthal variation, compared to the estimates which ignored seasonal changes in radial profile but took azimuthal variation into consideration, have lower comparability with the best estimate value of transpiration. Especially in trees with smaller DBH, and was found to have less clear linear relationships between aspects in the previous azimuthal variation analysis. In these trees, differences between the fixed ratio estimates and the best estimate values there can even go to about 50% in winter, while in other trees the difference is around 20%. Tateishi et al. (2008) also reported errors up to 20% in transpiration made with one direction measurement. Transpiration estimates based on sap flow measurement made on one, two and three direction have respectively 30%, 20% and 10% difference compared with estimates based on four-direction measurement (Tsuruta et al. 2010).

With enough knowledge of sap flow spatial variation within tree, transpiration estimates can be made more accurately. However, if the relation between different parts of sapwood is constant, estimates of the same level of accuracy can be made with less measurement. This concept is mentioned in several previous studies, and Delzon et al. (2004) had proposed a correction factor (C) to extrapolate sap flux measured by a single sensor at the outer most layer of sapwood to whole tree sap flux. Correction factors account for the radial sap flow profile and the sapwood annulus area sampled at each different depth in the stem.

First the sap flux ratios (R_i) is calculated as the ratio of sap flow rate measured by sensors which placed at different depth (mobile sensors), to flow rate measured by a sensor at the outer most part of sapwood (reference sensor). Then calculate the ratio of annulus areas of sapwood at each depth (A_i) to the total sapwood cross-sectional area (A_{total}). And finally correction factor can be calculated as:

$$\mathbf{C} = \sum \mathbf{R_i}\ (\mathbf{A_i}/\mathbf{A_{total}}).$$

Correction factors for different tree sizes value ranged from 0.6–1, and have a negative linear relationship with stem diameter. Correction factors are not affected by meteorological changes, and Delzon et al. (2004) suggest that these correction factors can replace permanent sensor installed at multiple sapwood depth.

Previously, few studies have examined applicability of the correction factor through the year. The variable correction factor through the year could be expected according to the previous studies (e.g., Lu et al. 2000, Ford et al. 2007), however, our study suggests we may be able to use constant correction factor at this site where rainfall have been mostly distributed thorough the year with no distinct dry season.

Chapter 5

Conclusions

It is a complicated process to estimate transpiration of large spatial scales like forest stands or catchment landscapes from the sap flow measurement through the method of thermal dissipation technique. There lies variability in each level of spatial scales, and error can occur at each extrapolating steps when crossing one level to another. Therefore the extrapolation of transpiration estimation should be done carefully, with enough knowledge of potential error and sampling.

Scaling up sensor measured sap flow data to whole-tree transpiration is one of the important procedures for estimating larger-scale transpiration using sap flow measurement. Although significant spatial variations in sap flow within-tree have been reported, most of them focused on radial variations and azimuthal variations ignored by many early studies. Furthermore, few studies have examined seasonal change characteristics of variability in sap flow.

Thus, to clarify within-tree spatial and temporal variations, this study applied Granier's thermal dissipation technique to two smaller sized, three middle sized and three larger sized trees respectively, in the Japanese cypress forest, Sitou NTU experimental forest. Through this study we tried to answer the flowing questions: 1) How sap flow varied across sapwood in radial and azimuthal directions, 2) is there seasonal change in radial and azimuthal variations, and 3) do these variations have any impact on estimating transpiration.

In radial profile analysis, we found that inner sap flux density measured at depth of 2–4 cm was found to be approximately half of the outermost sap flux density measured at depth of 0–2 cm, and the sap flux density in inner and outer sapwood were closely related within each tree regardless of tree size through the whole measurement period. In azimuthal variations analysis, as well, the relationships between one aspect and the others were mostly fairly consistent through the measurement period, depend on individual trees. There were significant azimuthal variations in sap flux density between different aspects, and one aspect may be 50–200 % of another. No dependency of sap flux density on direction was found. This study also showed seasonal changes of the radial and azimuthal variations in sap flow could have insignificant impacts on accuracy of individual tree-scale transpiration estimates based on a simple numerical exercise.

Studies using multiple sap flow measurement sensors, which measure sap flow at several different depths and aspects, with longer monitoring period help to better understand spatial and temporal sap flow variability within trees. And understanding this variability helps researchers to avoid its effects and lower the errors in the transpiration estimates. If variability is large and changeable, then it is clear that more sensors and longer measuring period is required. However, if variability is relativity limited, then maybe the same level of accuracy can be available even with less sensors and short period of measuring. This way we can not only save a lot of work and time, but also making sap flow measurement more applicable because it requires electricity for heating up sensors. Another concern about multi-sensor long time measuring is that probes inserted have potential to injure the tissue around through long period of time, and can therefore, affects the result. Models of within-tree sap flow variation, similar to the correction factor proposed by Delzon et al. (2004), we might be able to establish based on studies like ours which examine spatial and temporal variability of sap flow. And in the future, this kind of within-tree sap flow distribution models technique can be applied to studies such as of long term transpiration monitoring.

Studies about sap flow measurement and transpiration of higher spatial scales estimated through this technique in Taiwan are still very rare. Most studies measured sap flow with only a small number of trees with very few sets of sensors, and the measurement periods are mostly short (吳聲沅 2008; 洪志凱 2004; 陳俐如 2005; 羅勻謙 2004). Within-tree sap flow variation is essential for research of transpiration using sap flow measurement. However, this kind of studies provides little useful information for the extrapolation of transpiration to both larger spatial and temporal scales, and more study is regarded.

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