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發展林分相對密度指數於檜木及松樹混合林

Developing Relative Stand Density Index for Structurally Complex Mixed Species Cypress and Pine Forests

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本論文係楊婷茹 君（R05625014）在國立臺灣大學森林環境暨資源學系完成之碩士學位論文，於民國 106 年 06 月 16 日承下列考試委員審查通過及口試及格，特此證明。

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中文摘要

林分密度指數可以呈現林內競爭強度，其利用決定初期栽植密度與疏伐等方式來經營林木的空間分布、控制樹冠的發展及維持森林的健康程度。最典型的林分密度指數在 1933 年由 Reineke 所建立，此指數於人工純林有很佳的研究結果，但並不適於混合林，目前可替代的林分密度指數仍被探索中。在臺灣，天然林的面積大約佔有 105 萬公頃，其中 85 %的天然林面積屬於混合林，當前林分密度指數的相關研究多著重於單一優勢物種的天然林或是單一物種的人工林，以紅檜與柳杉的研究較多，極少研究致力於調查或發展可適用於臺灣天然混合林的林分密度指數。由於進行林分密度的管理，對於森林保護與水土保持等目標極為重要，因此，開發天然混合林的林分密度指數來制定森林經營管理方針是有必要的。本研究將臺灣第四次森林資源調查的檜木混合林及松樹混合林等資料，代入 Ducey 和 Knapp 在 2010 年建立的相對密度模式，為了使臺灣的資料能在此模式下有顯著的結果以及得到更完整的相對密度模式建立方針，代入的過程需要再額外加入三個步驟，包括添加 1 %的隨機雜訊於所有樣木的比重值、以大於 10 %的檜木或松樹胸高斷面積比例作為樣區挑選的基準值、選擇最大值、最小值的相交分位數以及各參數平均值來決定相對密度模式的參數估計。本研究不僅提供獲取某混合林林分相對密度公式的初步流程，更提供一個快速評估檜木混合林以及松樹混合林等樣區的相對密度公式，以利對此樣區進行森林經營管理之策略。

關鍵字: 林分密度指數、相對密度、分位數迴歸、混合林、森林經營管理

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Abstract

Stand Density Index (SDI) is a numerical value that captures intensity of competition within a forest stand. It is a tool for managing spatial arrangement of trees, controlling crown development and maintaining degree of forest health through decision made on initial planting density and thinning schedule. However, classic Reineke's SDI (Reineke 1933) has been found to be unsuitable for mixed species and structurally complex forest stands. Alternative measures of SDI are being explored. Natural forests in Taiwan cover an area of approximately 1.5 million ha with 85% of them classified as mixed species forests. Current SDI research in Taiwan focuses on single-species natural and plantation forests such as *Chamaecyparis formosensis* and *Cryptomeria japonica* forests. Very few studies investigate and develop SDI for mixed species natural forests in Taiwan. Because management of these forests is crucial for conservation and protection against soil erosion, it is necessary to develop SDI for mixed species natural forests to establish guidelines for management of these forests. Therefore, based on the model by Ducey and Knapp (2010), relative SDI was developed for false cypress and pine forests using data from the 4th Taiwan National Forest Inventory. Plots with at least 10% of basal area per hectare of target species were used for model fitting. During model fitting, it was discovered that specific gravity played an important role on model convergence. Lastly, three different relative SDI models for each forest type were produced that predicted minimum, mean and maximum relative SDI for a forest stand. The major result from this study was that relative SDI could now be calculated for the mixed-species and structurally complex false cypress and pine forests that allows a manager to meet forest management strategies.

Keywords: Stand density index (SDI), Relative density (RD), Quantile regression, Mixed-species forest, Forest management

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Chapter 1 Introduction

In 1933, Reineke's stand density index (SDI) representing a relationship between tree number and size was published and became an available measure for assessing density in single-species, even-aged stands (Reineke 1933). In order to be more useful for resource managers to depict stand dynamics, Japanese scientists developed stand density management diagrams (SDMDs) in early 1960s, which graphically illustrated relationships such as competition-density effect, yield-density effect and the power law of self-thinning (Newton 1997). Consequently, stand density measure is a tool for managing spatial arrangement of trees (Hurst 2012) and maintaining degree of forest health (Nyland 1996) by determining initial planting density and thinning schedules.

However, Reineke's SDI is generally inappropriate for use in mixed species forests or irregularly structured stands. To apply SDI in mixed species forests, an additive form of SDI (ASDI) closely related to Curtis relative index (Curtis 1982) was developed based on the assumption that a value of SDI can be additively partitioned into components with each representing a contribution from different stand components (Stage 1968; Long and Daniel 1990). Furthermore, incorporating factors such as canopy properties (Dean and Baldwin 1996) and wood specific gravity (Woodall et al. 2005) into ASDI to portray growing space occupancy offers alternative ways to determine stand density index in mixed species stands. Ducey and Knapp (2010) developed a relative density index that was built using the tree-area ratio concepts (Chisman and Schumacher 1940; Curtis 1971, 1982) and relating maximum stand density to a new prediction variable, wood specific gravity. This index is close to Reineke's (1993) SDI in form and purpose, which Zeide (2005) described as one of the best stand density measures in monocultures. Moreover, Ducey and Knapp (2010) showed that their

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models when applied to mixed species structurally complex forests were in line with SDI measure for plantation of the dominant species of those forests.

The land area of Taiwan is about 3.6 million ha, of which forest area occupies 2.2 million ha representing 60 % coverage of the land mass (Taiwan Forest Bureau 2016). Area of natural forests in Taiwan is approximately 80 % with the rest being plantation forests (Taiwan Forest Bureau 2016). Both natural and plantation forests are classified into four forest types: broad-leaved forest, coniferous forest, mixed coniferous and broad-leaved forest, and bamboo forest. Among the 2-million ha of forests, broad-leaved forests make up 65 % with coniferous forests about 14 %, mixed forests about 8 %, and bamboo forest about 13 % (Taiwan Forest Bureau 2016). Because of subtropical and tropical marine climates associated with Taiwan’s proximity to the Tropic of Cancer, abundant rainfall from monsoons and typhoons, and the impact of plate activities, there are many high mountains, rugged landscapes, and diverse ecosystems such as coastal, estuaries, lakes, streams, forests, and island ecosystems that form rich habitats (Hsu 2014) that contribute to a high proportion of endemic species and subspecies (Lin 2003). In Taiwan, there are 4875 species of angiosperms and 36 species of gymnosperms (Hsu 2014). Natural coniferous forest types average about 500 m^3 ha^{-1}, with the cypress forests averaging about 750 m^3 ha^{-1} for the highest average volume, and spruce forests with 660 m^3 ha^{-1} being the second highest (Taiwan Forest Bureau 2016; Table A1). The maximum average volume in planted coniferous forests is found in Japanese cedar plantations with 340 m^3 ha^{-1}, and only 150 m^3 ha^{-1} in planted broad-leaved forest (Taiwan Forest Bureau 2016; Table A1).

Past research on SDI of forests in Taiwan focused either on natural forests dominated by one tree species or plantation forests of a single species. For example,

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Yen (2002) used SDI and volume to develop a stand density management diagram for cypress plantation forests, including *Chamaecyparis formosensis* and *Chamaecyparis obtusa*. Su (2014) also used SDI to obtain self-thinning lines for both cypress natural forests in Qilan Mountain and cypress plantation forests in the 1st, 2nd, and 3rd national forest inventories. Most studies just use number of trees as a measure of stand density when assessing effects of stand density management on various tree and stand characteristics, including the growth of Taiwania plantations (Lin and Horng1991; Wang et al. 2009) and Japanese cedar (Yu et al. 2011), the crown characteristics of Chinese fir (Yen 2006), and forest development of Japanese cedar (Cheng et al. 2014). None of the studies, to the best of our knowledge, investigated and developed SDI for mixed species natural forests in Taiwan. However, management of these forests is crucial for conservation and environmental protection such as soil erosion. It is therefore necessary to develop SDI for mixed species natural forests to refine guidelines for regenerating and management of these forests from catastrophic events such as severe typhoons, wildfires, and insect and disease infestations.

1.1 Goals and Objectives

The specific objectives were: (1) to develop relative SDI measures for *Chamaecyparis* and *Pinus* natural and mixed species planted forests based on the models by Ducey and Knapp (2010); (2) to understand the limitations of these models when applied to a mixed species natural and planted forests in Taiwan; and (3) to explore applications of relative SDI in designing forest management strategies for natural forests in Taiwan.

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Chapter 2 Literature Review

2.1 Definitions and Effects of Stand Density

Stand density is an absolute measure of one or more physical characteristics of a forest stand per unit area (Kershaw et al. 2016). Measures of stand density can be expressed quantitatively as tree counts, basal areas, or volumes. One of the most well-known indices of stand density is Reineke's (1933) stand density index (SDI), based on a predictable relationship between quadratic mean diameter (QMD) and tree count per unit area. The relation between average size and number of individual trees in a stand is associated with growth and mortality. The phenomenon is commonly referred as "self-thinning" (Yoda et al. 1963). In a stand of a fixed area, both site resources and growing space are limiting factors that control number and size of trees. So, stand density also can describe the degree of site occupancy and crowding within an area, as determined by the number, size, and spatial distribution of trees (Tappeiner et al. 2007).

In addition to being an absolute measure, stand density can also be represented as a relative measure. Relative density is a measure of absolute stand density relative to the biological maximum that can be attained across different stages of stand development for a given site and species combination. It is expressed as a percentage of some reference level and provides corresponding levels of stocking (Stout et al. 1987). Relative density is also used as a silvicultural tool for density management, that uses initial spacing and subsequent thinning, or other intermediate treatments, to control stocking to achieve specific management goals (Long 1985). Both stand density and relative density provide forest managers simple ways to design density management, and they are indispensable in understanding competitive interactions between individuals in a population and the intensity of competition for water, light, and

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nutrients on different site qualities and at different stand ages (Hutchings and Budd 1981; Long and Smith 1984).

Stocking is a measure of stand density relative to some specific management objectives, that can be represented by specific target levels of density (Tappeiner et al. 2007). The stocking status of a stand is generally qualitatively expressed relative to the ideal level with terms such as over-stocked, fully-stocked, and under-stocked. Stocking also can be expressed as bounds on management objectives. For example, Gingrich's (1967) A-level stocking curve, which is about 100% relative density, or B-level stocking curve, which is considered the minimum stocking for full site utilization, represent bounds on upper and lower stocking limits for maximizing stand and tree growth (Gingrich 1967). These qualitative statuses describe the adequacy of any observed level of stand density to a specified management or silvicultural goal. Over-stocked implies that growing space in a stand is completely occupied by trees with many trees in suppressed conditions that generally slow tree growth. A fully-stocked stand is also called a normal stand, whereby trees effectively occupy all growing space, and management objectives are reached or maintained. For an under-stocked stand that is not at its optimal stocking, the site is not used to its full capacity and stand density is not regulated. Thus, in contrast to stocking, stand density and relative density imply biological limitations instead of optimal conditions relative to some management objective (Tappeiner et al. 2007).

2.1.1 Stand Density-Management Diagrams (SDMDs)

A successful density management regime must translate general management objectives into specific stand structure attributes such as appropriate tree sizes and levels of growing stock (Long and Daniel 1990). Utilizing the concepts of stand

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density, relative stand density, and stocking, stand density management diagrams (SDMDs) are developed for depicting development of even-aged stands and for planning thinning regimes and other silvicultural treatments.

Traditionally, SDMDs have been developed on the basis of three different depictions of the size-density space. Basal area stocking diagrams have been widely developed in eastern North America for use in mixed hardwood forests (Gingrich 1967; Roach 1977; Kershaw and Fischer 1991), while diameter-density diagrams (e.g. McCarter and Long 1986) and volume-density diagrams (e.g., Drew and Flewelling 1977) have been developed primarily for even-aged, pure species stands. Other components of stand density have been used, but have not been as widely developed (Kershaw et al. 2016, Chapter 8). Choice of diagrams depends largely on local practice, inventory methods, and silvicultural approaches.

2.1.2 Related Effects Caused by Density Management

A stand is managed by the density of planting or natural regeneration and by treatments such as thinning of saplings and large trees and removal of shrubs from around small trees to ensure their survival and growth. Thinning is the major way to manage stand density and maybe done before the trees are of a desired size or on older stands to meet objectives such as developing wildlife habitat, yielding commercial wood, maintaining stand and tree vigor, increasing resistance to fire, insect and pathogen activity, and aesthetic. Thinning is also very important for the landowner to ensure the species composition, volumes, and tree sizes that will support future economic returns.

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2.1.2.1 Effects on Growths of Individual Trees

Current annual individual tree growth is related to growing stocking. If the management objective is to maximum individual tree growth and size and without regard to volume production per ha, because thinning has a major effect on the growth of individual trees, the appropriate strategy is using advanced thinning to maintain the stand in a small percentage of stocking. The positive effect is that, as trees are provided more growing space, water, and light, they increase their rate of annual increment. The reason is that trees can respond to thinning by expanding their crowns and maintaining or increasing the density of their foliage when thinning provides lots of growing space for crown expansion (Tappeiner et al. 2007). Then, trees can carry out more photosynthesis to strengthen their growth capacity. However, the effect may be negative, at least initially, from sunscald, logging damage, and wind (Harrington and Reukema 1983).

Thinning from below can increase the growth of trees in the larger size classes and increase average stand diameter (Cochran and Barrett 1993), but unaffected apparently the height growth of dominant and codominant conifer trees (Marshall and Curtis 2002). Thinning can reduce height growth temporarily and trees increase height growth if they are overstocked or growing on sites of low productivity. However, thinning of mixed hardwood and conifer stands might increase both the height and diameter growth of relatively shade-tolerant hardwood species (Devine and Harrington 2004).

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2.1.2.2 Effects on Wood Volume and Quality

For a given site quality, wood volume production is related to the stand density. Initial planting density, precommercial thinning, and commercial thinning are ways of regulating stand density and volume production. In general, the denser the stand, the higher the volume of wood in the stand. In higher-density stands, competition and self-thinning lead to the loss of volume from mortality and volume yields dropping below potential or total volume (surviving trees plus mortality). As a result, diameter growth decreases as stand density increases (Oliver et al. 1994). Severe thinning in young stands might increase tree taper as diameter growth increases relative to height growth (low ratio of height to diameter). Increase in stem taper can reduce the yield of poles and pilings, which are high-value products. Standards for these products are with regard to length, diameter, straightness, and taper.

Another major effect of density management is on the sizes and kinds of knots that occur in the major part of stem (Grah 1961). Dead branches below the crown produce loose knot. Knots from live limbs are tight knots in saw lumber. Large knots, especially loose ones, reduce the strength and overall quality of wood (Megraw 1986). They are undesirable in pulp and remanufactured wood products. The other considerable management is pruning. Pruning trees will eliminate branches and knots in the pruned part of the stem. Pruning in dense stands may result in little knot-free wood, because diameter growth may be slow for much wood to cover the pruned bole (Tappeiner et al. 2007).

Because density management affects the diameter growth of trees, it may affect wood density and strength. The core of within-crown or juvenile wood increases as stand density decreases. Juvenile wood has lower specific gravity and other

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properties that are undesirable from a structural standpoint. Trees growing rapidly at low densities will produce more juvenile wood than will slower-growing trees in dense stands, but they will also produce larger volume of mature wood. Although wood density decreased with an increase in growth rate because the proportion of early wood was greatest in the wider ring, the lower wood density may not have caused a commercially important decrease in wood quality (Tappeiner et al. 2007).

For timber-management objectives, relative uniform spacing provides optimal growth of individual trees, the easiest thinning operations, and the greatest uniformity in log size and quality. If spacing is very irregular, individual tree development follows a course that would be expected under the higher mean stand densities commensurate with the local density in a clump of trees (Stiell 1982).

2.1.2.3 Effects on Developments of Stands

Thinning to achieve multiple resource values, including financial, biological, or multi-resource objectives, will have effects on the development of a stand. All these considerations generally suggest maintaining stands at lower rather than higher densities.

When trees are at the beginning of a period of rapid diameter and height growth, they have the potential to develop large and live crown. In the early stage of stand development, trees respond rapidly to thinning, which provides resources for the growth of tree and stand. If thinning is delayed, trees may be slower to respond because their crowns have receded, and they have to reverse a trend of declining both diameter and height. In young stands, it is important to set goals for trees size and volume at the first commercial thinning. SDMDs are useful in determining average

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stand diameter when the stand becomes dense enough to begin self-thinning. Although thinned stands have less volume than, more resources and growing spaces can make the volume is concentrated in the larger trees. Because thinning can increase both average stand diameter and the diameters of large trees, the wood yield of that stand in the future may be more valuable. The live crown ratios and ratios of height to diameter are also affected by the early thinning. As stand density increase, crown size increases and ratios of height to diameter decreases. Thus, trees become more vigorous and stable with decreasing density (Tappeiner et al. 2007).

In summary, thinning early has many advantages of stand development. Because thinning slows crown recession and trees have a considerable period of height growth remaining during which crowns can expand, both crown maintenance and development are enhanced. Besides, diameter growth and basal-area growth are rapid at young ages. Large trees can be grown more readily by maintaining rapid growth rates rather than waiting for diameter-growth rates to recover from the effects of high stand density (Tappeiner et al. 2007). Controlling species composition should be executed early in the life of the stand. Species which have relatively slow early-growth rates, must be given space to grow if they are to become part of the main canopy, otherwise they will become suppressed in the understory or die soon. Development of trees selected for wildlife habitat can be effectively managed by thinning at young ages. Early thinning is good tool to increase tree vigor for enhancing insect and disease resistance. In mixed-species stands, early thinning may increase the proportion or dominance as well as the vigor of resistant species (Tappeiner et al. 2007).

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2.1.2.4 Effects on Forest Stand as Ecosystem

Thinning decreases canopy density which leads to increase radiation and makes temperature increases extremely. Because increased light is accompanied by an increase in soil water for a time, the understory can grow and develop. Besides, when thinning is carried out on large, the volume and timing of stream flow can be affected.

In uneven-age stands, thinning is often the principle way to regulate the species composition and vigor of the smaller trees in the stand. Thinning is also good for seedling establishment and the growth of the less-shade-tolerant species. After thinning, new trees and shrubs can be established in the understory, and seedling and saplings already established can be released, too. Besides, thinning also has the potential to increase exotic species. Seed of non-native species may enter thinned stands either from wind dispersal or from machinery and foot traffic. The multi-storied stands developed by herbs, shrubs, and tree communities provide cover for nesting and food for a variety of wildlife species. Although thinning reduces mortality from self-thinning and will reduce habitat for wildlife species or insects that live in small dead trees. However, in long term, large trees in thinned stands are likely to produce large, long-lasting snags and logs that can be used by foraging and cavity-nesting wildlife (Tappeiner et al. 2007).

Besides, thinning has an effect on maintaining the degree of forest healthy. Thinned stands are resistant to insects because temperatures in these stands rise above the level for successful insect reproduction (Amman et al. 1988). By changing the species composition to favor resistant species, changing the stand structure, or both may make stands less susceptible to bad insects or defoliators.

2.2 Types of Stand Density Measures

Stand density can be characterized by either absolute or relative measures. The choice depends upon available data for analysis and preferences of forest managers. In general, stand density can be presented by eight different measures:

2.2.1 Number of Trees (N, N/ha)

Number of trees per unit area is the simplest measure of stand density, and it is very useful in stands of seedlings or small trees. For seedlings and small trees having small diameters, using basal area or volume to represent stand density may not adequately capture stand conditions. Furthermore, measuring diameter or height of individual seedlings or small trees is expensive and time consuming (Tappeiner et al. 2007). Thus, number of trees per unit area is often suitable for describing density of young stands after planting or thinning, which in turn can be used to determine expected quadratic mean diameter (QMD) of a stand using growth models or density-management diagrams (Tappeiner et al. 2007).

2.2.2 Basal Area (BA, m^2/ha)

Basal area, expressed on a per unit area basis, is often used as a measure of stand density. The measure often is used to represent the degree to which trees utilize growing space in a stand. In many stand structures, the measure is used to predict stand volume when estimates of average tree height and form factor are available. However, as a simple measure, BA masks the number of trees and the diameter distribution in a stand. Furthermore, it is easily affected by site quality and stand age. Hence, the measure cannot be directly expressed as a comparison of observed to

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expected number of trees. However, to generate a relative stand density measure, the expected basal area should first be established for a given species, site and age. The relative measure is then,

$$\frac{BA_o}{BA_e} = \frac{N_o \cdot D_o^2 \cdot 0.00007854}{N_e \cdot D_e^2 \cdot 0.00007854} \tag{1}$$

where BA_o and BA_e are observed and expected basal area, D_o and D_e are observed and expected QMD, respectively. Because a given basal area of a stand could represent a stand with many small trees or a stand with few large trees, the level of inter-tree competition is obviously different in absolute terms. However, relative measures have no such issues because relative density can represent the level of inter-tree competition though different average tree sizes in even-aged stands (Tappeiner et al. 2007).

2.2.3 Volume (V, m^3ha^{-1})

Mean volume per tree is sometimes used for comparing an observed stand to a standard condition. The metric represents economic values of timber and is strongly related to growing stock, and wood or biomass production. In addition, volume is also related to amount of functioning tissue in sapwood and cambium, to leaf area in tree crown, and physiological stand growth. The relative stand density measure expressed as the ratio of mean tree volume to a given "full-density curve" is $v = kN^a$, $a \sim -1.5$, and is built upon the -3/2 power law of self-thinning (Yoda et al. 1963) as expressed by Tadaki (1968). The power law of self-thinning can be used to represent the upper limit of a competition-density effect and has two assumptions:

(1) For the same species, its dimension does not vary by growth stage and site quality. The area occupied by a plant (A) is proportional to the square of some linear dimension of the plant, L^2,

$$\mathrm{A} \ \alpha \ L^2 \ \alpha \ \frac{1}{N} \tag{2}$$

thus,

$$N_e = k_a \cdot L_e^{-2} \tag{3}$$

where k_a is a coefficient that is empirically determined from stands at maximum density.

(2) Self-thinning only happens after the site is fully covered by plants. The biomass or volume of the plant is proportional to the cube of some linear dimension, L^3,

$$w \ \alpha \ L^3 \tag{4}$$

thus,

$$w_e = V_e = k_b \cdot L_e^3 \tag{5}$$

where k_b is a coefficient that is determined from trees in stands that have reached maximum density.

The relationship between average tree volume and the linear dimension is as follows,

$$\mathrm{A} \ \alpha \ L^2 \ \alpha \ \left(1/N\right) \ \alpha \ \left(w\right)^{\frac{2}{3}} \tag{6}$$

so that finally we derive

$$V_e = k_a^{\frac{3}{2}} \cdot k_b \cdot N_e^{\frac{-3}{2}} \tag{7}$$

The relationship is typically presented in the form of equation or as a stand density management diagram with logarithm to the base 10 of mean tree volume on the Y-axis and logarithm to the base 10 of tree density on the X-axis. The exponent of -3/2 to N_e in the equation and the slope of -3/2 in the diagram gives the law its name. Alternatively, the expected tree density, N_e, can in turn be expressed as a function of observed mean tree volume, V_o,

$$N_e = k_a \cdot k_b^{\frac{2}{3}} \cdot V_o^{\frac{-2}{3}} \tag{8}$$

The relative stand density index (RSDI) developed by Drew and Flewelling (1979) makes use of the above relationships. The RSDI is the ratio of observed to maximum tree density, whereby the expected number of trees at maximum tree density is a function of average observed tree volume,

$$RSDI = \frac{N_o}{N_e} = \frac{N_o}{k_a \cdot k_b^{\frac{2}{3}} \cdot V_o^{\frac{-2}{3}}} \tag{9}$$

2.2.4 Tree-Area Ratio (TAR)

Tree-area ratio (TAR) was introduced by Chisman and Schumacher (1940) to show the expected maximum level of some mathematically derived density measures in undisturbed stands of a forest type. TAR can predict changes in conditions as a stand develops with easily measured stand attributes. Chisman and Schumacher

(1940) suggested that ground area occupied by an individual tree is related to its diameter that could then be expressed by a quadratic equation:

$$A_i = C_0 + C_1 DBH_i + C_2 \left(DBH_i\right)^2 \tag{10}$$

where A_i is the ground area theoretically occupied by the ith tree, DBH_i is diameter at breast height of the ith tree, and c_0, c_1, and c_2 are coefficients. For the total ground area occupied by N trees in a stand or a sample plot, TAR is expressed as:

$$TAR = \sum A_i = C_0 N + C_1 \sum_i DBH_i + C_2 \sum_i \left(DBH_i\right)^2 \tag{11}$$

where the summation is over N trees in a unit area. TAR ranges from 0 to 1. TAR = 0 represents a completely empty stand, and TAR = 1 represents a stocking level consistent with “normal” or A-line stocking within conventional stocking guides. The parameters can be estimated using data from a number of separate and independent sample plots by means of least-squares regression,

$$\min\left[1 - C_0 N - C_1 \sum_i DBH_i - C_2 \sum_i \left(DBH_i\right)^2\right] \tag{12}$$

Minimizing the above objective function results in an estimate of the proportion of a unit area occupied by trees in a stand. Chisman and Schumacher (1940) applied TAR to a single species plantation and found that it performed adequately. However, in a mixed species stand, each species could have its own values of parameters, which increases complexity of the formulation and results in a large number of parameters to be estimated (Stout, Marquis, and Ernst 1987).

2.2.5 Stand Density Index (SDI)

Reineke (1933) observed that the maximum values formed a constant slope when the logarithm to base 10 of QMD was plotted against the logarithm of base 10 of number of trees per hectare. The constant-slope curve representing the maximum size-density relationship for a species or forest type in the plot was expressed as,

$$\log N = -1.605 \log QMD + k \tag{13}$$

where N is the number of trees per hectare and k is a constant value dependent on species. QMD is the diameter of the tree of average basal area. To compare stand densities across different sites, Reineke developed a Stand Density Index (SDI) that had no appreciable correlation with age or site index for silviculturists to estimate growing stock in single-species, even-aged forests. An advantage of Reineke's SDI is the ease with which it can be estimated and applied. SDI is based on the relationship between number of trees per hectare and QMD of a stand, which is expressed as,

$$\mathrm{SDI} = \mathrm{N}\left(\frac{\mathrm{QMD}}{25}\right)^{1.605} \tag{14}$$

It should be noted that 25 cm is usually used for SI units while 10 inches is used for Imperial units in the denominator. SDI is interpreted as the number of 25-cm or 10-in trees that would experience approximately the same level of inter-tree competition as the observed number of trees per hectare of a specified QMD in a stand. A relative density (RD) measure is derived from SDI by expressing it as a proportion of maximum SDI (SDI_{max}):

$$RD = \frac{SDI}{SDI_{\max}} = \frac{N_o \frac{QMD_o^{1.605}}{25}}{N_e \frac{QMD_o^{1.605}}{25}} = \frac{N_o}{N_e} \tag{15}$$

Where N_e is the maximum number of trees per hectare with a specific QMD in a stand. Hence, relative SDI is merely the ratio N_o/N_e. SDI_{max} is estimated empirically by measuring a large number of stands at maximum stand density.

However, SDI masks actual sizes of trees present in a stand. A disadvantage of SDI is that it does not describe contribution of various classes of trees in a stand, which may be necessary to compare densities among different stands (Stage 1968). Consequently, SDI cannot indicate rates of stand development (McCarter and Long 1986; Long et. al 1988; Dean and Jokela 1992), and it is inappropriate for uneven-aged stands with skewed diameter distributions (Shaw 2000).

2.2.6 Curtis's Relative Density (CRD)

When stand density was estimated by BA (Eq. 1), its exponent value is about 2.0. However, because trees occupy areas not necessarily proportional to the square of diameter (Gingrich 1967), the degree of crowding or cumulative effects of competition on average tree development cannot entirely be captured by basal area. Curtis (1971) showed that the appropriate exponent of basal area for computing stand tree-area ratios in Douglas-fir stands was 1.55 which is roughly 3/2. The exponent is consistent with Reineke's (1933) equation (Eq. 14), and the corresponding tree area diameter curve is almost indistinguishable from that obtained with the original Chisman and Schumacher TAR equation (Curtis 1971; Eq. 11). An expression of this form is:

$$TAR_{1.55} = \frac{k\sum\left(D_i^{1.55}\right)}{unit \quad area} \tag{16}$$

Therefore, this is an expression of stand density which is consistent with other related formulae. The measure of stand density, $\sum\left(D_i^{1.55}\right)$ per unit area, is simpler than other equivalent measures, and has direct biological interpretation as a sum of expected tree areas per unit area. So, the measure can be an index of average degree of crowding of stems relative to the maximum stand density. The distinction between direct measures of density (stand attributes expressed on a per unit area basis) and relative measures of density (ratios of observed values to those of the maximum stand density as a standard) disappears (Curtis 1971).

With the above relationships among stand density measures, Curtis (1982) developed a relative density index (CRD) that could be interpreted as a function of the ratio, N_o / N_e. CRD can be expressed as a function of any two of the following quantities: (1) basal area per unit area, BA; (2) quadratic mean diameter, QMD; and (3) number of trees per unit area, N_o. The forms of CRD can be:

$$CRD = BA \cdot \sqrt{QMD} = (k)^{1/4} \cdot N_o^{1/4} \cdot BA^{3/4} = k \cdot N_o \cdot QMD^{3/2} \tag{17}$$

where k is 0.00545415 for Imperial units and 0.00007854 for SI units. Within an SDI expression, any equation that shows the expected maximum number of trees per unit area can become a function of QMD:

$$N_e = CRD_{\max} \cdot k^{-1} \cdot QMD^{-3/2} \tag{18}$$

where $\mathrm{CRD_{max}}$ is an empiric coefficient from stands of maximum density. As a result, CRD can be expressed as:

$$CRD/CRD_{\max} = N_o/N_e = N_o\Big/\left(CRD_{\max} \cdot k^{-1} \cdot QMD^{-3/2}\right) \tag{19}$$

Similarily to SDI, the expected number of trees at maximum density is dependent upon the observed average size.

2.2.7 Relative Spacing (RS, %)

Because average diameter is based on a stand with an undisturbed distribution of diameter classes, this distribution could be disturbed and average diameter could be increased by periodic thinning. But for height, its distribution is generally negligibly affected by spacing within reasonable limits of stocking (Wilson 1946). Wilson (1979) suggested that observed number of trees per unit area was relative to average stand height. Relative spacing (RS) is a measure of stand density based on average tree height and is typically expressed as,

$$RS = \frac{\sqrt{\dfrac{Area}{N_o}}}{H} = \frac{S}{H} \tag{20}$$

where S is average spacing between trees and H is an average tree height. At maximum stand densities, Douglas-fir and other species usually exhibit the non-linear relationship between height and diameter (Curtis 1970),

$$H = k_2 \cdot D^{0.8} \tag{21}$$

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where k_2 is an empirically determined constant. By relating to Reineke's (1933) constant-slope curve (Eq. 13), the relationships among the number of trees per unit area, QMD, and H can be expressed as follows,

$$N_e = k \cdot QMD^{-1.605} = k_2^2 \cdot \left(H\right)^{-2} \tag{22}$$

The expected number of trees at maximum stand densities becomes a function of H, and the relative spacing index can be rearranged to,

$$RS = \sqrt{\frac{\frac{Area}{N_o}}{\frac{k_2^2}{N_e}}} = \left(\frac{Area}{k_2^2}\right)^{\frac{1}{2}} \cdot \left(\frac{N_o}{N_e}\right)^{-\frac{1}{2}} \tag{23}$$

There is a consistent relationship between tree height and diameter among stands at maximum stand density, which could be translated into a spacing to height ratio interpreted in the form of N_o/N_e (Tappeiner et al. 2007). Obviously, the RS formula is similar to Reneike’s SDI, but uses stand height instead of stand diameter as the basis for comparing an observed stand with a maximum stand density. Thus, RS is seen as a ratio between observed number of trees per unit area and the maximum possible number of trees for a given average height. Note that the relative spacing increases with decreasing number of observed trees (N_o).

2.2.8 Crown Competition Factor (CCF)

Crown Competition Factor (CCF) assumes that the ground area occupied by an open grown tree is proportional to its crown projection area (Krajicek, Brinkman, and

Gingrich 1961). The relationship between Crown Width (CW) of an open grown tree and its diameter can be presented as,

$$CW = a + bD_i \tag{24}$$

where D_i is individual DBH or i^{th} DBH class, and a and b are coefficients. The Maximum Crown Area (MCA) per tree is then,

$$MCA = \frac{\pi \cdot CW^2}{40,000} = 0.007854 \cdot \left(a^2 + 2abD + b^2D^2\right) \tag{25}$$

For unit area, the measure of stand density is proportional to:

$$CCF = \frac{1}{A}\left[k_0\sum_{i=1}^{j} N_i + k_1\sum_{i=1}^{j} N_iD_i + k_2\sum_{i=1}^{j} N_iD_i^2\right] \tag{26}$$

where A is plot area, N_i is number of trees in ith DBH class, and k_0, k_1, and k_2 are coefficients. The difference between CCF and TAR is that the former uses open grown conditions instead of a mean number of trees at maximum stand density as a reference. CCF is an estimate of the competition among crowns for growing space. Krajicek et al. (1961) indicated that the method could be applied in even-aged stands, and theoretically can be used for uneven-aged stands equally well. Besides that, stand age and site quality have minimal effect on CCF. The disadvantage is that CCF does not portray the actual canopy size.

2.3 Developments of SDI from Pure to Mixed-Species Forests

As discussed above, there are many approaches to measuring stand density in single-species or in simple mixed-species even-aged stands. However, for complex stands with large numbers of tree species, suitable approaches are relative few (Woodall et al. 2005). Applying Reineke’s SDI to mixed-species or multiple cohort stands has proved challenging (Shaw 2000). Some research efforts have attempted to extend Reineke's (1933) SDI to such complex stands (Stage 1968; Curtis 1971; Long and Daniel 1990; Woodall et al. 2005; Ducey and Knapp 2010).

Reineke's (1933) original SDI was based on the concept of normal stocking, which implied maximum density at the stand scale and akin to the A-line in stocking diagrams (Gingrich 1967). However, the usefulness of SDI has been limited by lack of methods to describe composition of the growing stock according to species and their size classes (Stage 1968). This form (Eq. 14) is only used to compare densities from stand to stand of the same species. In order to extend SDI to account for species and size classes, it must be computed tree by tree within a stand. Thus, the total SDI is essentially subdivided to represent contribution of different classes of trees within a stand (Stage 1968). As a result, Stage (1968) proposed that the total SDI should be the sum of partial SDI in each class. Because the concept that total SDI is additive, Curtis (1971) developed a power-law density measure which is closely related to SDI. It was then reformulated by Long and Daniel (1990) for used in mixed-species stands where diameter distributions are skewed and need a division of growing stock among various diameter classes or stand components. The additive SDI equation is:

$$\text{ASDI}=\sum_i N_i\left(\frac{DBH_i}{25}\right)^{1.6} \quad (27)$$

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where ASDI is the additive formulation of SDI, N_i is the number of trees per hectare in the i^{th} diameter class, and DBH_i is the diameter of trees in the class. For a continuous diameter distribution, the summation (Eq. 27) can be replaced by an integral, and N_i can become the product of N and an appropriate probability density function (Ducey and Larson 2003). Shaw (2000) showed that summation is the superior method of calculating SDI in uneven-aged or irregular stand structures. However, the need of establishing a maximum SDI for comparison has made use of the equation difficulty in mixed-species stands.

Woodall et al. (2005) suggested that the maximum ASDI in mixed-species stands could be estimated as a function of mean specific gravity (SG) of the trees in a stand. The function is built upon the mechanistic model proposed by Dean and Baldwin (1996). Dean and Baldwin (1996) showed that maximum SDI could be expressed in terms of foliage density and mean live-crown ratio. For a given mean live-crown ratio, the SDI value would increase with increasing foliage density (Dean and Baldwin 1996). A plausible explanation is that as more leaf area is concentrated towards the upper part of the stem, both wind drag (Jacobs 1954; Larson 1965) and crown weight would cause higher bending stress, which is generated in the tree stem and results in larger diameters (Kellogg and Steucek 1980; Dean 1991). Similarly, for a given foliage density, SDI values would increase as mean live-crown ratios decrease (Dean and Baldwin 1996). Smaller mean live-crown ratios could increase bending stresses by lengthening the moment arm or increasing the leverage the crown exerts on the stem (Dean and Baldwin 1996). If stem curvature is constrained by certain biological limits, then maximum SDI would be negatively related to SG (Dean and Baldwin 1996). Furthermore, the maximum values of SDI for a range of species was found to be linearly related to SG, showing that density indices are functions of the mechanical

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relationship between the canopy and stem (Dean and Baldwin 1996). As a result, SG can be a powerful predictor of other wood mechanical properties important for estimating maximum SDI. When trees have denser and stronger stems, the maximum SDI for species with high SG will be lower than that of species with low SG. With this trend, Woodall et al. (2005) presented the relationship between SG and SDI_{max} as,

$$E\left[SDI_{\max}\right] = a_0 + a_1(SG) + e \tag{28}$$

where $E[SDI_{max}]$ is the expected maximum ASDI for the mixture, SG is the mean specific gravity of trees in a given stand, a_0 and a_1 are empirical coefficients (a_1 should be negative), and e is a random error term. With this model, Woodall et al. (2005) used linear regression to estimate the relationship between the 99th quantile SDI (SDI_{99}) and classes of SG_m for stand within his dataset. Although using SG_m to represent SDI_{max} had slight bias toward over predicting SDI_{99} (Woodall et al. 2005), the model was still better than estimating SDI_{max} based on forest types (USDA Forest Service 2005) and was helpful when estimating SDI_{max} in species-rich stands where it was difficult to determine forest type. In addition, when Woodall et al. (2006) used

$$relative \quad density = \frac{ASDI}{E\left[SDI_{\max}\right]} \tag{29}$$

to compare stands with different stand compositions, the relative density is not additive (Ducey and Larson 1997) but rather separable (Ducey and Larson 2003). This property leads to minor annoyances, including bias when estimating stand density from a small sample (Ducey and Larson 1999).

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By integrating the concept of Curtis's (1971) relative density (CRD) and following Dean and Baldwin (1996) and Woodall et al. (2005) in combining SG into CRD, Ducey and Knapp (2010) developed a relative density measure (RD) for use in mixed species stands, and applied his model to forests of the northeastern United States (Ducey and Knapp 2010). Their equation was,

$$RD = \sum_i (b_0 + b_1 \mathrm{SG}_i)(\frac{DBH_i}{25})^{1.6} = b_0 \sum_i (\frac{DBH_i}{25})^{1.6} + b_1 \sum_i \mathrm{SG}_i (\frac{DBH_i}{25})^{1.6} \tag{30}$$

where b_0 and b_1 are empirical coefficients. In this formulation, there are only two estimated parameters no matter how many species are under consideration (Ducey and Knapp 2010). In this formulation, RD ranges from 0 to 1. When RD is equal to 0, it represents a completely empty stand, and RD = 1 represents a stocking level consistent with normal or A-line stocking. Following Chisman and Schumacher (1940), Curtis (1971), and Stout et al. (1987), their methods require selection of stands meeting the normal or reference density criterion. Then, Eq. 30 could be set to 1 for every stand, and the parameters could be estimated by ordinary least-squares regression. For Ducey and Knapp's (2010) application, they fitted Eq. 30 using quantile regression ensuring compatibility between mixed-species density measures and existing single-species or simple-mixture guidelines (Ducey and Knapp 2010).

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Chapter 3 Materials and Methods

3.1 Materials

3.1.1 Cypress and Pine Forests of Taiwan

Taiwan is located southeast of mainland China. It belongs to western part of the Pacific Ocean Islands. The longitude of Taiwan is from East 120° to East 122°, and the latitude is from North 22° to North 25°. The Tropic of Cancer passes through the middle of Taiwan. The length from north to south of the island is about 380 km, the width from west to east is approximately 140 km. Due to interactions between the Eurasian plate and the Philippine sea plate, the plate extrusion produces the main mountain range in a north-south direction. On the island, there are 268 mountains higher than 3000 m, of which the tallest mountain is Yushan mountain having the height of 3952 m. As a result, rapid changes in altitude provide diverse habitat conditions for different fauna and flora. The climate in Taiwan is influenced by the northeast monsoon from mainland China during winter, and the southwest monsoon from the west of India during summer. During summer and fall, there are typhoons, which bring high amounts of rainfall and causes damage due to high wind speeds. Because of the range in altitudes, tropical, subtropical, temperate and alpine forests can be found in Taiwan resulting in a complex composition of forest types.

There are more than four thousand species of vascular plants including ferns, gymnosperms, and angiosperms in Taiwan. The high species diversity in Taiwan is due to its geographical location, climate, and topography. The west, north and south of Taiwan are close to China, Japan and Philippines, respectively. In the process of geological change, there has been several changes associated with the mainland block and separation. During the glacial period and the mainland block, species migrated southwardly to warmer climates. A variety of flora and fauna from neighboring areas were brought together in Taiwan. During the interglacial period, with higher temperatures, those flora and fauna that were adapted to colder climates could not survive in the lower elevation of Taiwan. Some species migrated back to higher latitudes on the mainland, while a small number of species migrated to the higher Taiwan mountains. The evolution of plant distribution has been affected by these disturbance factors for millions of years. The vegetation zones in Taiwan can be classified by elevation (Taiwan Forest Bureau 2004, pp. 9-12; Figure A2) with common species associated with the range of altitudes (Table A3). This study focused on two forests types: cypress and pine forest types.

Cypress forests in Taiwan are distributed between the temperate and subtropical climatic zones, which is the transition zone between coniferous forests at higher elevations and broad-leaved forests at lower elevations. Due to large amounts of water vapor from southwest monsoons during summer and northeast monsoons during winter, the mountains of Taiwan intercepts most of the precipitation. The increase in daytime temperatures increases the water vapor, and, as the mountain temperatures gradually decrease in the afternoon, thick cloud cover forms daily. It is this daily cloud cover that produces the montane forests at elevations between 1,800 to 2,500 m in Taiwan. Both *Chamaecyparis formosensis* and *Chamaecyparis obtusa* are the dominant species in the cypress forests. Broadleaved tree species, such as *Trochodendron aralioides* and *Lithocarpus kawakamii*, and other coniferous tree species, such as *Cunninghamia konishii* and *Taiwania cryptomerioides*, are associated with the cypress forests (Taiwan Forest Bureau 2004, p. 11). Thus, cypress forests have complex forest structures and greater species compositions than other

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coniferous forests. *C. formosensis* is a very large tree that can grow up to 65 m height and 6.5 m in diameter. (Li and Keng 1994, p.586). It occurs in mountainous regions of the northern and central parts of the island at altitudes between 1000 to 2900 m, and is often mixed with *C. obtusa* and other conifer species (Li and Keng 1994, p.588). *C. obtusa* can grow up to 40 m in height and 3 m in diameter. This species is found in Japan; however, the variety found on Taiwan is endemic. The species occurs in the northern and central parts of the island mostly distributed between elevations of 1300 m to 2800 m. It also is commonly mixed with *C. formosensis* at lower elevations (Li and Keng 1994, p.588).

In pine forests, *Pinus taiwanensis*, *Pinus armandii* and *Pinus morrisonicola* are common species. *P. taiwanensis* is a large tree, that can grow up to 35 m in height and 80 cm in diameter. The bark of the species fissures into small scales and it is a two-needle pine species (two needles per fascicle). It is found only in Taiwan and grows in the mountains of interior Taiwan or along the mountainous coast at elevations between 750 m to 3000 m (Li and Keng 1994, p.577). It often forms large pure stands. Due to its adaptability to a wide range in elevation, *P. taiwanensis* occurs in different forest zones from warm temperate to subalpine, but it is restricted to open spaces, exposed ridges and places with sandy, acidic and nutrient-poor soil at lower to middle elevations. When a region is steep, subjected to landslides or damaged by forest fires, the first species to colonize these areas are pioneer species such as *P. taiwanensis* and *Alnus formosana*. *P. armandii* is a large tree, that can grow up to 20 m height and 1 m in diameter. It is a 5-needle pine species. The species occurs in southwestern and northern China and is confined to northern and central parts of Taiwan at high elevations between 2300 to 3000 m (Li and Keng 1994, p.573). *P. morrisonicola* is a large tree, that can grow up to 15-25 m height and 1.2 m in

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diameter. This species is distributed at altitudes between 300 to 2300 m elevation throughout the island. It is usually scattered and is often associated with broad-leaved trees (Li and Keng 1994, p.573). Both *P. armandii* and *P. morrisonicola* are 5-needle pine species.

3.1.2 Fourth Taiwan FRI Data

The data for this study were obtained from the 4th Taiwan Forest Resource Inventory (TFRI4) in Taiwan between 2008 and 2012, and were provided by the Taiwan Forest Bureau. There were 1,564 plots established based on systematic sampling with a grid 3 km by 3 km covering the whole of Taiwan (Figure 3.1). By initial design, plot size was 0.05 ha; however, if a plot was found to include three trees with DBH > 100 cm, its plot size was expended to 0.1 ha. Dead trees and trees with DBH < 6.0 cm were not measured. The tree level data from TFRI4 included plot ID, plot coordinates, tree ID, species identification, and DBH. In order to scale each tree to a unit hectare, we calculated tree expansion factors (EF):

$$EF = \frac{1}{plot \quad area} \tag{31}$$

Classification of forest types was carried out by TFRI4. Except for cypress natural forests, cypress plantations, pine natural forests, and pine plantations, some plots classified as coniferous and broad-leaved mixed forests or coniferous forests also have cypress or pine species. So, if a plot included *C. formosensis* or *C. obtusa*, it was regarded as a cypress forest plot and included in this study. If a plot included *P. taiwanensis*, *P. armandii* or *P. morrisonicola*, it was added into the pine forest plots in this study.

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For cypress forests, there were 254 species within 215 plots, and the average values of N, QMD, and SG were 1196 stems/ha, 29.3 cm, and 0.587, respectively (Table 3.1). For pine forests, there were 246 species within 199 plots, and the average values of N, QMD, and SG were 1241 stems/ha, 22.5 cm, and 0.585, respectively (Table 3.1). Only 65 plots in cypress forests had more than 50% cypress BA, and the mean number of species was about 10 when % BA is less than 80% (Table 3.2). In pine forests, there were 90 plots with greater than 50 % pine BA. The mean number of species for each % BA class is usually lower than that in cypress forests (Table 3.2). Across the range of % BA, N generally decreased by 50%, while QMD doubled in the cypress forests. In contrast, in the pine forests, N decreased about 30% across the range of % BA, and QMD remained essentially unchanged (Table 3.2).

3.1.3 Specific Gravity (SG)

The values of SG for each species in this study (Table A2) were obtained mainly from published sources including Taiwan Forestry Research Institute (1992) and Kanehira (1926) in Japan. However, some species were without associated SG values. We estimated these species by averaging the SG values of other species in the same genus. If genus-level average SG was not available, we estimated SG for these species by averaging the SG values of other species in the same family. When neither the genus-level or family-level averaged values were available, we calculated mean SG by conifer and by broadleaved and applied accordingly. We used SG with volumes measured at 12% moisture content. When a particular species had only SG measured at green volume, we developed a linear regression model for converting SG from green volume to 12% oven-dry volume based on data from species which had both green and 12% oven-dry SG (Figure A1). From Table A2, there were only 58

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species with species-specific SG values, 146 species used genus-level average SG, 55 species were based on family-level average SG, and 63 species used an average SG value for all broadleaved species.

3.2 Methods

For each plot in each forest type, we calculated the two sums found in the right-hand portion of Eq. 30, using the EF (Eq. 31) to scale each tree to a per hectare basis:

$$X_0 = \sum_i EF_i \left(\frac{DBH_i}{25} \right)^{1.6} \tag{32}$$

$$X_1 = \sum_i EF_i SG_i \left(\frac{DBH_i}{25} \right)^{1.6} \tag{33}$$

A variety of statistical techniques is available to determine maximum density levels including ocular estimation (Reineke 1933), ordinary least squares (Chisman and Schumacher 1940; Su 2014), reduced major axis regression (Solomon and Zhang 2002), quantile regression (Ducey and Knapp 2010; Su 2014) and segmented regression (Zhang et al. 2005). In this paper, we followed Ducey and Knapp (2010) in using quantile regression. Quantile regression is a useful approach when solving an optimization problem of minimizing an asymmetric function of absolute error loss (Koenker and Bassett 1978). Quantile regression is able to provide parameter estimates for linear regressions fit to any portion of a response distribution, including near the upper bounds, without imposing stringent assumptions on the error distribution (Scharf et al. 1998; Cade et al. 1999; Cade and Noon 2003). So, quantile regression has been suggested for estimating boundaries or envelopes in a variety of ecological settings (Scharf et al. 1998; Cade and Noon 2003). Following the concept of TAR (Chisman and Schumacher 1940), RD is set to 1 to estimate each parameter and to determine maximum stand density index. Rewriting Eq. 30 using Eq. 32 and Eq. 33 we get,

$$RD = 1 = b_0 X_0 + b_1 X_1 + \varepsilon \tag{34}$$

For quantile regression, the parameter values were chosen as minimizing the weighted sum of absolute values of errors ($\rho_\tau(\varepsilon)$) over all observations, where the weight depended on whether the error was positive or negative. For an individual observation,

$$\rho_\tau(\varepsilon) = \varepsilon\left[\tau - \mathrm{I}\left(\varepsilon < 0\right)\right] \tag{35}$$

where τ is a predetermined quantile between 0 and 1. The function $\mathrm{I}(\varepsilon < 0)$ was equal to 1 if $\varepsilon < 0$, and the function was 0 when $\varepsilon >= 0$. So, quantile regression chooses parameters such that the τ^{th} quantile of ε is zero, and the fraction of observations that fall below their predicted values is τ.

In this study, quantile regression found a relationship such that RD=1 described the τ^{th} quantile of density within all datasets for each forest type. When τ was set to very close to 1, the parameters would be chosen so that RD=1 described the upper limit of observed density. It should be noted that, because we set RD equaled to 1 and τ was set to be close to 1, the absolute values of errors would be positive values which means I ($\varepsilon < 0$) would always be equal to 0. This characteristic leads to maximizing the sum of the $\rho_\tau(\varepsilon)$. Thus, in this study, the τ^{th} quantile becomes 1 - τ for estimating the limit of observed density within the entire dataset. We used quantile regression to fit Eq. 34 with quantiles from 0.50 to 0.99. All analyses were conducted using the “quantreg” library (Koenker 2004) within the R statistical package (R Development Core Team 2016).

Observed maximum stand density depends not only on stand biology, but also on sampling methods employed. For example, small plot sizes generally result in higher estimates of stand density than those from larger plot sizes. Also, maximum stand density or normal stocking might occur at quantiles less than 1, and the distribution of the data itself was not adequate to determine which quantile should be used (Ducey and Knapp 2010). So, in order to select a suitable quantile, we hypothesized that all trees have DBH = 25 cm and RD was equal to 1, and we then used the TFRI4 dataset to estimate the coefficients for X_0 and X_1 for each quantile to solve for N, which is referred to as the implied maximum ASDI,

$$N=\frac{1}{b_0+b_1SG} \tag{36}$$

where SG is an average SG determined from all trees in all plots. The mean SG and SG range for each forest type are presented in Table 3.1. We also used published equations to obtain the number of trees per hectare (N) when QMD was set to 25 cm and this number was regarded as a reference SDI. For pine forests, there were no related published equations in Taiwan to obtain reference SDI. So, we chose plots where % BA of the desired species were over 80 % to fit Reineke's model (Eq. 13), and used quantile regression to estimate coefficients. With the fitted equation, we also set QMD equal to 25 cm and solved for N. So, the fitted equation for each quantile was viewed as a method to estimate reference SDI. For a successful mixed-species density measure, its result should be consistent with previous research developed for both single-species stands and well-studied simple mixtures. So, with both implied ASDI and reference SDI, we chose the quantile where implied ASDI and reference SDI intersected. A

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flowchart summarizing the sequence of steps in the method used here is presented in Figure 3.2. The step-by-step procedures were,

Step 1. Calculate X_0 (Eq. 32) and X_1 (Eq. 33) to scale up our dataset to per ha levels and fit to Ducey's model (Eq. 30)

Step 2. Set RD = 1 (Eq. 34) and use quantile regression to estimate the coefficients of X_0 and X_1 for quantiles from 0.50 to 0.99, keeping in mind that the τ^{th} quantile is fit as the 1 - τ^{th} quantile.

Step 3. Calculate an average SG by all trees in all plots, and then substitute the coefficients of X_0 and X_1 and the mean SG into Eq. 36 to estimate implied maximum ASDI for each quantile.

Step 4. Use published equations and diagrams, or fit Reineke's model (Eq. 13) to "pure" plots having at least 80 % of the BA constituted by desired species to obtain reference SDI.

Step 5. The best quantile is chosen as the one where implied maximum ASDI intersects reference SDI. The parameter estimates associated with this quantile form the RD formula for the mixed-species forest.

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Chapter 4 Results

4.1 Data Summary on X_0 and X_1 by Forest Type

After scaling up our dataset to per ha levels, we calculated the X_0 and X_1 values for all plots using Eq. 32 and Eq. 33, respectively. For cypress forests, the mean value of X_0 was about 1022, the range was from 176 to 2781, and the coefficients of variation (CV) was 44.5 % (Table 4.1). The mean value of X_1 was about 541, the range was from 96 to 1556, and CV was 46.6 % (Table 4.1). Because SG values for all species in the study were less than 1 (Table A2) and the range of SG among all plots in cypress forests was from 0.362 and 0.828 (Table 4.1), X_1 should be less than X_0. The mean and CV of SG were 0.587 and 15.2 % (Table 4.1). The correlation between X_0 and X_1 was about 0.938 for the cypress forests.

For pine forests, the mean value of X_0 was about 875, the range was from 47 to 2100, and CV was 48.6 % (Table 4.1). The mean value of X_1 was about 386, the range was from 27 to 1257, and CV was 51.4 % (Table 4.1). Because QMD in pine forests was less than that in cypress forests (Table 3.1), X_0 in pine forests should be less than that in cypress forests, too. The mean value of SG was 0.585, the range of SG was from 0.406 and 0.872 (Table 4.1). Mean SG was similar between cypress forests and pine forests. As a result, for both forest types, X_1 was almost a half of X_0 (Table 4.1). The correlation between X_0 and X_1 was about 0.955 for the pine forests.

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4.2 Reference Maximum SDI

Reference SDIs for cypress forests in Taiwan were obtained from published equations (Su 2014) and diagrams (Yen 2002). In Su's dataset, there were 350 plots and N and QMD were 1361 and 19.1 cm, respectively. CV for N and QMD were 41.4 % and 31.7 %, respectively. Both N and QMD had lower values of CV in Su's dataset than those in our study (Table 3.1). Su used six methods to estimate maximum SDI (Table 4.2, Figure A3), including ordinary least squares (OLS, Su.A1), corrected ordinary least squares (COLS,Su.A2), reduced major axis (RMA,Su.A3), quantile regression(Su.A4), stochastic frontier product functions(Su.A5), and stochastic frontier cost functions (Su.A6). When QMD was set to 25 cm, the reference SDI values of Su's dataset ranged from 548 to 2099 (Table 4.2) across the various fitting methods. Among the 350 plots, 178 plots were from cypress plantations that were sampled in the 1st National Forest Inventory (NFI1), 2nd National Forest Inventory (NFI2) and 3rd National Forest Inventory (NFI3), and N and QMD of the 178 plots were 1208 and 21.2 cm. CV for N and QMD were 35.1 % and 27 %, respectively. The reference SDIs of Su's equations (including Su.N1, Su.N2, Su.N3, Su.N4, Su.N5, Su.N6) estimated only by NFI's dataset ranged from 500 to 3732 (Table 4.2, Figure A4). The remaining 172 plots were obtained from Qilan Mountain Forest Inventory (QMFI). The mean values of N and QMD were 1520 and 17.0 cm, respectively and CV for N and QMD were 42.3 % and 31.7 %, respectively. The reference SDIs of Su's equations (including Su.Q1, Su.Q2, Su.Q3, Su.Q4, Su.Q5, Su.Q6) estimated only by QMFI's dataset ranged from 500 to 1264 (Table 4.2, Figure A5). For Yen (2002)'s SDMD, it was established using 36 thinned plots and functions relating N to QMD, mean height and volume were developed follow the approach used by Drew and Flewelling (1979). From the diagram (Figure A6), when QMD was set to 25 cm, the volume was approximately 500 m^3 and

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N was between 1000 and 1500. Then, substituting this volume into Yen’s equation, the reference SDI was 1076 (Table 4.2).

In addition to published resources, we also used plots having more than 80 % of BA constituted by cypress or pine species to fit our own Reineke’s model using quantile regression with quantiles from 0.50 to 0.99. A total of 18 plots were used to establish reference SDIs for cypress forests (Figure 4.1). The resulting reference SDI (Rei.80, Rei.85, Rei.90, Rei.95, Rei.99) values ranged from 931 to 1157. For the 0.95 and 0.99 quantiles, the slopes were flatter than those of both Su’s and Yen’s models (Table 4.2).

For pine forests, there were no related published equations or diagrams for obtaining reference SDIs. So, only an estimated Reineke’s model was used to establish a reference SDI (Figure 4.2). There were 57 plots with greater than 80% pine BA of pine species in the plots. The reference SDIs in pine forests ranged from 1023 to 1618 (Table 4.3). The slope of the equations for each quantile was very close to Reineke’s slope (Table 4.3).

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4.3 Relative Density (Ducey and Knapp Model)

4.3.1 Preliminary Fit

When using TFRI4 datasets to fit Eq. 30 for cypress and pine forests, the coefficients of X_0 and X_1 were usually not significantly different from 0 ($p>.05$) for both forest types for range of quantiles (Figure 4.3). For cypress forests, coefficients for X_0 ranged from 0.00025 to 0.00075 and b_0 was not significant for the 0.99 quantile (Table 4.4). The highest value of b_0 was associated with the 0.99 quantile and the lowest one was associated with the 0.90 quantile (Figure 4.3.a). Coefficients for X_1 ranged from -0.00070 to 0.00053 and b_1 was not significant for all quantiles except for the 0.60 quantile (Table 4.4). In contrast to b_0, the highest value of b_1 was associated with the 0.90 quantile, and the lowest one was associated with the 0.99 quantile (Figure 4.3.b). So, the trend of b_0 was counter to that of b_1.

For pine forests, coefficients for X_0 ranged from 0.00033 to 0.00115 and b_0 was significant for all quantiles (Table 4.4). The highest value of b_0 was associated with the 0.80 quantile and the lowest one was associated with the 0.99 quantile (Figure 4.3.c). Coefficients of X_1 ranged from -0.00075 to 0.00035, and, similar to cypress forests, b_1 was not significant for all quantiles (Table 4.4). The highest value of b_1 showed up when quantile was 0.50, and the lowest one was for the 0.80 quantile (Figure 4.3.d). Similar to cypress forests, the trend for b_0 was counter to that for b_1. From Figure 4.3, for both forest types, all coefficients for X_1 were not significantly different from 0 ($p>.05$) and were not be used to estimate implied maximum ASDI (Eq. 38).

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4.3.2 Random Noise for SG

The correlations between X_0 and X_1 in cypress and pine forests were 0.937 and 0.955, respectively. Because the difference between X_0 and X_1 was due to limited information available on SG by species. Only 58 species out of 322 species had their own SG values. Thus, many species shared similar SG values on either genus-, family-, or group-levels. Furthermore, the difference between X_0 and X_1 is the multiplicative factor of SG. These issues caused high correlation between X_0 and X_1 in both forest types. To decrease the correlation between X_0 and X_1, we used a random noise method, generating random deviates and added them to SG for each tree in each plot so that SG varied between trees. We generated 6 levels of random noise: 1, 2, 4, 6, 8, 10 %. Then, following the described methods above (Figure 3.2), we recalculated X_1 for each plot and refit to Eq. 30 using quantile regression to estimate the coefficients of X_0 and $X_{1.}$

Figure 4.4 showed that b_0 in cypress forests became significantly different from 0 ($p < .05$) for all quantiles from 0.50 to 0.99 no matter how much % noise was added to SG. The coefficients of X_0 for each quantile were still close to the original values obtained from the data with no random noise added (Table 4.5). For b_1 in cypress forests (Figure 4.5), when 1 % noise was added, all parameter estimates became significant no matter what quantile was used. From 2 % noise to 6 % noise, b_1 for the 0.75 quantile was not significant (Figure 4.5). For 8 % to 10 % noise, b_1 was not significant for the 0.70, 0.75 and 0.95 quantiles (Figure 4.5). So, when random noise increased from 1 % to 10 %, 95 % confident levels of both b_0 and b_1 for each quantile increased, and a number of non-significant coefficients for X_1 were obtained. Similar to b_0, the coefficients for X_1 were not affected very much by the addition of random noise (Table 4.5).

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For pine forests, b_0 was similar to the coefficients obtained from the data without noise added. The coefficients were significantly different from 0 (Figure 4.6) and values of b_0 were barely affected by random noise (Table 4.6). With 1 % noise added, only the coefficient for the 0.65 quantile was still not significant (Figure 4.6). When random noise was from 2 % to 10 %, all coefficients of X_1 were significant except for the 0.65 and 0.70 quantile (Figure 4.7). Similar to cypress forests, 95 % confident levels of both b_0 and b_1 for each quantile increased with increasing random noise (Figure 4.6, 4.7). No matter how much the random noise was used, the coefficients for X_0 and X_1 in both cypress and pine forests were close to the original values obtained from the data with no random noise added (Table 4.4, 4.5, 4.6).

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4.4 Implied Maximum ASDI

4.4.1 Effects of Random Noise

Estimation of implied maximum ASDI requires significant estimates of b_0 and b_1. The use of random noise reduced the correlation between X_0 and X_1, thus reducing the variance inflation, and resulted in significant estimates of b_0 and b_1, without substantially changing the parameter estimates from the original values obtained using the original data with no random nose added (Table 4.4, 4.5). Figure 4.8 shows that implied maximum ASDIs in cypress forests were able to be estimated since both b_0 and b_1 were significant for each quantile across the range of % random noise. The range of implied maximum ASDI for each % random noise was about 1100 to 2950 as quantiles increased from 0.50 to 0.99 (Table 4.7). For pine forests, the range of implied maximum ASDI for each % of the random noise was from 1100 to 2000 (Figure 4.9; Table 4.7).

As % random noise increased, so did the 95 % confident levels for each parameter estimate. The 1 % random noise resulted in the most precise confidence intervals, so we chose this level of random noise to perturb SG for each tree in each plot. Using these values, we estimated the b_0 and b_1 parameters and solved for implied maximum ASDI for each quantile from 0.50 to 0.99 in this study.

4.4.2 Effects of Basal Area Threshold

As the % of BA constituted by target species increased, the mean number of species within plots decreased gradually (Table 3.2). Cypress forests decreased from 10 species per plot down to 4 species per plot as % cypress BA increased from 0% to 90%.

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Similarly, in pine forests, the number of species per plot decreased from 10 to 3 across the range of % pine BA.

For cypress forests, when the percentages of the BA increased from 0 % to 10 %, implied maximum ASDI for the 0.99 quantile dramatically dropped from 2938 to 1991 (Table 4.8). From 10 % to 40 %, cypress BA, implied maximum ASDI for each quantile generally increased (Figure 4.10). At 50 % cypress BA, b_1 for the 0.65 quantile was not significant and implied maximum ASDI peaked (Figure 4.10). Increasing percentages of cypress BA resulted in decreasing mean values of SG. Mean SG gradually decreased from 0.587 to 0.564 as % cypress BA increased from 0 % to 50 % (Table 4.8).

For pine forests, both 0 % and 50 % pine BA produced estimates of b_1 that were not significantly different from 0. For the 0 % to 10 % pine BA class, implied maximum ASDIs across the range of quantiles were not very different (Figure 4.11). Implied maximum ASDIs slightly decreased for the 10 % to 20 % pine BA class (Figure 4.11), and the dramatically decreased across the range of pine BA from 20 % to 50 % with a stair-step trend appearing (Figure 4.11). Similar to cypress forests, the mean value of SG decreased from 0.585 to 0.557 as % pine BA increased from 0 % to 50 % (Table 4.9). The range of implied maximum ASDI for 0 % to 20 % is about 1050 to 1970 (Table 4.9). When over 30 %, the maximum implied ASDIs for the 0.99 quantile will decrease a lot (table 4.9).

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4.5 Final Relative Density Models by Forest Type

4.5.1 Selection of Quantiles

Comparing the implied maximum ASDI to the reference maximum SDIs in cypress forests, no matter what % cypress BA we used, many reference SDIs were lower than the values we obtained for implied SDI.

For 0 % threshold cypress BA, 10 reference SDIs intersected with the implied ASDI (Table 4.10), 7 were values from from Su (2014)'s results and the others were from our fit to Reineke's model using 0.90, 0.95 and 0.99 quantiles. The 10 reference SDIs have two apparent groups: a low-point group and a high-point group (Figure 4.12). For the low-point group, Su's reference SDIs based on only QMFI data were similar to those of our Reineke's models, and 3 reference SDIs intersected with the implied maximum ASDI for quantiles between 0.54 and 0.60 (Table 4.10). Our Reineke's models for the 0.90, 0.95 and 0.99 quantiles intersected with the implied ASDI at the 0.50 and 0.52 quantiles (Table 4.10). Su's reference SDIs based on the NFI1 to NFI3 data or both the NFI and QMFI data composed the high-point group (Figure 4.12). The range of intersected quantiles were from 0.86 to 0.96 (Table 4.10).

As the threshold % of target species BA increased from 0 % to 10 %, 1 reference SDI did not intersect with the implied maximum ASDI (Figure 4.13) because the implied maximum ASDI for the 0.99 quantile dropped dramatically (Figure 4.13). For the low-point group, Su' reference SDIs based on QMFI data intersected with the implied maximum ASDI for quantiles between 0.54 and 0.61 (Table 4.10). All of our Reineke's models for the 0.90, 0.95 and 0.99 quantiles intersected with the implied

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ASDI at the 0.50 quantile (Table 4.10). For the high-point group, 3 of Su's reference SDIs intersected at quantiles between 0.84 to 0.96 (Table 4.10).

When threshold % of target species BA increased from 10 % to 20 %, there were no intersections between the implied maximum ASDI and the reference SDI based on our Reineke's models (Figure 4.14). For the low-point group, Su' reference SDIs based on QMF data intersected with the implied maximum ASDI when the quantiles were between 0.52 and 0.55 (Table 4.10). For the high-point group, four of Su's reference SDIs intersected with the implied maximum ASDI when the quantiles were between 0.80 to 0.97 (Table 4.10).

For 30 % threshold, only four intersections were observed in the high-point group (Figure 4.15). The quantiles for the intersection points were between 0.80 to 0.98 (Table 4.11). For the 40 % or 50 % BA thresholds, because of the observed peak, some reference SDIs had more than one intersection with the implied maximum ASDI (Figures 4.16 and 4.17), further complicating the choice of final values for b_0 and b_1 (Table 4.11).

Comparing the low-point to the high point groups, at thresholds of 0 % or 10 % both the two groups had a stable b_0 and b_1 for all intersected quantiles, except for Su. A2 (Table 4.10). As the % BA threshold increased from 10 % to 30 %, implied maximum ASDI generally increased (Figure 4.10) thus decreasing the number of intersected quantiles in the low-point group and decreased the quantile were intersection occurred (Tables 4.10 and 4.11). When % BA threshold was 40 % or 50 %, the trend of implied ASDI had a peak, leading to more than one intersection between reference SDI and implied maximum ASDI (Figures 4.16 and 4.17). As a result, for the low-point group, the observed stable range of threshold percentages of target species BA was between 0 % and 10 % and were used as our selection from which to estimate implied ASDI for each quantile for final comparison with reference SDIs from Su.Q2, Su.Q4, Su.Q5, Rei.90, Rei.95 and Rei.99 (Table 4.10). For the high-point group, the observed stable range of threshold percentages of target species BA was between 0 % and 30 % and were used as our selection from which to estimate implied ASDI for each quantile for final comparison with reference SDIs from Su.A4, Su.N4 and Su.N5 (Table 4.10, 4.11).

For pine forests, when the threshold % of target species BA was more than 0, one reference SDI did not intersect with the implied maximum ASDI (Figure 4.18) due to the non-significant estimate of b_1 at the 0.65 quantile. The quantiles ranged from 0.74 to 0.89 at the point of intersection with the implied maximum ASDI (Table 4.12). When the threshold percentages were between 0 % and 10 %, although the intersected quantiles for each reference SDI changed a little, the coefficients of b_0 and b_1 for the same reference SDI were similar to those observed at the 0 % threshold (Table 4.12). The quantiles were between 0.71 to 0.89 at the points of intersection with the implied maximum ASDI (Table 4.12). When the threshold percentages were 20 % or 30 %, the values of implied ASDI decreased rapidly relative to those of 0 or 10%, and a stair-step trend appeared (Figure 4.19). The quantiles were between 0.73 to 0.94 at the point of intersection with the implied maximum ASDI (Table 4.12, 4.13). For the 40 % BA threshold, the quantiles were between 0.74 to 0.98 at the points of intersection with the implied maximum ASDI (Table 4.13). When threshold percentage of target species BA was 50 %, reference SDIs from Rei.95 and Rei.99 were higher than implied maximum ASDI (Figure 4.20). The quantiles were between 0.81 to 0.98 at the point of intersection with the implied maximum ASDI (Table 4.13). So, for pine forests, the observed stable range of threshold % BA was between 0 % and 20 % and were used as our selection

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from which to estimate implied ASDI for each quantile for final comparison with reference SDIs based on our Reineke's models (Table 4.12).

4.5.2 Final Relative Density Formulae

After selecting the range of quantile intersections for each threshold % BA and each forest type, we used the maximum and minimum quantiles as final values to obtain parameter estimates and develop relative density formulae for each forest type. We also used the mean of parameter estimates from all intersected quantiles to develop relative density formulae for each forest type.

In cypress forests, we used 1 % random noise to obtain significant coefficients for b_1 and a threshold of 10 % BA for estimating implied maximum ASDI for low-point and high-point groups. For the low-point group, the quantiles were between 0.50 and 0.61, so the maximum, and minimum quantiles were 0.61 and 0.50, respectively (Table 4.14). The relative density formulae for the low-point group in cypress forests were

$$\mathrm{RD}_{\max} = \sum_i \left(0.000505 + 0.000487 SG_i\right)\left(\frac{DBH_i}{25}\right)^{1.6} \tag{37}$$

$$\mathrm{RD}_{\min} = \sum_i \left(0.000770 + 0.000167 SG_i\right)\left(\frac{DBH_i}{25}\right)^{1.6} \tag{38}$$

$$\mathrm{RD}_{mean} = \sum_i (0.000654 + 0.000322 SG_i)(\frac{DBH_i}{25})^{1.6} \tag{39}$$

For the high-point group in cypress forests, the quantiles were between 0.84 to 0.96, and maximum and minimum quantiles were 0.96 and 0.84, respectively (Table 4.14), yielding the following relative density formulae:

$$\mathrm{RD}_{\max} = \sum_i \left(0.000353 + 0.000273 SG_i\right)\left(\frac{DBH_i}{25}\right)^{1.6} \tag{40}$$

$$\mathrm{RD}_{\min} = \sum_i \left(0.000319 + 0.000429 SG_i\right)\left(\frac{DBH_i}{25}\right)^{1.6} \tag{41}$$

$$\mathrm{RD}_{mean} = \sum_i (0.000314 + 0.000393 SG_i)(\frac{DBH_i}{25})^{1.6} \tag{42}$$

For pine forests, we also used 1 % random noise to get significant estimates for b_1 and a threshold % BA of 10 % as a standard for plot selection. All reference SDIs intersected with the line of implied ASDI (Table 4.12) and the selected quantiles were between 0.71 to 0.89; therefore, we used 0.89 and 0.71 for the maximum and minimum quantiles (Table 4.14) to obtain final parameter estimates yielding the following relative density formulae for pine forests

$$\mathrm{RD}_{\max} = \sum_i \left(0.000983 - 0.000634 SG_i\right)\left(\frac{DBH_i}{25}\right)^{1.6} \tag{43}$$

$$\mathrm{RD}_{\min} = \sum_i \left(0.000711 + 0.000172 SG_i\right)\left(\frac{DBH_i}{25}\right)^{1.6} \tag{44}$$

$$\mathrm{RD}_{mean} = \sum_i (0.001065 - 0.000597 SG_i)(\frac{DBH_i}{25})^{1.6} \tag{45}$$

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Chapter 5 Discussion

5.1 Trends of Coefficients

Before using the random noise method, trends of estimated parameter by preliminary fit were totally different than those of Ducey and Knapp (2010). Both b_0 and b_1 in Ducey and Knapp’s paper have a decreasing trend as quantiles increased from 0.50 to 0.99. Here, estimates for b_0 and b_1 for each forest type varied (sometimes increasing, sometimes decreasing) as quantiles increased from 0.50 to 0.99 (Figure 4.3). In some cases, b_0 and b_1 have opposite trends for certain quantiles that does not appear in Ducey and Knapp’s results.

In Ducey and Knapp’s (2010) study they had more than 1000 sample plots to use to fit the Eq. 30 and estimate coefficients for X_0 and X_1. They also only had about 130 species in their dataset, each with its own estimate of specific gravity. In this study, there were 215 plots with 254 species for cypress forests and 199 plots with 246 species for pine forests (Table 3.1). For many of our species, we did not have unique specific gravity estimates and relied on genus-level averages, family-level averages, or, in some cases, broadleaved species averages. The combination of small sample sizes, complex stand composition, and non-unique specific gravity estimates impacted the estimates of b_0 and b_1 and the observed trends across the quantiles. While we cannot clearly distinguish which reason produced the differences between our results and those of Ducey and Knapp (2010), we can speculate that the non-unique specific gravity estimates played a major role, given how well even low levels of random noise improved our results. The reduction in correlations between X_0 and X_1, resulting in lower variance inflation and more stable and significant parameter estimates, improved our results, though there were still some differences in trends between our study and those of Ducey and Knapp (2010). The strength of Ducey and Knapp's (2010) dataset suggests that their results is what should be expected; however, this is the first study that we are aware of that has attempted to apply their approach to a new forest type. The smaller sample sizes, increased species complexity, lack of species-specific specific gravity values, and the lack of independent reference SDIs, all highlight important constraints on the approach proposed by Ducey and Knapp (2010) to estimate implied maximum ASDI.

5.2 Random Noise

Different tree species have different life history strategies and, therefore, allocate resources differently. For fast-growing and short-lived species, wood cells are generally larger and thinner walled, thus producing trunks with less woody biomass and more space filled with water or air. For slow-growing and long-lived species, it is hypothesized that trees need to invest in greater trunk strength to survive more extreme disturbance events. For these species, wood cells are generally smaller and the cell walls thicker, thus producing stronger trunks with more woody biomass and less space. The SG of wood is a measure of the amount of structural material that a tree species allocates to support and strength. While SG generally reflects tree life history strategy, there is much variation in SG from pith to bark. SG may remain constant, increase or decrease dramatically, moderately, or slightly from pith to bark. For example, in some tropical pioneer and second growth species, SG can increase 4-fold or more (Wiemann and Williamson 1988, 1989a, b). In mature forests, some species may only show slight differences where heartwood may have higher SG than sapwood because of the presence of secondary compounds (Williamson 2010). In addition, the SG can be strongly affected by wood formation relative to the of the live crown or by the formation of tension or compression wood (Williamson 2010). SG also varies by height along the trunk but this variation is rarely known for most species (Rueda and Williamson 1992). Because of these factors and differences microclimate and genics, SG within trees and between trees on the same plot, and even classified as the same species, can be quite different. Published SG values are averages and may be based on limited samples from a limited range of sites, age, and climates – often this information is unpublished or unknown.

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In this study, more than half of species did not have species average SG values available, and we used genus-level average SG, family-level average SG, or an average SG value for all broadleaved species (Table A2.). The use of so many group-level averages increased the correlation between X_0 and X_1, resulting in variance inflation and produced many estimates of b_0 and b_1 that were not significantly different from 0. These factors were the primary motivation for our use of random noise with SG. Adding just 1 % random noise to SG was sufficient to produce significant coefficients so that we could estimate implied maximum ASDI. We feel that the addition of the random noise not only had statistical benefits, but also reflects the inherent variation in SG expected.

As added random noise increased from 1 % to 10 %, 95% confidence interval of b_1 increased, which was likely due to increasing variation in estimates of X_1 that could affect the fit of quantile regression (Figure. 4.5, 4.7). Although we expect that SG to vary between species due for different ecological reasons, a random noise of 10% may appear to be too much of noise. Thus, judging from this, adding 1 % of noise to SG for each tree in each plot would be more reasonable.

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5.3 Basal Area Threshold

When quantile is from 0.80 to 0.99, we can see that b_1 is usually a positive value for cypress forests and a negative value for pine forests (Table 4.9, 4.10). As increasing % of the BA constituted by target species, mean SG has a decreasing trend for each forest type. Because the higher percentages of the BA, the higher number or size of cypress species or pine species. For *C. formosensis* and *C. obtusa*, their SG were 0.354 and 0.445, respectively (Table A2). For *P. taiwanensis*, *P. armandii* and *P. morrisonicola*, their SGs were 0.514, 0.468 and 0.472, respectively (Table A2). So, the mean SG from selected plots was gradually close to the two of cypress species or the three of pine species. For cypress forests, because of a positive value of b_1 and a decreasing trend of mean SG, when solving for implied maximum ASDI, there will be an increasing trend as increasing % of the BA (Figure 4.10). Then, values of the intersected quantile estimated by increasing implied maximum ASDIs and fixed reference maximum SDIs will become small as increasing % of the BA (Table 4.10, 4.11). For pine forests, there are a negative value of b_1 and a decreasing trend of mean SG. So, the trend of implied maximum ASDI is decreasing as increasing % of the BA (Figure 4.11) and the quantiles intersected by decreasing implied maximum ASDIs and fixed reference maximum SDIs will become large as increasing % of the BA (Table 4.12, 4.13).

For mixed-species forests, it is arbitrary to decide on a threshold of percentage of the BA constituted by target species in a plot. Initially, if a plot includes one of *C. formosensis* or *C. obtuse*, this plot will be classified as one member of cypress forests. If a plot includes one of *P. taiwanensis*, *P. armandii* and *P. morrisonicola*, the plot will become one of pine forests. However, if target species only occupies very few % of the

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BA in the plot, it is questionable whether the plot should be regarded as the other forest type or not. In the study, both cypress and pine forests choose 10 % as their BA threshold. From Table 3.2, we can see that the mean number of observed species is about 10 below 50 % of the BA. As a result, 10 % of the BA is not only located in a stable range to obtain significant parameter estimations, it also presents that the target species has reached the minimum standard proportion.

For irregular trends of implied maximum ASDI, we figure out one possible reason. As increasing % of the BA, the number of available plots will gradually decrease (Table 3.2). Because of the small sample size in our study, trends of implied maximum ASDI for 40% and 50% are irregular. Besides, for cypress forests, low % of the BA has a large proportion. When % of the BA increases from 0 to 50 %, sample size decreased dramatically compared to pine forests. Therefore, it can be a reason that the irregular trend of implied maximum ASDI for cypress forests appears at lower % BA than pine forests.

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5.4 Guideline of Establishing Relative Density Measurements

In order to establish a relative density measurement (Eq. 30) for the mixed-species forest, we need to used reference maximum SDI and implied maximum ASDI to result in intersected quantiles for deciding parameter estimations. When we used TFRI4 to fit Ducey and Knapp's model, we face three limitations. The first limitation is that we usually obtained insignificant coefficients of b_1 for each quantile that we cannot estimate implied maximum ASDI for each quantile. To resolve this problem, we can use a random noise method to decrease the correlation between X_0 and X_1 and get significant coefficients of b_1. The second one is that how can we decide a suitable percentage of the BA constituted by the target species to select plots for estimating implied maximum ASDI. We can use basal area threshold as a way of sensitive analysis to see the trends of implied maximum ASDI and find out a stable range of % of the BA, then we can choose a suitable % within the range. The third limitation is that there are plenty of reference maximum SDIs available for cypress forests and the range of the reference maximum SDIs is large. So, we separate intersected quantile for cypress forests into two groups, low-point and high-point group, and use the maximum, minimum of intersected quantiles and mean of all parameter estimates from all intersected quantiles to decide our parameter estimations and establish the relative density measurement for each group and forest type. The step-by-step guideline were,

Step 1. Add 1 % noise to SG for each tree and each plot.

Step 2. Calculate X_0 (Eq. 32) and X_1 (Eq. 33) to scale up our dataset to per ha levels and fit to Ducey's model (Eq. 30)

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Step 3. Set RD = 1 (Eq. 34) and use quantile regression to estimate the coefficients of X_0 and X_1 for quantiles from 0.50 to 0.99, keeping in mind that the τ^{th} quantile is fit as the $1 - \tau^{th}$ quantile.

Step 4. Calculate an average SG by all trees in all plots, and then substitute the coefficients of X_0 and X_1 and the mean SG into Eq. 36 to estimate implied maximum ASDI for each quantile.

Step 5. Use basal area threshold to select plots from 0 % to 50 %, and then repeat Step 2. to Step 4. to find out a stable range of basal area threshold by trends of implied maximum ASDI and decide a suitable percentage of the BA to estimate implied maximum ASDI for each quantile.

Step 6. Use published equations and diagrams, or fit Reineke’s model (Eq. 13) to “pure” plots having at least 80 % of the BA constituted by desired species to obtain reference maximum SDI.

Step 7. Choose the maximum and minimum of the quantiles where implied maximum ASDI intersects reference maximum SDI. The parameter estimates associated with each chosen quantile and mean of parameter estimates from all intersected quantiles form the RD formula for the mixed-species forest.

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5.5 Design Forest Management Strategies

There are many management objectives desired by forest owners or government officers, including producing high-value commercial forest products, maintaining wildlife habitat and water quality, promoting the effects of soil and water conservation and activities of forest recreation and forest treatment and so on. No matter what the objective is, understanding stand density, species composition, and stand structure is the first step to designing suitable forest management strategies.

In mixed-species forests, due to differences in species and vigor of the growing stock, growth response of individual trees may be quite variable and stand structure can be very complex with multiple stories. With the relative density formula, we can use SG to control species composition and predict the change of RD. We can also fix species composition in the plot, and find the desired average tree diameter to attain a specific RD. As a result, with the relative density measurement estimated by the method in this study, it can be a tool to release growing spaces by remove a portion of undesired species and maintain vigorous growing stock enough to create effective regeneration. Besides, for different stories, the relative density measurement can be provided by three possible relative density formulas for managers to choose flexibly and estimate rapidly.

However, for pure stands, only a relative density measure is not very useful unless it is presented diagrammatically and it in relation to measured stand parameters, such as the number of tree, BA, and QMD. Before designing the schedule of forest managements, Gingrich (1967) used upland hardwood forests data to build A-line (stocking percent is 100 %), B-line (stocking percent is 58 %), and C-line (stocking percent is 40 %) to establish over-stocked, fully-stocked and under-stocked zones,

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respectively. When stocking is between A- and B-line, it means that the stand is considered for thinning. If the stand is located in the under-stocked zone, then the stand need some treatments such as planting or fertilization. In the study, the range of the relative density measurement is from 0 to 1. The minimum and maximum relative density values of fully-stocked zone in both cypress and pine mixed-species forests in Taiwan are still unknown and should be tested. If we want to make this method used widely and easily by managers, developing an available SDMD based on number of trees per ha, relative density, and average tree diameter will be necessary in the future.

Chapter 6 Conclusion

In the study, in order to successfully fit TFRI4 data to Ducey and Knapp's (2010) model which can have a great performance on estimating SDI for mixed-species forests in the northeastern United State, we added extra steps into the initial process and develop a guideline for establish relative density measurement in the mixed-species forests. The extra steps make the calculation reflecting underlying ecological processes and provide more flexible choices. However, after getting the relative density, how to make a decision on forest management for the stand still need to test which level of stocking the value stands for. Besides, establishing a SDMD for the mixed-species forest is also an important part in order to make the relative density can be used widely and easily.

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Figures

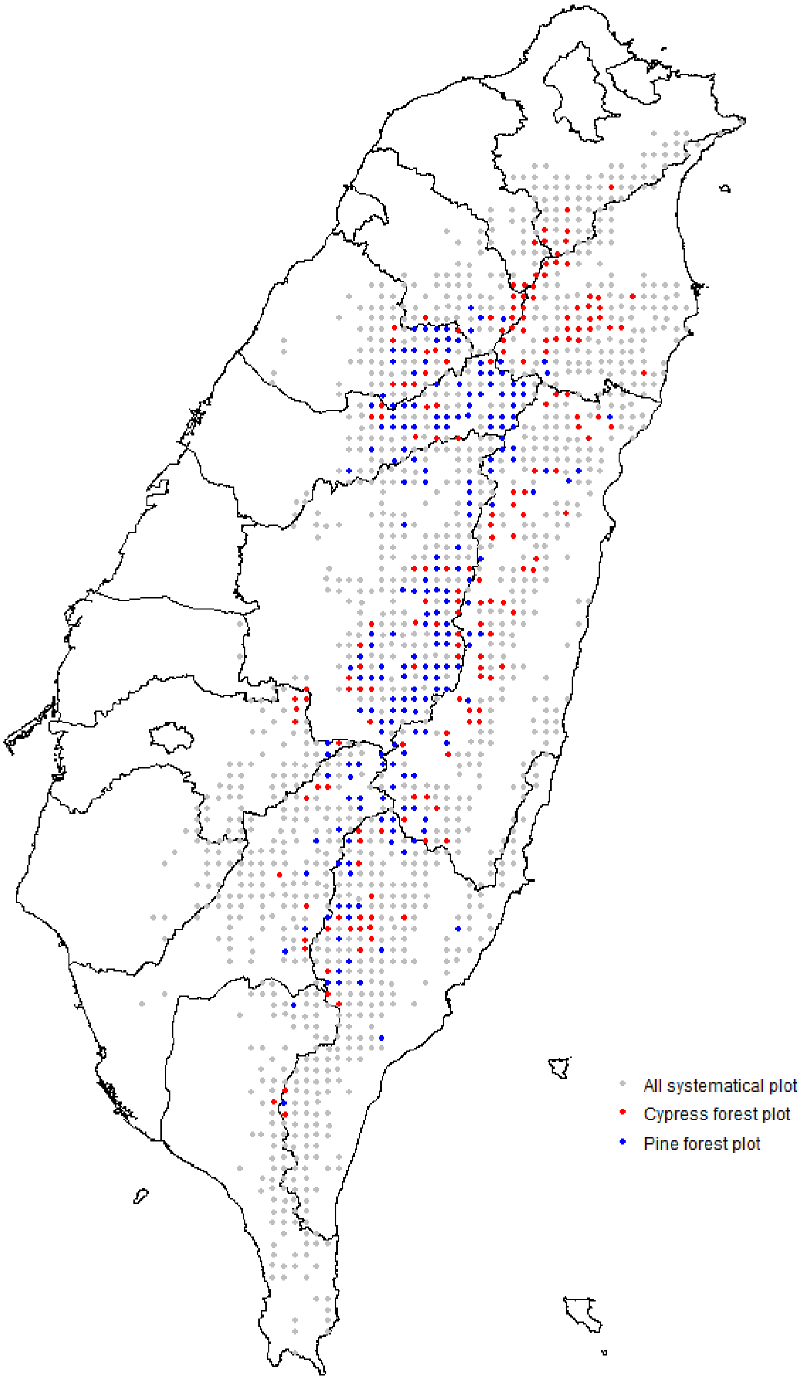

Figure 3.1 A map of Taiwan showing the distribution of the 4th National Forest Inventory (TFRI4) plots for cypress and pine forests.

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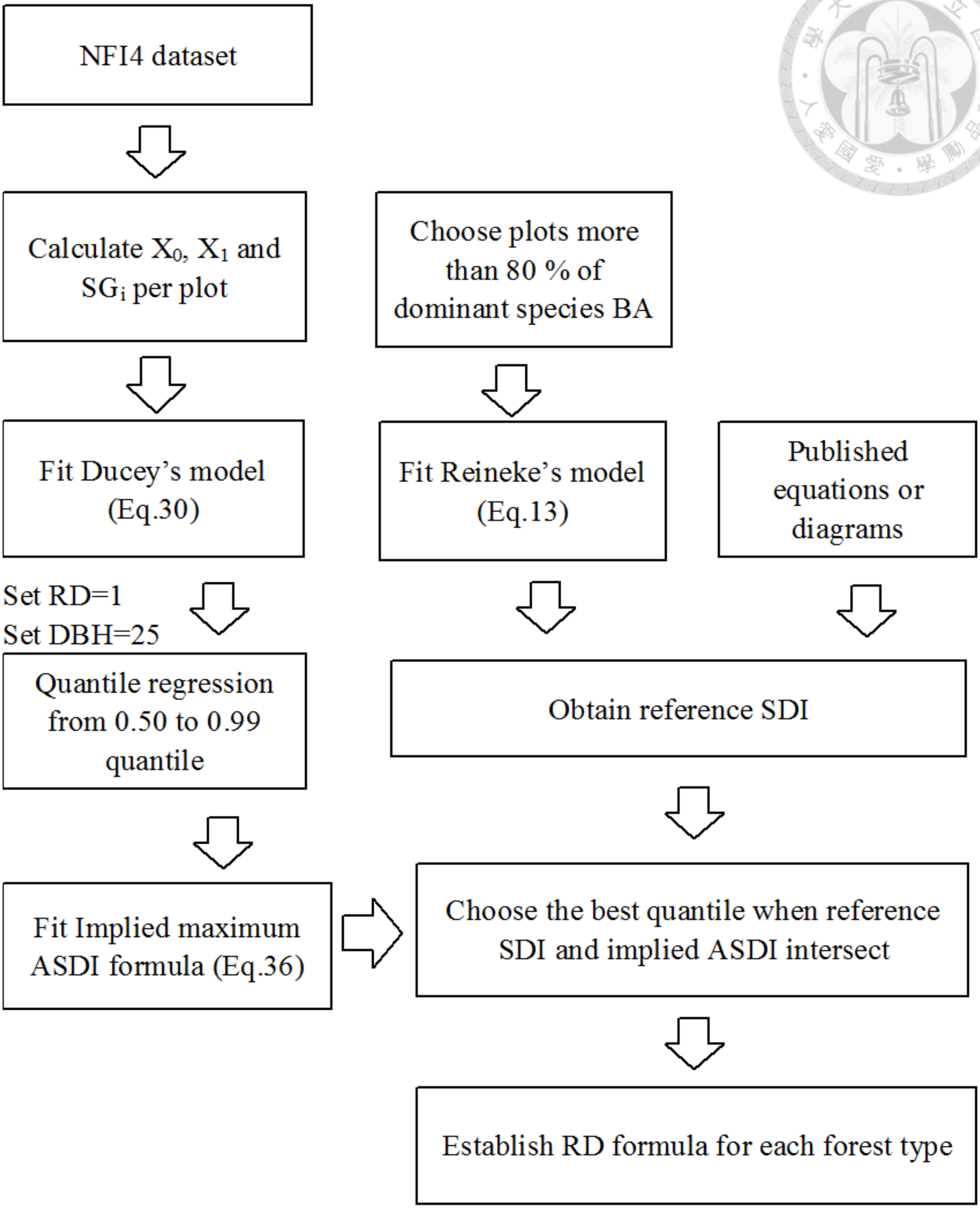

Figure 3.2 A flowchart summarizing the sequence of steps for determining relative density (RD) as implemented in the study.

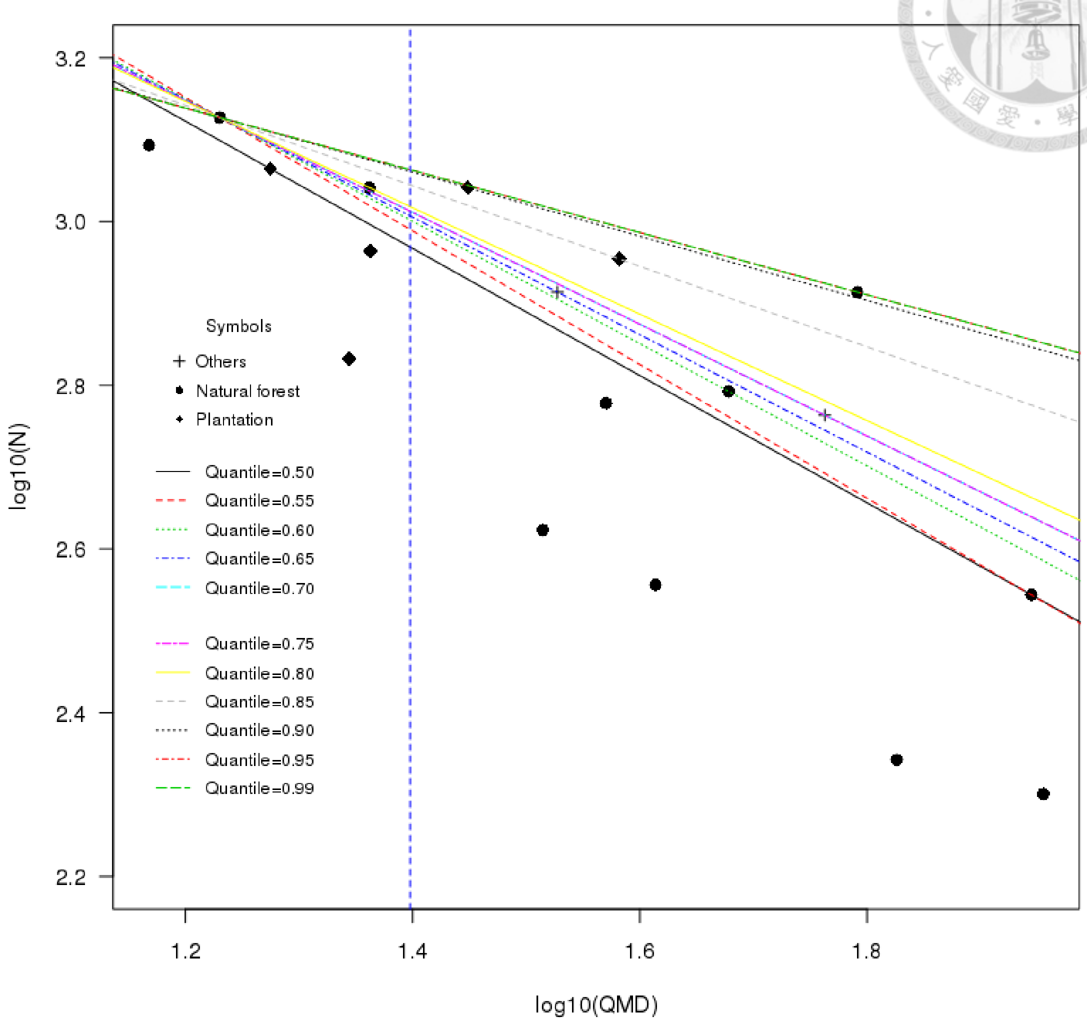

Figure 4.1 Estimated reference maximum stand density index (SDI) for pure cypress forests (plots with more than 80 % cypress BA) by Reineke's SDI equation (Eq. 13).

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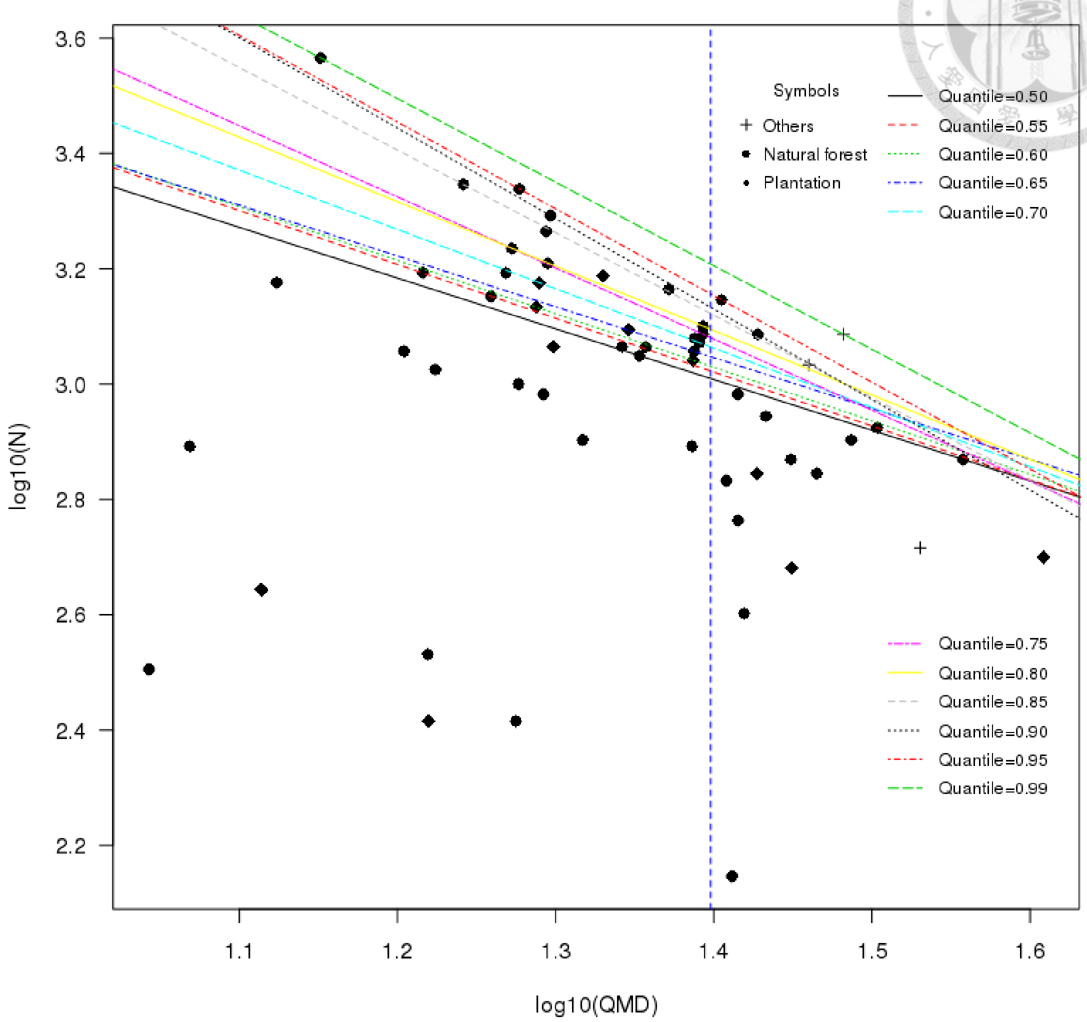

Figure 4.2 Estimated reference maximum stand density index (SDI) for pure pine forests (plots with more than 80 % pine BA) by Reineke's SDI equation (Eq. 13).

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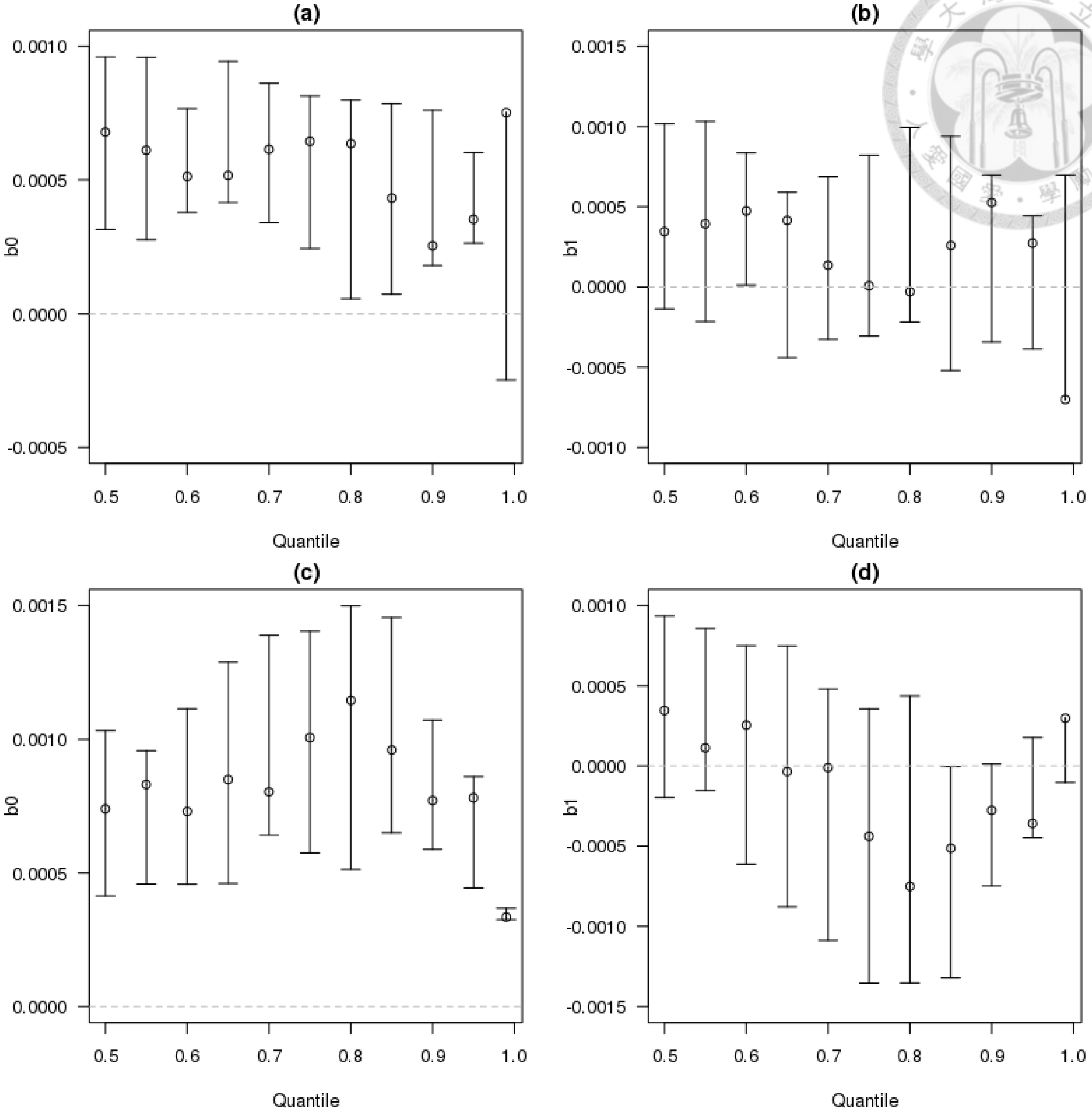

Figure 4.3 Parameter estimates and asymptotic 95 % confidence limits for cypress (a,b) and pine forests (c,d) by quantile applied to Ducey’s model (Eq. 30).

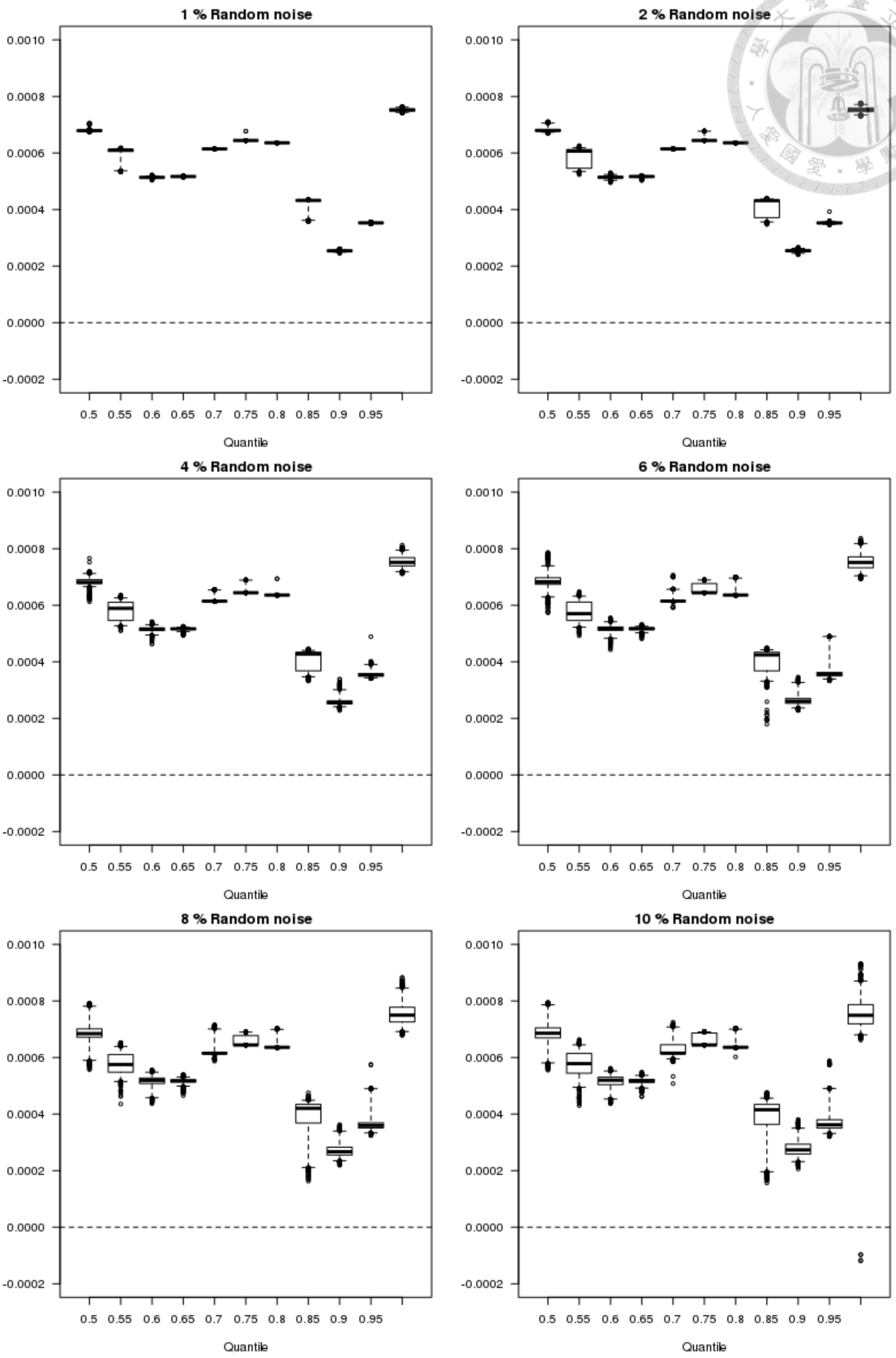

Figure 4.4 Coefficient estimates for X_0 (b_0) by quantiles and level of random noise for cypress forests.

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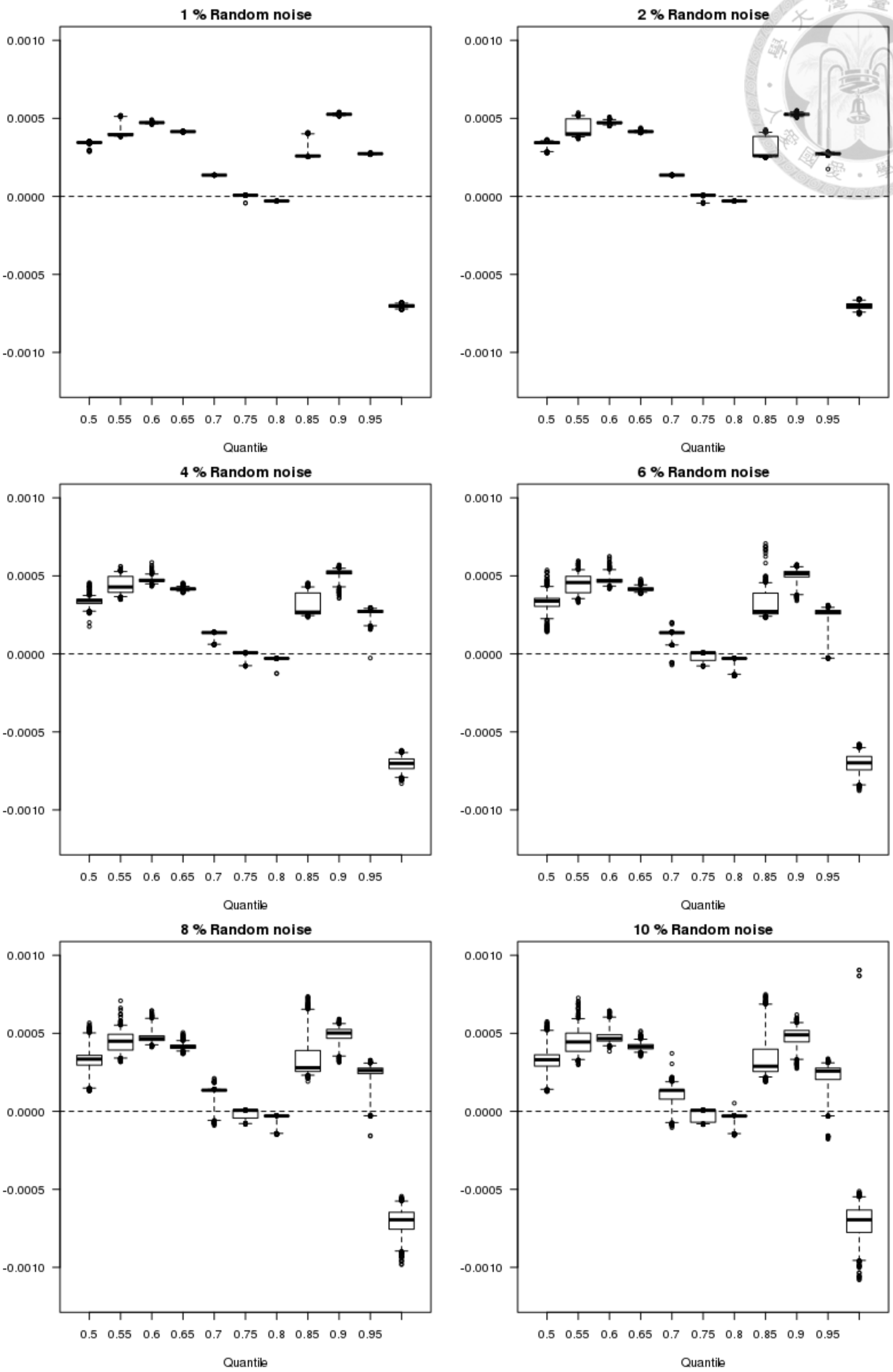

Figure 4.5 Coefficient estimates for X_1 (b_1) by quantiles and level of random noise for cypress forests.

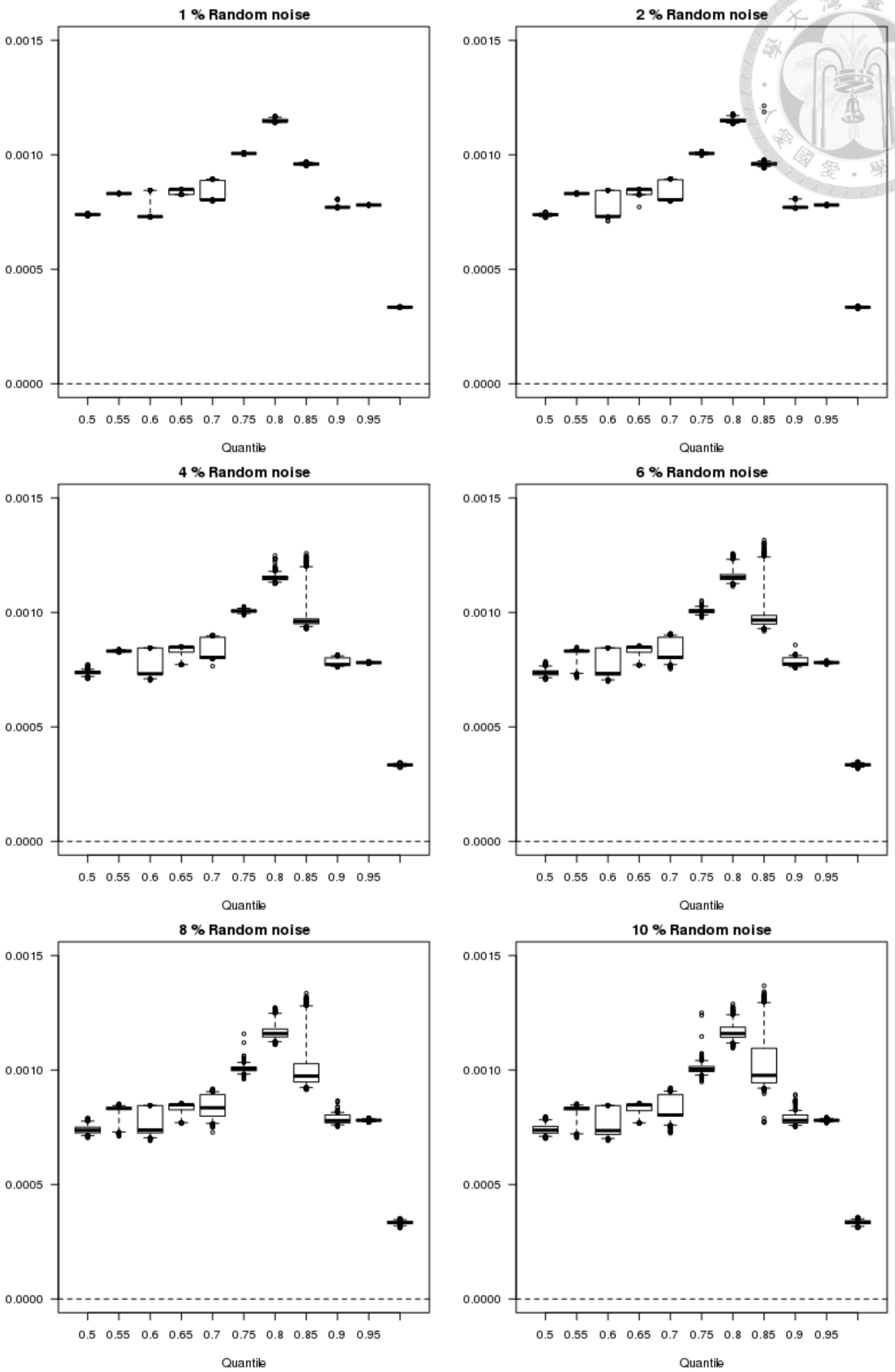

Figure 4.6 Coefficient estimates for X_0 (b_0) by quantiles and level of random noise for pine forests.

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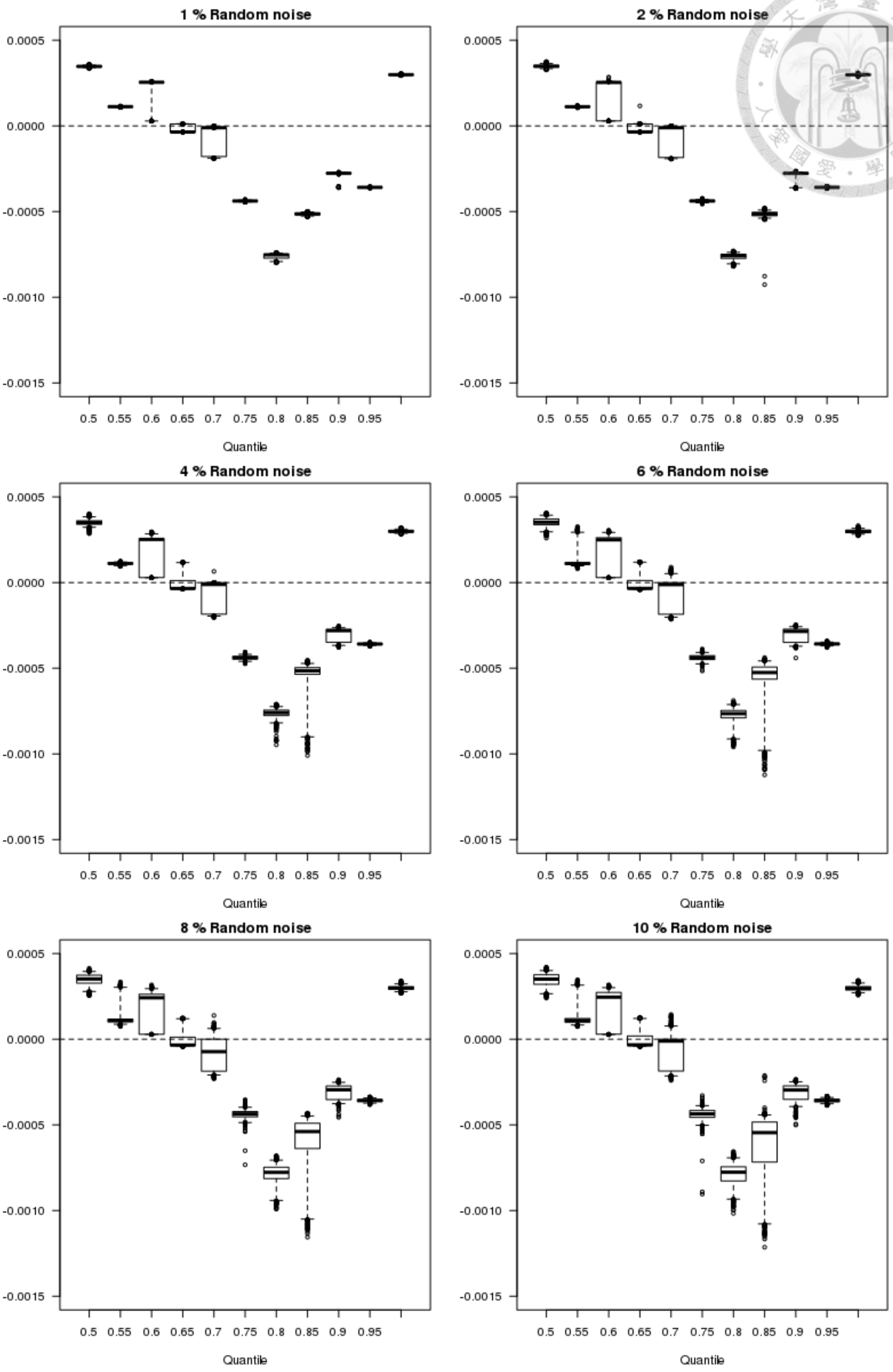

Figure 4.7 Coefficient estimates for X_1 (b_1) by quantiles and level of random noise for pine forests.

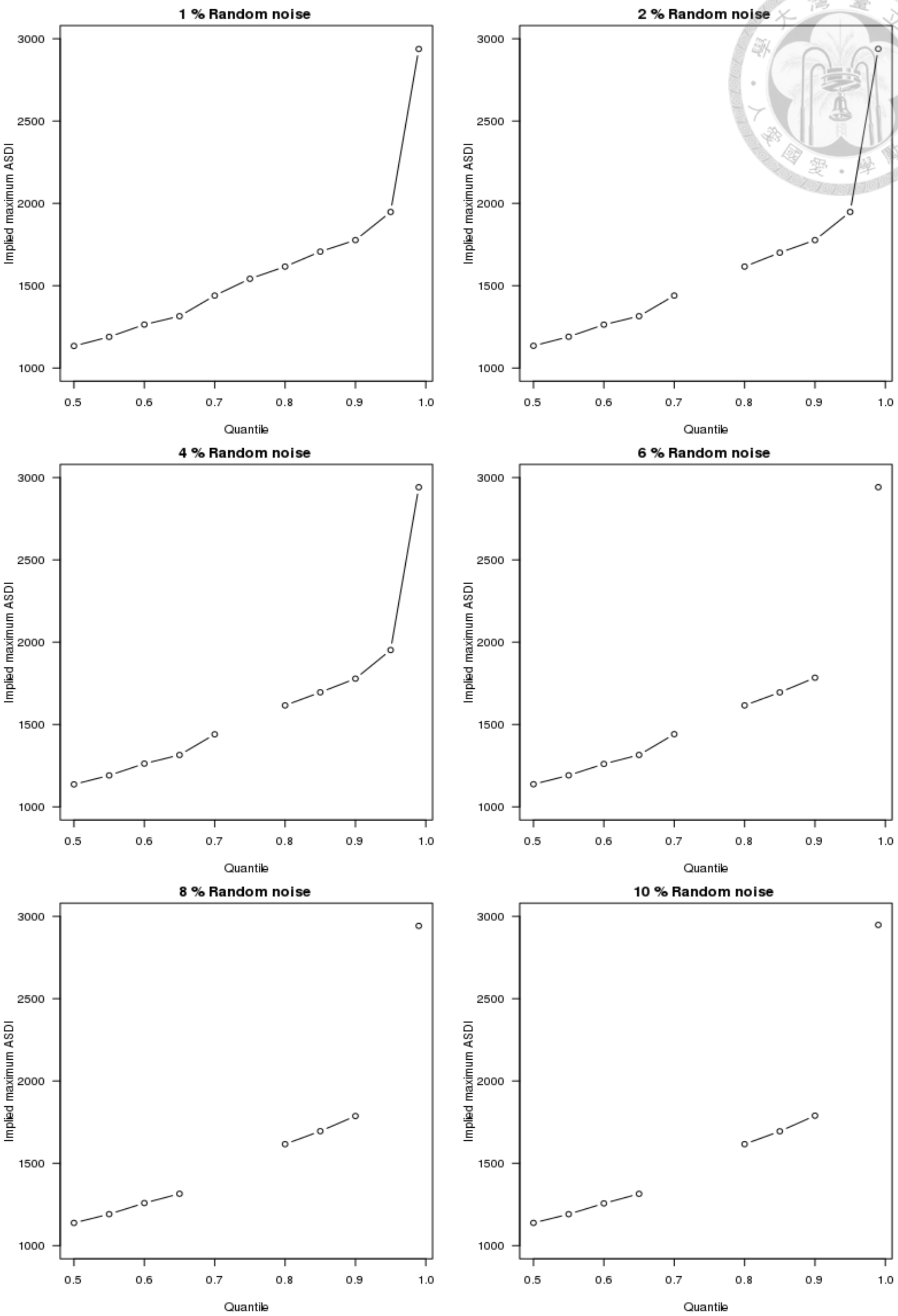

Figure 4.8 Estimates of implied maximum additive stand density index (ASDI) by quantiles and level of random noise for cypress forests (ASDI is only calculated when both b_0 and b_1 are significant).

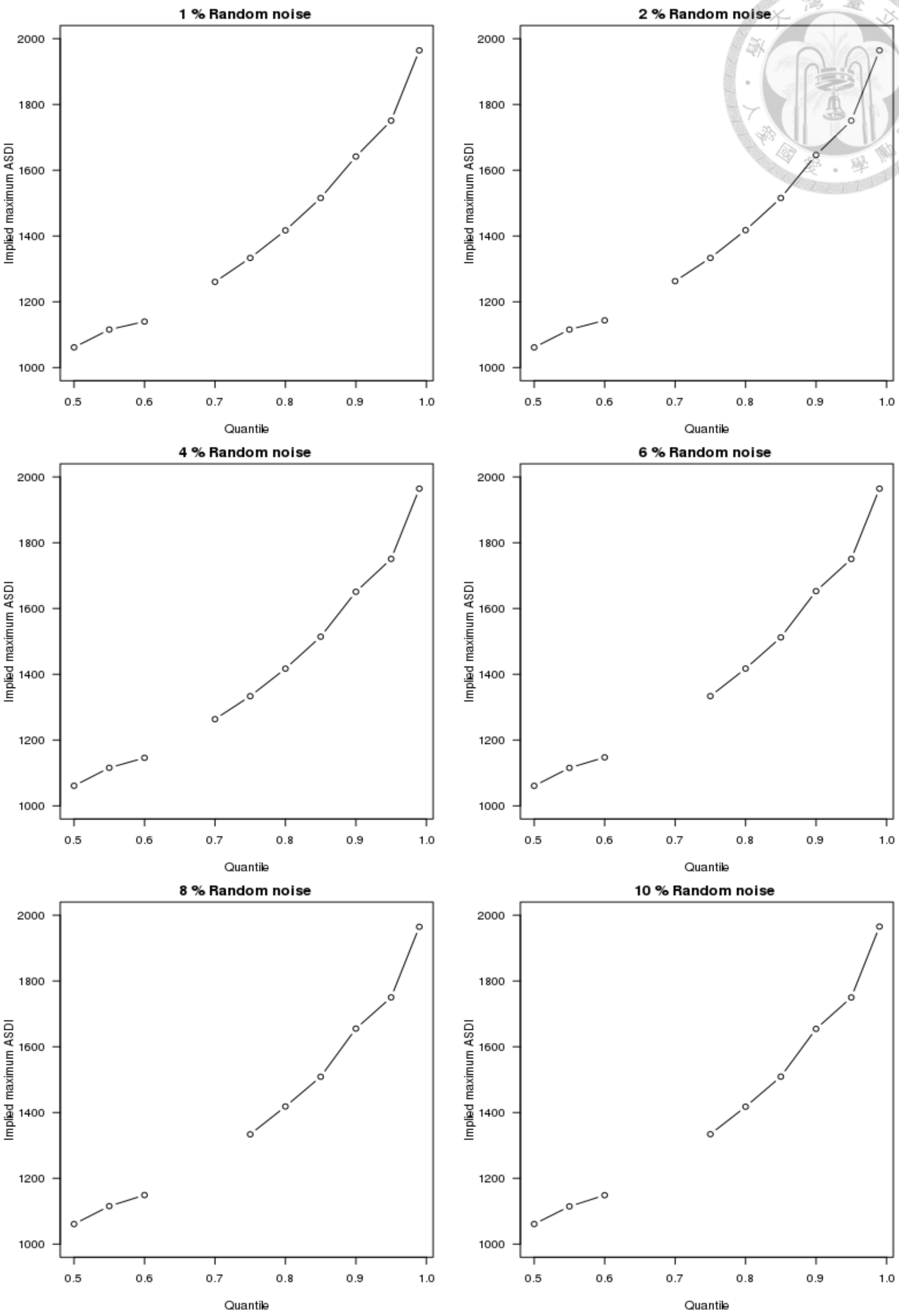

Figure 4.9 Estimates of implied maximum additive stand density index (ASDI) by quantiles and level of random noise for pine forests (ASDI is only calculated when both b_0 and b_1 are significant).

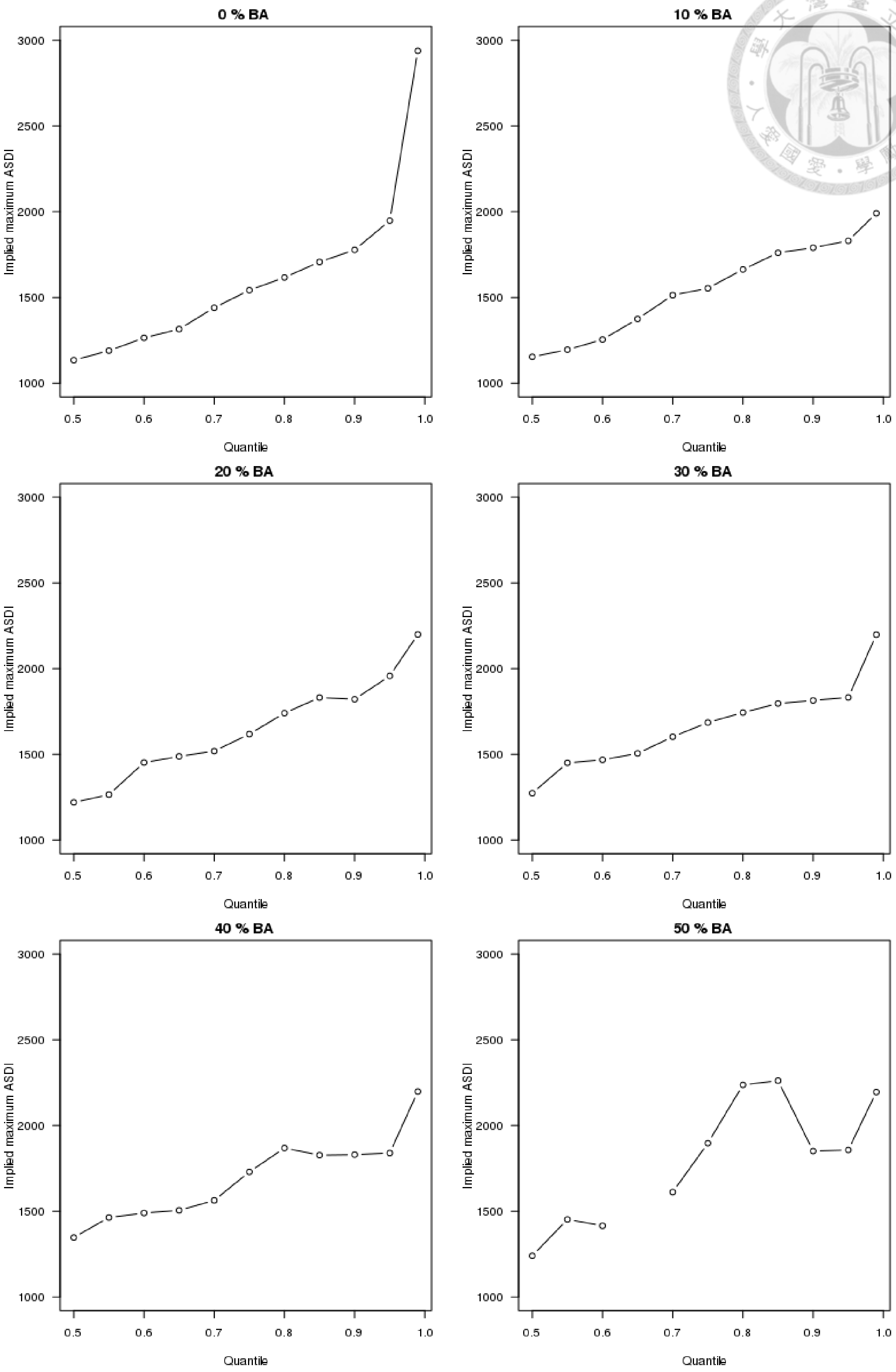

Figure 4.10 Based on 1 % random noise, estimated implied maximum ASDI by quantiles and level of basal area (BA) threshold for cypress forests.

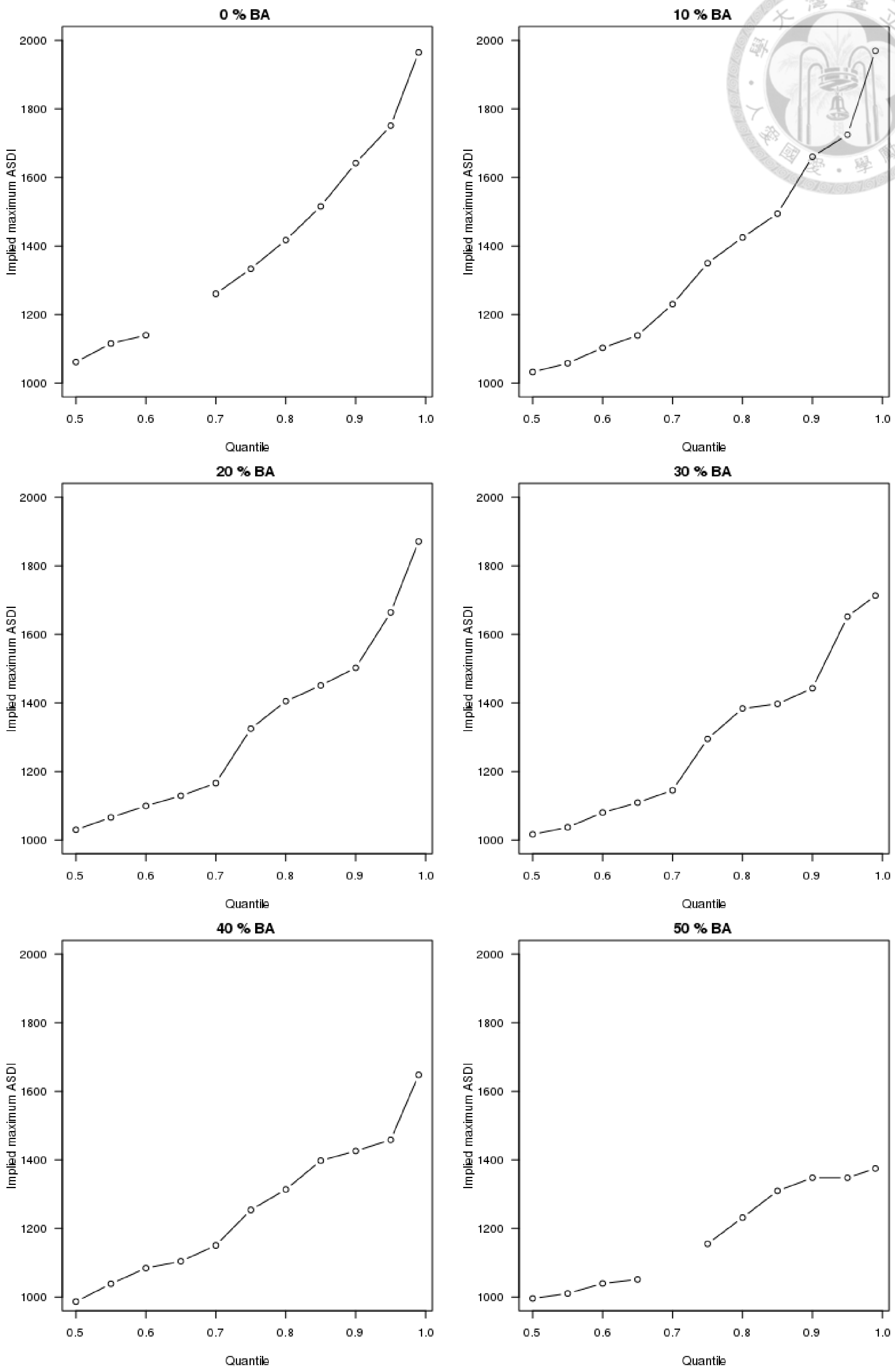

Figure 4.11 Based on 1 % random noise, estimated implied maximum ASDI by quantiles and level of basal area (BA) threshold for pine forests.

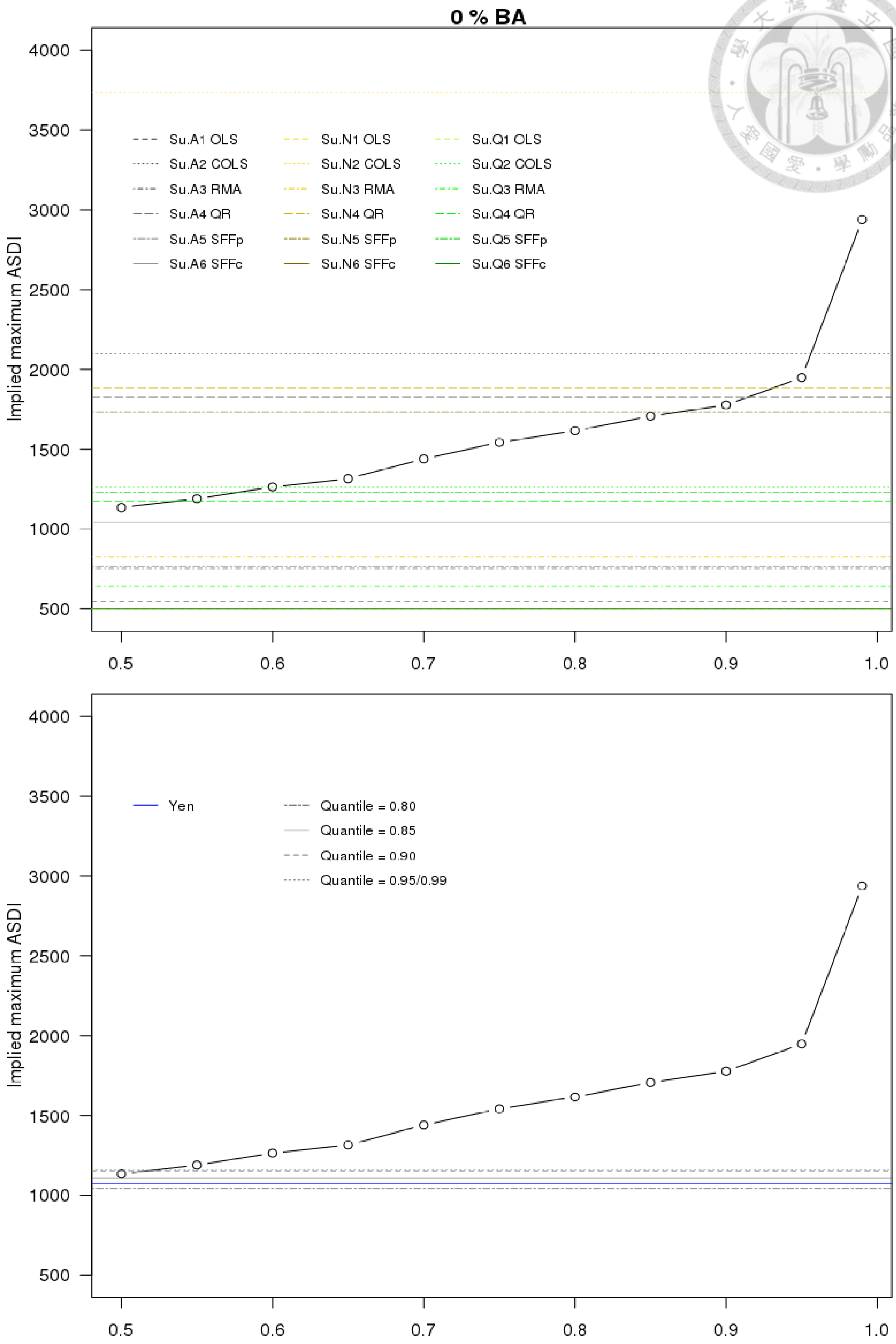

Figure 4.12 Implied ASDI for cypress forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 0 % cypress BA.

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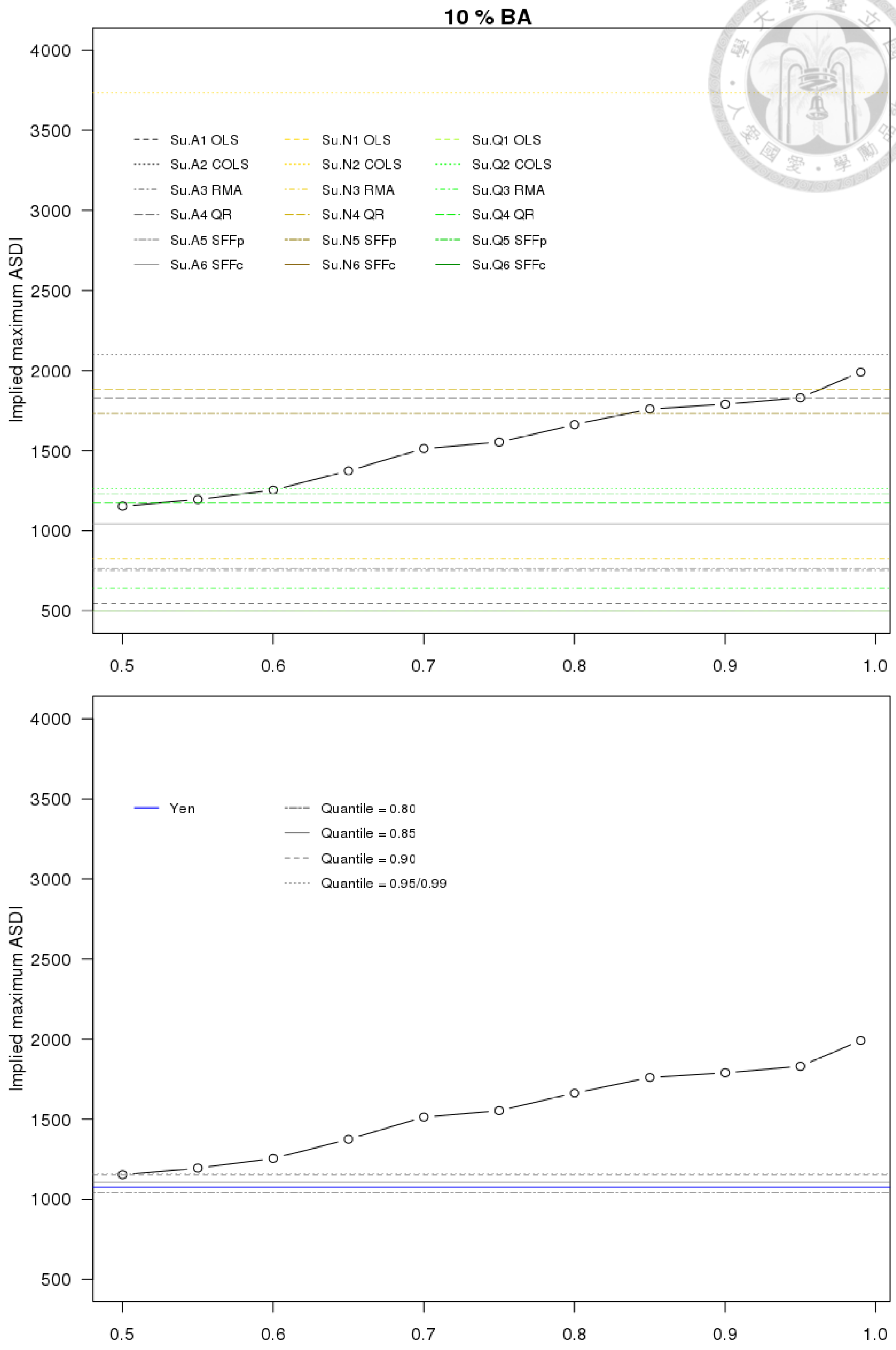

Figure 4.13 Implied ASDI for cypress forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 10 % cypress BA.

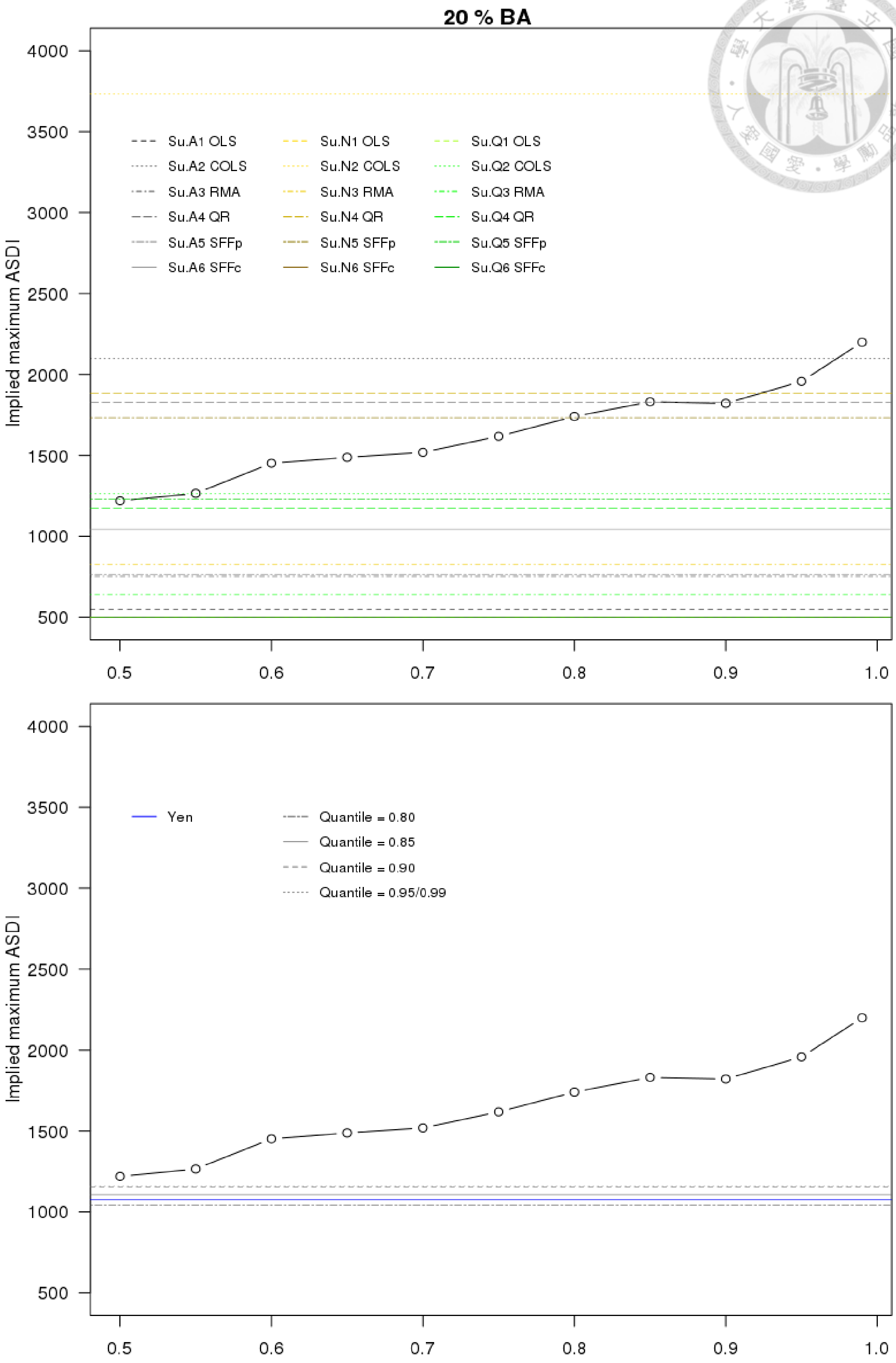

Figure 4.14 Implied ASDI for cypress forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 20 % cypress BA.

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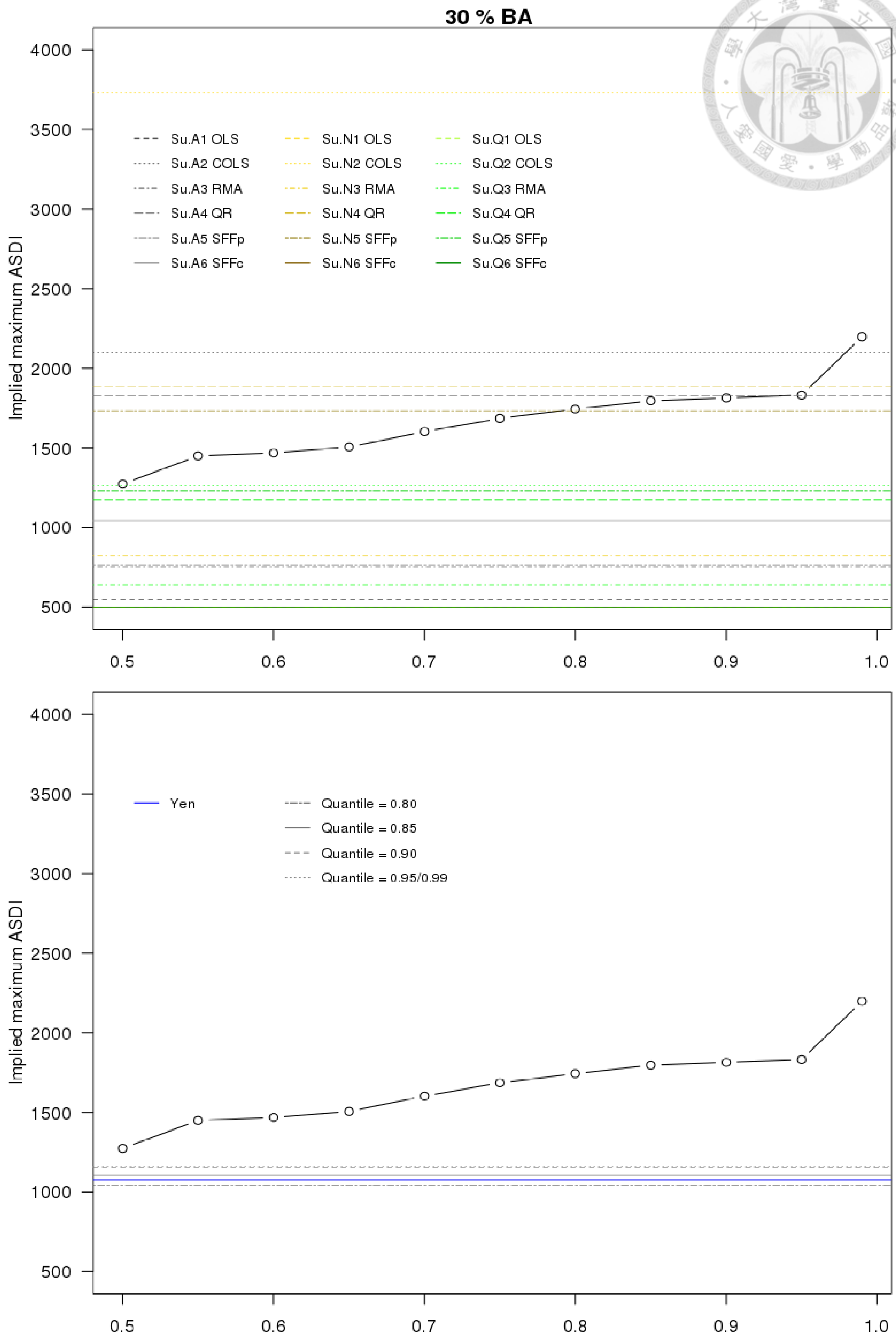

Figure 4.15 Implied ASDI for cypress forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 30 % cypress BA.

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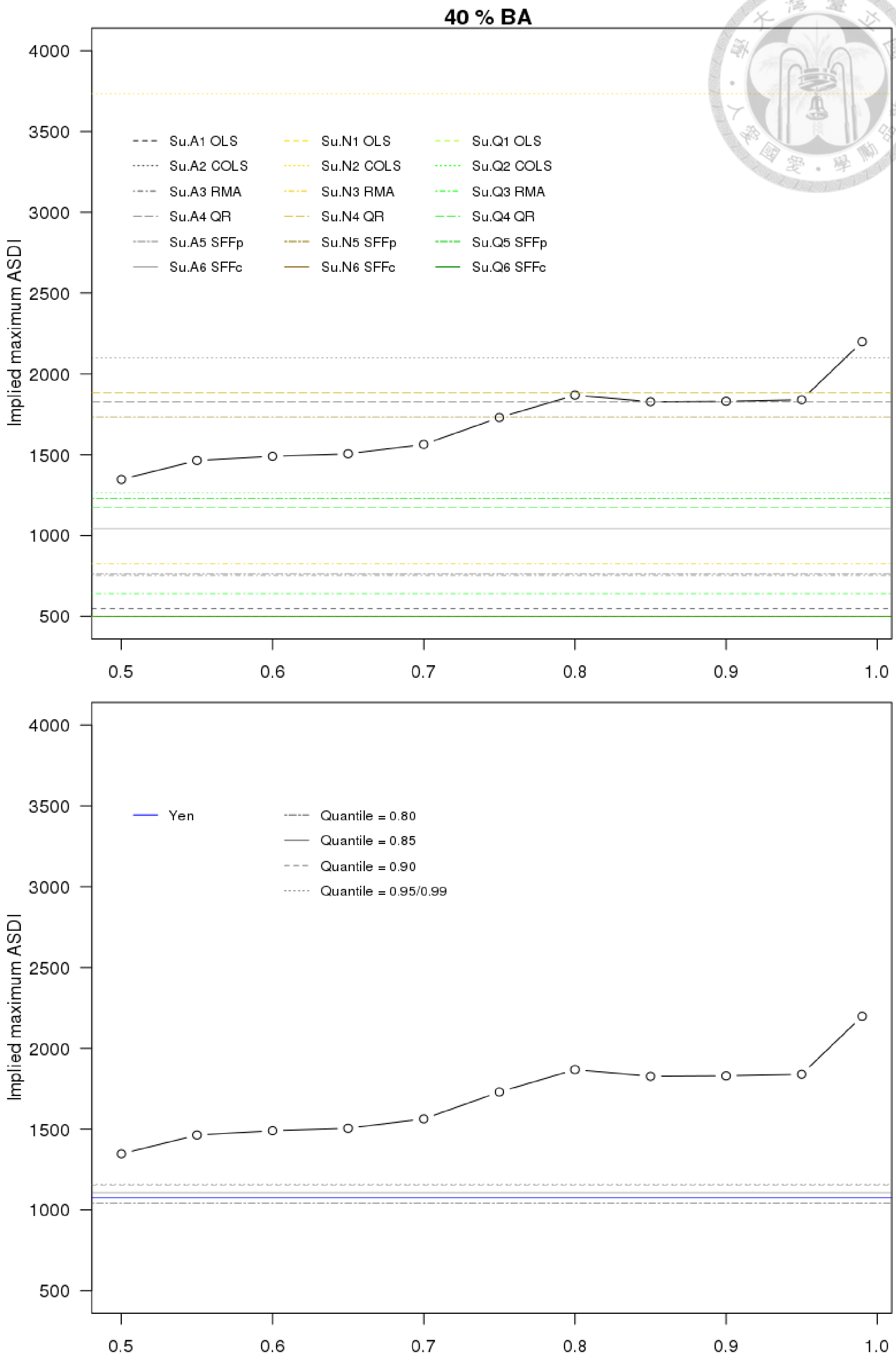

Figure 4.16 Implied ASDI for cypress forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 40 % cypress BA.

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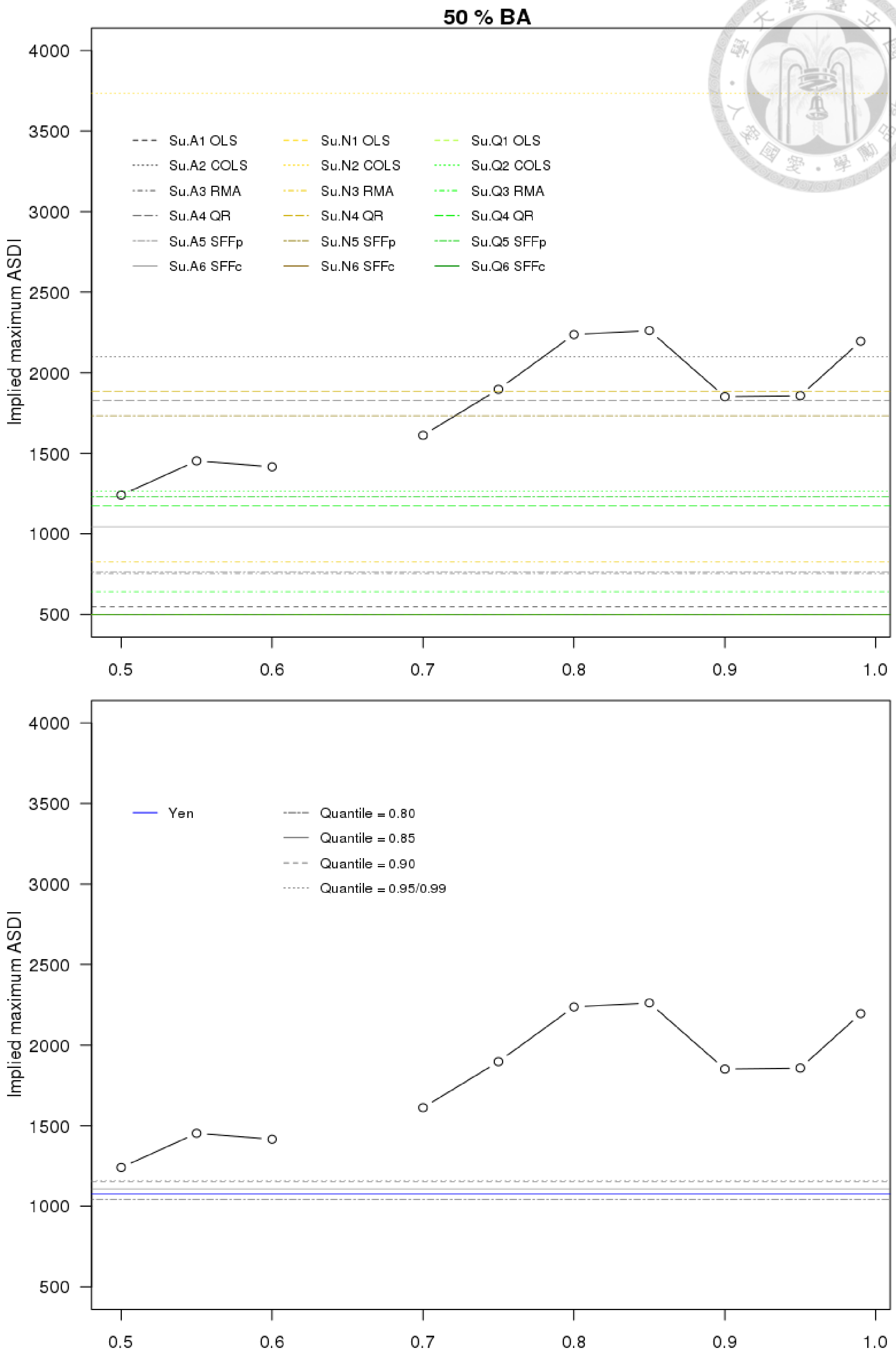

Figure 4.17 Implied ASDI for cypress forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 50 % cypress BA.

doi:10.6342/NTU201701706

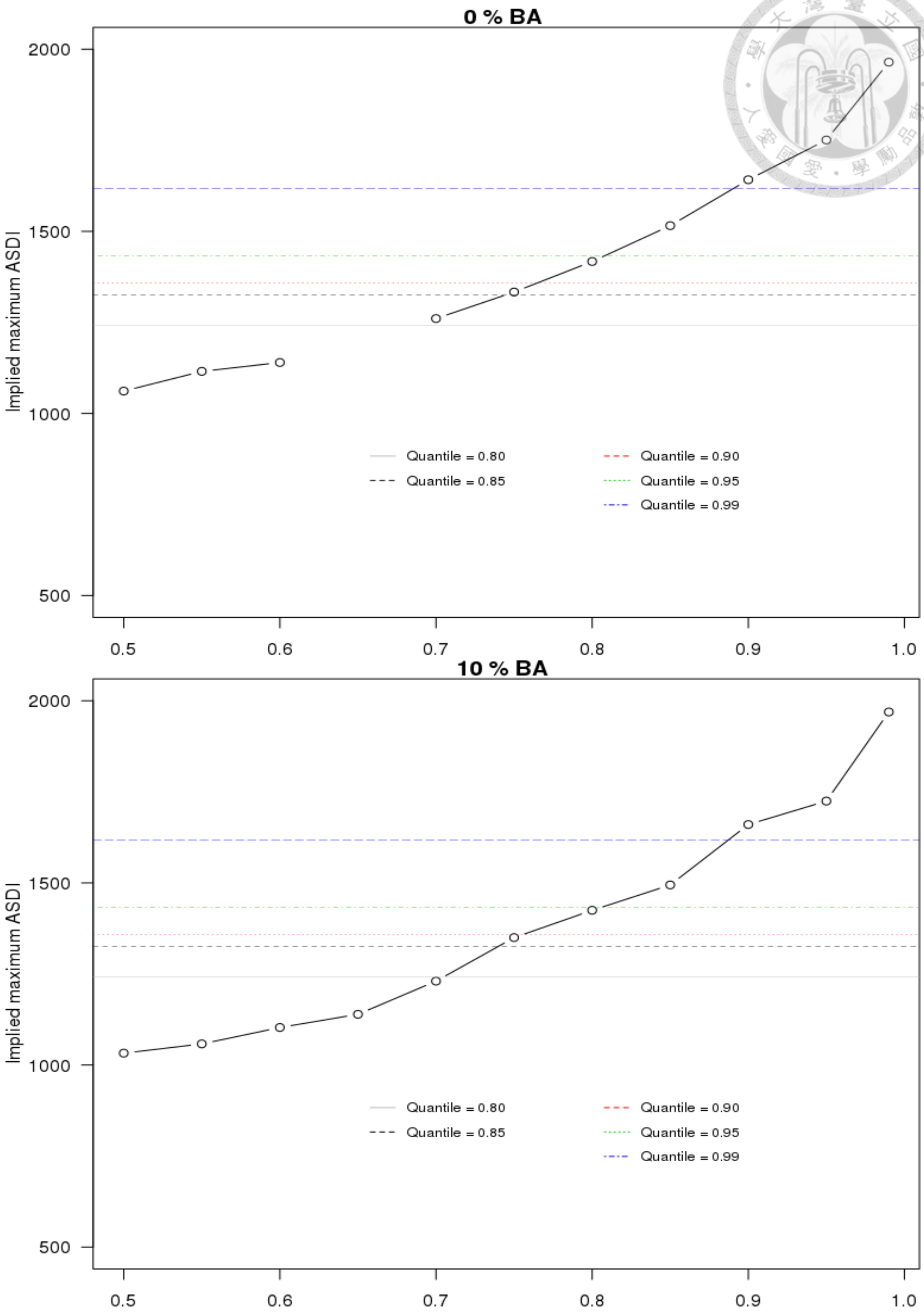

Figure 4.18 Implied ASDI for pine forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 0 or 10 % pine BA.

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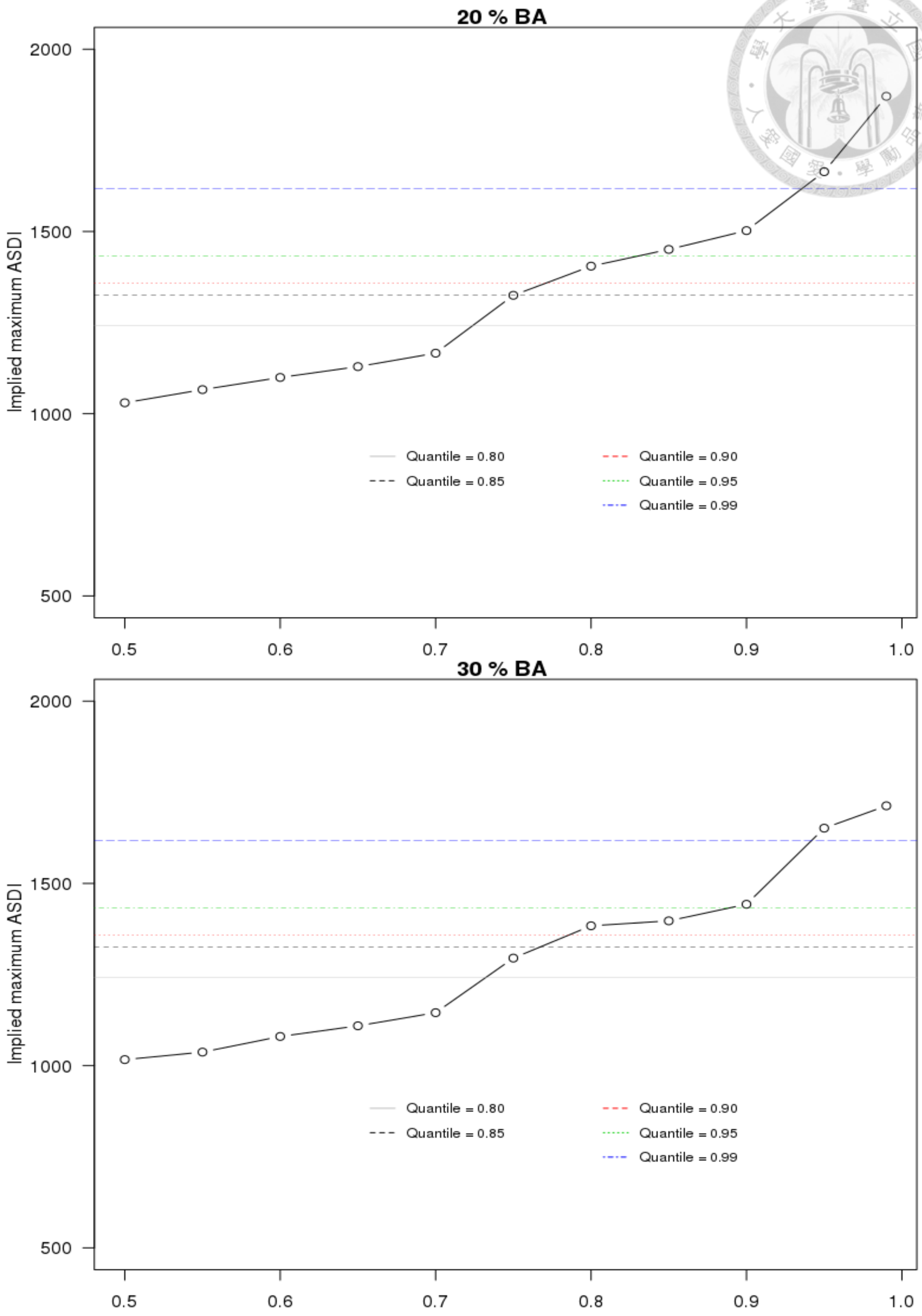

Figure 4.19 Implied ASDI for pine forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 20 or 30 % pine BA.

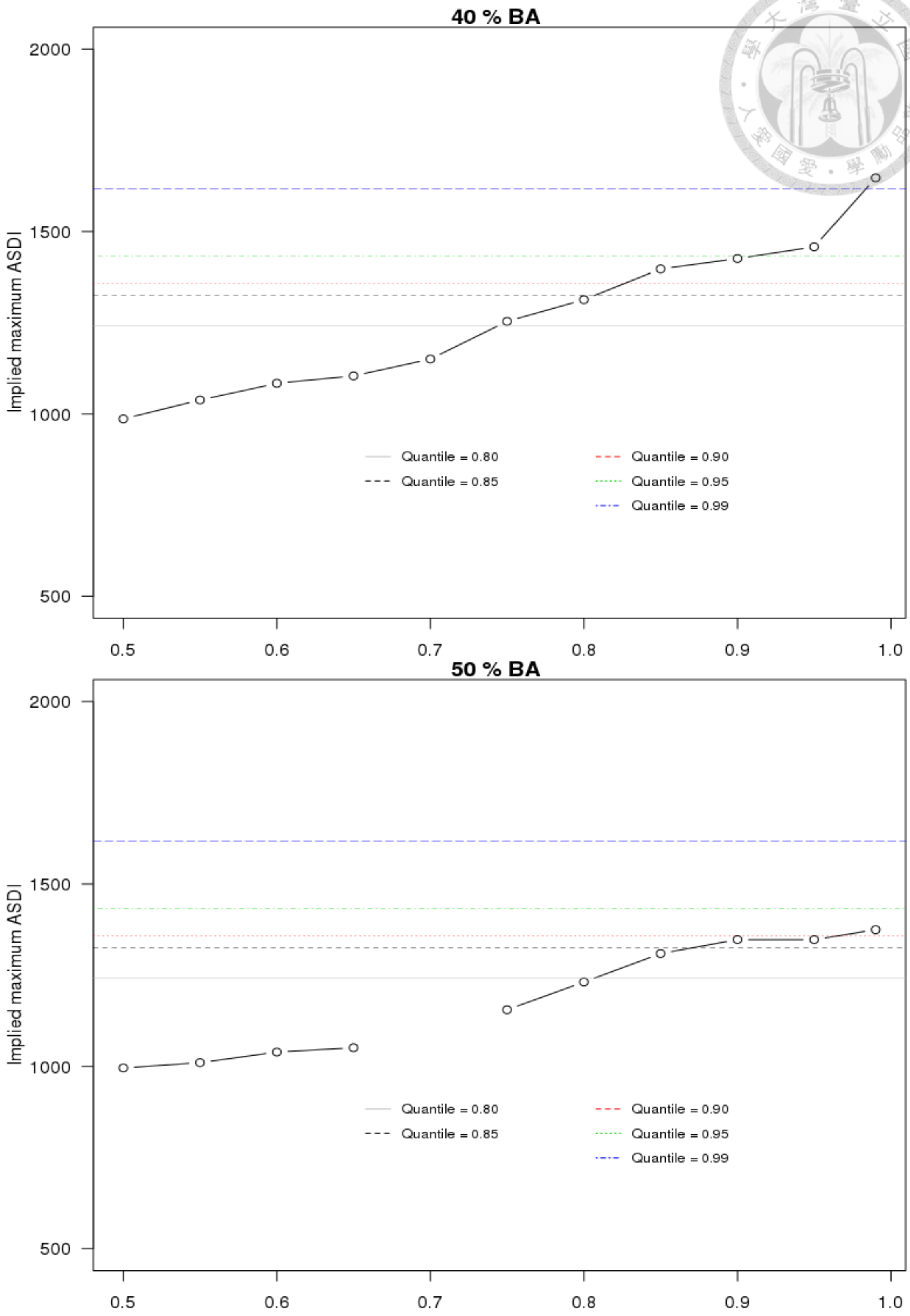

Figure 4.20 Implied ASDI for pine forests as a function of quantile and reference maximum SDI source. Plot selection based on 1 % random noise and 40 or 50 % pine BA.

Tables

Table 3.1 The number of plots and species observed, and the mean, range and coefficient of variation (CV, %) for trees/ha (N), quadratic mean diameter (QMD, cm), basal area (BA, m^2ha^{-1}), and specific gravity (SG) by forest type.

Forest type	Number of plot and species	Variable	Mean	Min	Max	CV
Cypress	(215, 254)	N	1196	140	3740	57.7
		QMD	29.3	10.1	138.2	54.8
		BA	3.58	0.43	21.29	86.7
		SG	0.587	0.362	0.828	15.3
Pine	(199, 246)	N	1241	120	3820	56.7
		QMD	22.5	8.6	48.4	30.7
		BA	2.42	0.09	18.25	71.5
		SG	0.585	0.406	0.872	15.1

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Table 3.2 The number of plots and species observed, and the mean and range of trees/ha (N), and quadratic mean diameter (QMD, cm) by % BA of target species and forest type.

Percent BA	Cypress Forests				Pine Forests			
of Target Species	#Plots	#Species	N	QMD	#Plot	#Species	N	QMD
0 – 10	64	12	1417	24.3	37	11	1509	21.5
		(2,22)	(300,3740)	(10.8,69.9)		(3,26)	(160,3820)	(10.8,48.4)
10 – 20	21	11	1344	21.7	16	11	1328	23.2
		(5,20)	(400,3440)	(10.8,45.8)		(4,19)	(400,3500)	(12.2,45.8)
20 – 30	19	10	1256	25.8	19	10	1220	24.4
		(3,15)	(280,3500)	(10.8,46.1)		(3,16)	(640,2100)	(11.8,40.6)
30 – 40	24	10	1185	31.0	23	8	1263	23.2
		(4,20)	(180,3280)	(12.3,77.8)		(2,18)	(160,3740)	(14.4,34.1)
40 – 50	22	12	1257	29.3	14	8	1333	19.8
		(5,21)	(200,3140)	(10.1,75.8)		(2,17)	(200,2800)	(8.6,36.9)
50 – 60	19	11	981	31.2	10	9	1214	24.3
		(4,19)	(280,1800)	(15.5,56.5)		(3,14)	(640,2200)	(16.7,38.3)
60 – 70	19	10	1011	36.2	14	8	1207	20.9
		(2,19)	(140,1920)	(14.2,138.2)		(3,18)	(160,2480)	(12.3,28.5)
70 – 80	9	10	782	41.9	9	7	804	23.4
		(4,14)	(340,1300)	(16.5,68.9)		(2,12)	(120,1300)	(12.7,35.3)
80 – 90	11	8	849	32.8	18	6	1113	22.8
		(4.12)	(360,1340)	(14.7,57.9)		(3,12)	(400,2180)	(13.0,33.9)
90 – 100	7	5	584	54.5	39	3	1096	22.6
		(3,7)	(200,1160)	(18.8,90.2)		(1,8)	(140,3680)	(11.0,40.6)

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Table 4.1 The mean, minimum (Min), maximum (Max), and coefficient of variation (CV) of X_0, X_1, and SG by forest type.

	Cypress Forests				Pine Forests			
Variable	Mean	Min	Max	CV	Mean	Min	Max	CV
X_0	1022.03	175.77	2781.21	44.5	874.64	46.81	2099.52	48.6
X_1	540.52	95.78	1556.14	46.6	485.77	26.47	1256.77	51.4
SG	0.587	0.362	0.828	15.2	0.585	0.406	0.872	15.0

Table 4.2 Reference maximum SDIs by equation source for cypress forests.

Equation Source	Intercept	Slope	SDI	Condition
Su.A1[a,X]	6.315	-2.558	548	Ordinary Least Squares
Su.A2[a,X]	6.898	-2.558	2099	Corrected Ordinary Least Squares
Su.A3[a,X]	5.055	-1.558	753	Reduced Major Axis
Su.A4[a,X]	6.328	-2.193	1829	Quantile Regression (99th quantile)
Su.A5[a,X]	6.423	-2.532	765	Stochastic Frontier Function (production)
Su.A6[a,X]	6.603	-2.564	1044	Stochastic Frontier Function (cost)
Su.N1[a,Y]	8.246	-3.968	500	Ordinary Least Squares
Su.N2[a,Y]	9.119	-3.968	3732	Corrected Ordinary Least Squares
Su.N3[a,Y]	5.073	-1.543	824	Reduced Major Axis
Su.N4[a,Y]	6.482	-2.294	1884	Quantile Regression (99th quantile)
Su.N5[a,Y]	8.214	-3.559	1733	Stochastic Frontier Function (production)
Su.N6[a,Y]	8.246	-3.968	500	Stochastic Frontier Function (cost)
Su.Q1[a,Z]	5.935	-2.315	500	Ordinary Least Squares
Su.Q2[a,Z]	6.338	-2.315	1264	Corrected Ordinary Least Squares
Su.Q3[a,Z]	5.238	-1.739	641	Reduced Major Axis
Su.Q4[a,Z]	6.599	-2.525	1173	Quantile Regression (99th quantile)
Su.Q5[a,Z]	6.778	-2.638	1231	Stochastic Frontier Function (production)
Su.Q6[a,Z]	5.935	-2.315	500	Stochastic Frontier Function (cost)
Yen[b]	7.002	-1.471	1076	Use volume ($500m^3$) to estimate SDI
Rei.80	3.927	-0.650	1043	0.80th quantile
Rei.85	3.732	-0.492	1107	0.85th quantile
Rei.90	3.610	-0.392	1153	0.90th quantile
Rei.95	3.595	-0.380	1158	0.95th quantile
Rei.99	3.595	-0.380	1158	0.99th quantile

[a] Su (2014)
[b] Yen (2002)
[X] Dataset from both NFI1 to NFI3 and Qilan Mountain
[Y] Dataset only from NFI1 to NFI3
[Z] Dataset only from Qilan Mountain

Table 4.3 Reference maximum SDIs by equation source for pine forests.

Name	Intercept	Slope	SDI	Condition
Rei.80	4.657	-1.118	1242	0.80th quantile
Rei.85	5.124	-1.432	1325	0.85th quantile
Rei.90	5.328	-1.570	1359	0.90th quantile
Rei.95	5.260	-1.505	1433	0.95th quantile
Rei.99	5.236	-1.450	1618	0.99th quantile

Table 4.4 Estimated coefficients for X_0 and X_1, asymptotic 95 % confidence lower limit (LL) and upper limit (UL) by quantiles and forest type.

Forest type	Quantile	b_0	b_0.LL	b_0.UL	b_1	b_1.LL	b_1.UL
Cypress Forests	0.50	0.00068	0.00032	0.00096	0.00035	-0.00014	0.00102
	0.55	0.00061	0.00028	0.00096	0.00039	-0.00021	0.00103
	0.60	0.00051	0.00038	0.00077	0.00047	0.00001	0.00084
	0.65	0.00052	0.00042	0.00094	0.00042	-0.00044	0.00059
	0.70	0.00062	0.00034	0.00086	0.00014	-0.00033	0.00069
	0.75	0.00064	0.00024	0.00081	0.00001	-0.00031	0.00082
	0.80	0.00064	0.00006	0.00080	-0.00003	-0.00022	0.00099
	0.85	0.00043	0.00007	0.00079	0.00026	-0.00052	0.00094
	0.90	0.00025	0.00018	0.00076	0.00053	-0.00034	0.00070
	0.95	0.00035	0.00026	0.00060	0.00027	-0.00039	0.00044
	0.99	0.00075	-0.00025	0.00075	-0.00070	-0.00070	0.00070
Pine Forests	0.50	0.00074	0.00041	0.00103	0.00035	-0.00020	0.00094
	0.55	0.00083	0.00046	0.00096	0.00011	-0.00015	0.00086
	0.60	0.00073	0.00046	0.00111	0.00026	-0.00061	0.00075
	0.65	0.00085	0.00046	0.00129	-0.00004	-0.00088	0.00075
	0.70	0.00080	0.00064	0.00139	-0.00001	-0.00109	0.00048
	0.75	0.00101	0.00057	0.00140	-0.00044	-0.00135	0.00036
	0.80	0.00115	0.00051	0.00150	-0.00075	-0.00135	0.00044
	0.85	0.00096	0.00065	0.00146	-0.00051	-0.00132	0.00000
	0.90	0.00077	0.00059	0.00107	-0.00028	-0.00075	0.00001
	0.95	0.00078	0.00044	0.00086	-0.00036	-0.00045	0.00018
	0.99	0.00033	0.00033	0.00037	0.00030	-0.00010	0.00030

Table 4.5 Estimated coefficients for X_0 and X_1, asymptotic 95 % confidence lower limit (LL) and upper limit (UL) by quantiles and % random noise (RN) for cypress forests.

% RN	Quantile	b_0	b_0.LB	b_0.UB	b_1	b_1.LB	b_1.UB
1%	0.50	0.00068	0.00068	0.00068	0.00035	0.00034	0.00035
	0.55	0.00059	0.00054	0.00061	0.00042	0.00039	0.00051
	0.60	0.00051	0.00051	0.00052	0.00047	0.00047	0.00048
	0.65	0.00052	0.00052	0.00052	0.00042	0.00041	0.00042
	0.70	0.00061	0.00061	0.00061	0.00014	0.00014	0.00014
	0.75	0.00064	0.00064	0.00064	0.00001	0.00001	0.00001
	0.80	0.00064	0.00064	0.00064	-0.00003	-0.00003	-0.00003
	0.85	0.00042	0.00036	0.00043	0.00027	0.00026	0.00040
	0.90	0.00025	0.00025	0.00026	0.00053	0.00052	0.00053
	0.95	0.00035	0.00035	0.00035	0.00027	0.00027	0.00028
	0.99	0.00075	0.00074	0.00076	-0.00070	-0.00072	-0.00068
2%	0.50	0.00068	0.00067	0.00071	0.00034	0.00029	0.00036
	0.55	0.00059	0.00053	0.00062	0.00044	0.00038	0.00052
	0.60	0.00051	0.00050	0.00052	0.00047	0.00046	0.00049
	0.65	0.00052	0.00051	0.00052	0.00042	0.00041	0.00042
	0.70	0.00061	0.00061	0.00062	0.00014	0.00013	0.00014
	0.75	0.00065	0.00064	0.00068	0.00000	-0.00004	0.00001
	0.80	0.00064	0.00064	0.00064	-0.00003	-0.00003	-0.00003
	0.85	0.00041	0.00036	0.00044	0.00030	0.00025	0.00041
	0.90	0.00025	0.00025	0.00026	0.00053	0.00051	0.00054
	0.95	0.00035	0.00035	0.00036	0.00027	0.00027	0.00028
	0.99	0.00075	0.00073	0.00077	-0.00070	-0.00074	-0.00066
4%	0.50	0.00068	0.00067	0.00071	0.00033	0.00027	0.00037
	0.55	0.00058	0.00053	0.00063	0.00044	0.00037	0.00053
	0.60	0.00051	0.00049	0.00053	0.00047	0.00045	0.00051
	0.65	0.00052	0.00051	0.00052	0.00042	0.00040	0.00043
	0.70	0.00062	0.00061	0.00065	0.00013	0.00006	0.00014
	0.75	0.00065	0.00064	0.00069	-0.00001	-0.00008	0.00001
	0.80	0.00064	0.00064	0.00064	-0.00003	-0.00003	-0.00003
	0.85	0.00040	0.00035	0.00044	0.00032	0.00025	0.00043

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	0.90	0.00026	0.00024	0.00030	0.00052	0.00043	0.00055
	0.95	0.00036	0.00034	0.00039	0.00027	0.00018	0.00029
	0.99	0.00075	0.00072	0.00080	-0.00071	-0.00079	-0.00063
6%	0.50	0.00068	0.00063	0.00074	0.00033	0.00023	0.00043
	0.55	0.00058	0.00052	0.00063	0.00045	0.00035	0.00054
	0.60	0.00052	0.00048	0.00054	0.00047	0.00043	0.00054
	0.65	0.00052	0.00050	0.00053	0.00042	0.00039	0.00044
	0.70	0.00062	0.00061	0.00066	0.00013	0.00006	0.00014
	0.75	0.00066	0.00064	0.00069	-0.00001	-0.00008	0.00001
	0.80	0.00064	0.00064	0.00070	-0.00003	-0.00013	-0.00003
	0.85	0.00040	0.00033	0.00044	0.00032	0.00024	0.00046
	0.90	0.00027	0.00024	0.00033	0.00050	0.00038	0.00056
	0.95	0.00036	0.00034	0.00049	0.00025	-0.00003	0.00030
	0.99	0.00075	0.00070	0.00082	-0.00070	-0.00084	-0.00060
8%	0.50	0.00069	0.00059	0.00078	0.00033	0.00015	0.00050
	0.55	0.00058	0.00052	0.00064	0.00045	0.00034	0.00055
	0.60	0.00052	0.00046	0.00055	0.00048	0.00043	0.00060
	0.65	0.00052	0.00050	0.00053	0.00041	0.00039	0.00045
	0.70	0.00062	0.00061	0.00070	0.00012	-0.00006	0.00014
	0.75	0.00066	0.00064	0.00069	-0.00002	-0.00008	0.00001
	0.80	0.00064	0.00064	0.00070	-0.00004	-0.00014	-0.00003
	0.85	0.00039	0.00021	0.00045	0.00033	0.00023	0.00065
	0.90	0.00027	0.00024	0.00034	0.00049	0.00035	0.00056
	0.95	0.00037	0.00033	0.00049	0.00023	-0.00003	0.00031
	0.99	0.00075	0.00069	0.00085	-0.00071	-0.00090	-0.00058
10%	0.50	0.00069	0.00058	0.00079	0.00032	0.00014	0.00052
	0.55	0.00058	0.00049	0.00064	0.00045	0.00033	0.00059
	0.60	0.00051	0.00045	0.00055	0.00048	0.00042	0.00060
	0.65	0.00052	0.00049	0.00054	0.00042	0.00038	0.00046
	0.70	0.00063	0.00060	0.00071	0.00011	-0.00007	0.00019
	0.75	0.00066	0.00064	0.00069	-0.00002	-0.00008	0.00001
	0.80	0.00064	0.00063	0.00070	-0.00004	-0.00014	-0.00003
	0.85	0.00039	0.00020	0.00046	0.00035	0.00022	0.00069

0.90	0.00028	0.00023	0.00035	0.00048	0.00033	0.00057
0.95	0.00038	0.00033	0.00049	0.00021	-0.00003	0.00031
0.99	0.00075	0.00068	0.00087	-0.00071	-0.00096	-0.00055

Table 4.6 Estimated coefficients for X_0 and X_1, asymptotic 95 % confidence lower limit (LL) and upper limit (UL) by quantiles and % random noise (RN) for pine forests.

% RN	Quantile	b_0	b_0.LB	b_0.UB	b_1	b_1.LB	b_1.UB
1%	0.50	0.00074	0.00073	0.00074	0.00035	0.00034	0.00036
	0.55	0.00083	0.00083	0.00083	0.00011	0.00011	0.00011
	0.60	0.00074	0.00073	0.00084	0.00023	0.00003	0.00026
	0.65	0.00084	0.00083	0.00085	-0.00002	-0.00004	0.00001
	0.70	0.00083	0.00080	0.00089	-0.00006	-0.00019	-0.00001
	0.75	0.00101	0.00100	0.00101	-0.00044	-0.00044	-0.00043
	0.80	0.00115	0.00114	0.00116	-0.00076	-0.00079	-0.00074
	0.85	0.00096	0.00095	0.00097	-0.00051	-0.00053	-0.00050
	0.90	0.00077	0.00077	0.00077	-0.00028	-0.00028	-0.00027
	0.95	0.00078	0.00078	0.00078	-0.00036	-0.00036	-0.00036
	0.99	0.00033	0.00033	0.00034	0.00030	0.00030	0.00030
2%	0.50	0.00074	0.00073	0.00075	0.00035	0.00033	0.00036
	0.55	0.00083	0.00083	0.00083	0.00011	0.00011	0.00012
	0.60	0.00076	0.00073	0.00084	0.00019	0.00003	0.00026
	0.65	0.00084	0.00083	0.00085	-0.00002	-0.00004	0.00001
	0.70	0.00084	0.00080	0.00089	-0.00008	-0.00019	0.00000
	0.75	0.00101	0.00100	0.00101	-0.00044	-0.00045	-0.00043
	0.80	0.00115	0.00114	0.00117	-0.00076	-0.00080	-0.00074
	0.85	0.00096	0.00095	0.00097	-0.00052	-0.00054	-0.00049
	0.90	0.00078	0.00077	0.00081	-0.00029	-0.00036	-0.00027
	0.95	0.00078	0.00078	0.00078	-0.00036	-0.00036	-0.00035
	0.99	0.00033	0.00033	0.00034	0.00030	0.00029	0.00031
4%	0.50	0.00074	0.00072	0.00075	0.00035	0.00032	0.00038
	0.55	0.00083	0.00083	0.00084	0.00011	0.00010	0.00012
	0.60	0.00077	0.00071	0.00084	0.00017	0.00003	0.00028
	0.65	0.00084	0.00077	0.00085	-0.00001	-0.00004	0.00012
	0.70	0.00084	0.00080	0.00090	-0.00009	-0.00020	0.00000
	0.75	0.00101	0.00100	0.00102	-0.00044	-0.00046	-0.00042
	0.80	0.00115	0.00113	0.00118	-0.00076	-0.00082	-0.00072
	0.85	0.00097	0.00094	0.00120	-0.00053	-0.00090	-0.00047

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	0.90	0.00078	0.00076	0.00081	-0.00030	-0.00037	-0.00026
	0.95	0.00078	0.00078	0.00078	-0.00036	-0.00037	-0.00035
	0.99	0.00033	0.00033	0.00034	0.00030	0.00029	0.00031
6%	0.50	0.00074	0.00071	0.00077	0.00035	0.00030	0.00039
	0.55	0.00083	0.00073	0.00084	0.00012	0.00010	0.00029
	0.60	0.00077	0.00071	0.00085	0.00017	0.00003	0.00029
	0.65	0.00083	0.00077	0.00085	0.00000	-0.00004	0.00012
	0.70	0.00084	0.00077	0.00090	-0.00009	-0.00020	0.00005
	0.75	0.00101	0.00099	0.00103	-0.00044	-0.00047	-0.00041
	0.80	0.00116	0.00113	0.00123	-0.00077	-0.00091	-0.00071
	0.85	0.00099	0.00093	0.00124	-0.00057	-0.00098	-0.00046
	0.90	0.00078	0.00076	0.00081	-0.00030	-0.00037	-0.00026
	0.95	0.00078	0.00078	0.00079	-0.00036	-0.00037	-0.00035
	0.99	0.00033	0.00032	0.00034	0.00030	0.00028	0.00032
8%	0.50	0.00074	0.00071	0.00078	0.00035	0.00028	0.00040
	0.55	0.00083	0.00073	0.00084	0.00012	0.00009	0.00030
	0.60	0.00078	0.00070	0.00085	0.00015	0.00003	0.00030
	0.65	0.00083	0.00077	0.00085	0.00000	-0.00004	0.00012
	0.70	0.00084	0.00077	0.00091	-0.00009	-0.00021	0.00006
	0.75	0.00101	0.00098	0.00103	-0.00044	-0.00049	-0.00040
	0.80	0.00117	0.00112	0.00125	-0.00079	-0.00094	-0.00071
	0.85	0.00102	0.00092	0.00128	-0.00062	-0.00105	-0.00045
	0.90	0.00079	0.00076	0.00082	-0.00031	-0.00038	-0.00025
	0.95	0.00078	0.00077	0.00079	-0.00036	-0.00037	-0.00034
	0.99	0.00033	0.00032	0.00035	0.00030	0.00028	0.00032
10%	0.50	0.00074	0.00071	0.00078	0.00035	0.00027	0.00040
	0.55	0.00082	0.00072	0.00085	0.00013	0.00008	0.00032
	0.60	0.00078	0.00070	0.00085	0.00016	0.00003	0.00030
	0.65	0.00083	0.00077	0.00085	0.00001	-0.00004	0.00012
	0.70	0.00084	0.00076	0.00091	-0.00008	-0.00021	0.00008
	0.75	0.00101	0.00098	0.00104	-0.00044	-0.00050	-0.00039
	0.80	0.00117	0.00112	0.00124	-0.00079	-0.00093	-0.00069
	0.85	0.00103	0.00092	0.00129	-0.00062	-0.00108	-0.00044

0.90	0.00079	0.00076	0.00082	-0.00031	-0.00039	-0.00025
0.95	0.00078	0.00077	0.00079	-0.00036	-0.00038	-0.00034
0.99	0.00033	0.00032	0.00035	0.00030	0.00027	0.00033

Table 4.7 Estimations of implied maximum ASDI by quantiles, % random noise and forest type (ASDI is only calculated when both b_0 and b_1 are significant).

Forest type	Quantile	Random noise					
		1%	2%	4%	6%	8%	10%
Cypress forests	0.50	1134	1135	1136	1137	1138	1138
	0.55	1189	1190	1191	1191	1191	1191
	0.60	1264	1263	1262	1261	1258	1256
	0.65	1315	1315	1315	1315	1315	1315
	0.70	1440	1440	1441	1441	-	-
	0.75	1542	-	-	-	-	-
	0.80	1616	1616	1616	1616	1616	1616
	0.85	1707	1701	1696	1695	1695	1695
	0.90	1777	1777	1779	1784	1787	1789
	0.95	1948	1948	1952	-	-	-
	0.99	2938	2939	2941	2942	2942	2948
Pine forests	0.50	1061	1061	1061	1061	1061	1061
	0.55	1116	1116	1116	1115	1115	1115
	0.60	1140	1144	1146	1147	1149	1149
	0.65	-	-	-	-	-	-
	0.70	1261	1263	1263	-	-	-
	0.75	1333	1333	1333	1334	1334	1334
	0.80	1417	1418	1417	1417	1418	1418
	0.85	1516	1516	1514	1512	1509	1509
	0.90	1642	1646	1651	1653	1655	1654
	0.95	1751	1751	1751	1751	1750	1750
	0.99	1964	1964	1964	1964	1965	1966

Table 4.8 Based on 1% random noise, estimated coefficients, average SG, and implied maximum ASDIs by quantiles and % basal area threshold for cypress forests.

Percentage	0%				10%				20%			
Quantile	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI
0.50	0.000679	0.000345	0.587	1134	0.000770	0.000167	0.581	1153	0.000883	-0.000108	0.578	1219
0.55	0.000594	0.000421		1189	0.000602	0.000404		1195	0.000750	0.000070		1265
0.60	0.000514	0.000472		1264	0.000480	0.000545		1254	0.000938	-0.000431		1452
0.65	0.000517	0.000415		1315	0.000612	0.000199		1374	0.000831	-0.000276		1488
0.70	0.000615	0.000136		1440	0.000720	-0.000118		1513	0.000723	-0.000112		1519
0.75	0.000644	0.000007		1542	0.000653	-0.000016		1553	0.000700	-0.000141		1618
0.80	0.000636	-0.000029		1616	0.000575	0.000044		1663	0.000517	0.000099		1741
0.85	0.000425	0.000274		1707	0.000319	0.000423		1760	0.000376	0.000294		1831
0.90	0.000254	0.000526		1777	0.000247	0.000529		1790	0.000287	0.000454		1821
0.95	0.000353	0.000273		1948	0.000270	0.000455		1830	0.000353	0.000273		1957
0.99	0.000752	-0.000702		2938	0.000170	0.000560		1991	0.000490	-0.000065		2199

Percentage	30%				40%				50%			
Quantile	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI
0.50	0.001010	-0.000391	0.573	1274	0.000846	-0.000180	0.575	1347	0.000715	0.000162	0.564	1240
0.55	0.000953	-0.000460		1450	0.000965	-0.000489		1464	0.000965	-0.000489		1453
0.60	0.000889	-0.000363		1468	0.000861	-0.000331		1490	0.000735	-0.000507		1415
0.65	0.000762	-0.000171		1506	0.000761	-0.000168		1505	0.000779	-		-
0.70	0.000722	-0.000171		1602	0.000766	-0.000220		1563	0.000818	-0.000351		1611
0.75	0.000722	-0.000225		1686	0.000743	-0.000286		1730	0.000883	-0.000630		1897
0.80	0.000482	0.000159		1744	0.000694	-0.000276		1868	0.001014	-0.001000		2237
0.85	0.000261	0.000515		1796	0.000303	0.000424		1827	0.001020	-0.001024		2262
0.90	0.000249	0.000527		1814	0.000263	0.000493		1830	0.000302	0.000421		1851
0.95	0.000253	0.000510		1832	0.000270	0.000475		1840	0.002703	0.000475		1857
0.99	0.000490	-0.000061		2198	0.000490	-0.000061		2199	0.000490	-0.000061		2195

Table 4.9 Based on 1% random noise, estimated coefficients, average SG, and implied maximum ASDIs by quantiles and % basal area threshold for pine forests.

Percentage	0%				10%				20%			
Quantile	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI
0.50	0.000739	0.000347	0.585	1061	0.000541	0.000737	0.581	1033	0.000591	0.000659	0.577	1030
0.55	0.000831	0.000112		1116	0.000462	0.000833		1058	0.000700	0.000412		1066
0.60	0.000742	0.000231		1140	0.000545	0.000622		1103	0.000570	0.000589		1099
0.65	0.000842	-		-	0.000548	0.000568		1139	0.000611	0.000475		1129
0.70	0.000828	-0.000060		1261	0.000743	0.000121		1230	0.000589	0.000467		1166
0.75	0.001006	-0.000438		1333	0.001150	-0.000705		1350	0.001111	-0.000618		1325
0.80	0.001149	-0.000759		1417	0.001258	-0.000958		1425	0.001310	-0.001038		1405
0.85	0.000960	-0.000514		1516	0.001305	-0.001094		1494	0.001340	-0.001129		1451
0.90	0.000771	-0.000277		1642	0.000882	-0.000481		1660	0.001343	-0.001174		1502
0.95	0.000781	-0.000359		1751	0.000859	-0.000480		1725	0.000902	-0.000522		1664
0.99	0.000334	0.000299		1964	0.000334	0.000299		1969	0.000529	0.000010		1871

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Percentage	30%				40%				50%			
Quantile	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI	b_0	b_1	SG	ASDI
0.50	0.000540	0.000775	0.572	1016	0.000336	0.001198	0.565	987	0.000324	0.001222	0.557	996
0.55	0.000557	0.000712		1037	0.000596	0.000648		1038	0.000199	0.001421		1010
0.60	0.000637	0.000505		1080	0.000637	0.000505		1084	-0.000041	0.001802		1039
0.65	0.000545	0.000622		1109	0.000457	0.000793		1104	-0.000135	0.001952		1051
0.70	0.000548	0.000568		1145	0.000548	0.000568		1150	-0.000142	-		-
0.75	0.001014	-0.000423		1295	0.000803	-0.000010		1254	0.000148	0.001289		1155
0.80	0.001360	-0.001114		1384	0.001075	-0.000554		1313	0.000511	0.000541		1231
0.85	0.001305	-0.001029		1397	0.001422	-0.001250		1398	0.000989	-0.000404		1309
0.90	0.001325	-0.001104		1443	0.001331	-0.001114		1426	0.001083	-0.000613		1348
0.95	0.001003	-0.000695		1652	0.001304	-0.001093		1458	0.000629	0.000204		1348
0.99	0.000859	-0.000480		1713	0.000905	-0.000527		1648	-0.000297	0.001841		1375

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Table 4.10 Estimated coefficients of intersected quantiles by equation source and % basal area threshold from 0 to 20 % for cypress forests.

% BA	0%			10%			20%		
Equation Source	Quantile	b_0	b_1	Quantile	b_0	b_1	Quantile	b_0	b_1
Su.A1^{a,X}	-	-	-	-	-	-	-	-	-
Su.A2^{a,X}	0.96	0.000454	0.000027	-	-	-	0.97	0.000324	0.000321
Su.A3^{a,X}	-	-	-	-	-	-	-	-	-
Su.A4^{a,X}	0.91	0.000287	0.000454	0.95	0.000270	0.000475	0.90	0.000287	0.000454
Su.A5^{a,X}	-	-	-	-	-	-	-	-	-
Su.A6^{a,X}	-	-	-	-	-	-	-	-	-
Su.N1^{a,Y}	-	-	-	-	-	-	-	-	-
Su.N2^{a,Y}	-	-	-	-	-	-	-	-	-
Su.N3^{a,Y}	-	-	-	-	-	-	-	-	-
Su.N4^{a,Y}	0.93	0.000269	0.000481	0.96	0.000353	0.000273	0.93	0.000263	0.000492
Su.N5^{a,Y}	0.86	0.000286	0.000494	0.84	0.000319	0.000429	0.80	0.000517	0.000099
Su.N6^{a,Y}	-	-	-	-	-	-	-	-	-
Su.Q1^{a,Z}	-	-	-	-	-	-	-	-	-
Su.Q2^{a,Z}	0.60	0.000514	0.000472	0.61	0.000505	0.000487	0.55	0.000750	0.000070
Su.Q3^{a,Z}	-	-	-	-	-	-	-	-	-
Su.Q4^{a,Z}	0.54	0.000632	0.000362	0.54	0.000639	0.000349	-	-	-

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Su.Q5[a,Z]	0.58	0.000502	0.000545	0.58	0.000468	0.000594	0.52	0.000753	0.000111
Su.Q6[a,Z]	-	-	-	-	-	-	-	-	-
Yen[b]	-	-	-	-	-	-	-	-	-
Rei.80	-	-	-	-	-	-	-	-	-
Rei.85	-	-	-	-	-	-	-	-	-
Rei.90	0.50	0.000679	0.000345	0.50	0.000770	0.000167	-	-	-
Rei.95	0.52	0.000606	0.000445	0.50	0.000770	0.000167	-	-	-
Rei.99	0.52	0.000606	0.000445	0.50	0.000770	0.000167	-	-	-

Table 4.11 Estimated coefficients of intersected quantiles by equation source and % basal area threshold from 30 to 50 % for cypress forests.

% BA	30%			40%			50%		
Equation Source	Quantile	b_0	b_1	Quantile	b_0	b_1	Quantile	b_0	b_1
Su.A1^{a,X}	-	-	-	-	-	-	-	-	-
Su.A2^{a,X}	0.98	0.000481	-0.000040	0.98	0.000490	-0.000061	0.78,0.87,0.98	-	-
Su.A3^{a,X}	-	-	-	-	-	-	-	-	-
Su.A4^{a,X}	0.95	0.000253	0.000510	0.95	0.000270	0.000475	0.74	0.000883	-0.000630
Su.A5^{a,X}	-	-	-	-	-	-	-	-	-
Su.A6^{a,X}	-	-	-	-	-	-	-	-	-
Su.N1^{a,Y}	-	-	-	-	-	-	-	-	-
Su.N2^{a,Y}	-	-	-	-	-	-	-	-	-
Su.N3^{a,Y}	-	-	-	-	-	-	-	-	-
Su.N4^{a,Y}	0.96	0.000253	0.000510	0.96	0.000393	0.000174	0.75,0.9,0.95	-	-
Su.N5^{a,Y}	0.8	0.000482	0.000159	0.75	0.000743	-0.000286	0.72	0.001052	-0.000937
Su.N6^{a,Y}	-	-	-	-	-	-	-	-	-
Su.Q1^{a,Z}	-	-	-	-	-	-	-	-	-
Su.Q2^{a,Z}	-	-	-	-	-	-	0.50	0.000715	0.000162
Su.Q3^{a,Z}	-	-	-	-	-	-	-	-	-
Su.Q4^{a,Z}	-	-	-	-	-	-	-	-	-

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Su.Q5[a,Z]	-	-	-	-	-	-	-	-	-
Su.Q6[a,Z]	-	-	-	-	-	-	-	-	-
Yen[b]	-	-	-	-	-	-	-	-	-
Rei.80	-	-	-	-	-	-	-	-	-
Rei.85	-	-	-	-	-	-	-	-	-
Rei.90	-	-	-	-	-	-	-	-	-
Rei.95	-	-	-	-	-	-	-	-	-
Rei.99	-	-	-	-	-	-	-	-	-

doi:10.6342/NTU201701706

Table 4.12 Estimated coefficients of intersected quantiles by equation source and % basal area threshold from 0 to 20 % for pine forests.

% BA	0%			10%			20%		
Equation Source	Quantile	b_0	b_1	Quantile	b_0	b_1	Quantile	b_0	b_1
Rei.80	-	-	-	0.71	0.000711	0.000172	0.73	0.001022	-0.000434
Rei.85	0.74	0.001021	-0.000461	0.74	0.001099	-0.000596	0.75	0.001111	-0.000618
Rei.90	0.76	0.000989	-0.000413	0.76	0.001215	-0.000851	0.77	0.001332	-0.001061
Rei.95	0.81	0.001223	-0.000904	0.81	0.001317	-0.001078	0.83	0.001310	-0.001062
Rei.99	0.89	0.000734	-0.000191	0.89	0.000983	-0.000634	0.94	0.000905	-0.000527

Table 4.13 Estimated coefficients of intersected quantiles by equation source and % basal area threshold from 30 to 50 % for pine forests.

% BA	30%			40%			50%		
Equation Source	Quantile	b_0	b_1	Quantile	b_0	b_1	Quantile	b_0	b_1
Rei.80	0.73	0.000511	0.000622	0.74	0.000778	0.000045	0.81	0.000536	0.000492
Rei.85	0.76	0.001151	-0.000687	0.81	0.001099	-0.000605	0.88	0.000976	-0.0004
Rei.90	0.78	0.001384	-0.001150	0.83	0.001242	-0.000899	0.98	-0.0003	0.001841
Rei.95	0.89	0.001331	-0.001114	0.91	0.001325	-0.001104	-	-	-
Rei.99	0.94	0.001376	-0.001248	0.98	0.000905	-0.000527	-	-	-

Table 4.14 Estimated coefficients for maximum, mean, and minimum of intersected quantile by forest type.

Forest Type	% BA	Max			Min			Mean	
		Quantile	b0	b1	Quantile	b0	b1	b0	b1
Cypress (Low)	10	0.61	0.000505	0.000487	0.50	0.000770	0.000167	0.000654	0.000322
Cypress (High)	10	0.96	0.000353	0.000273	0.84	0.000319	0.000429	0.000314	0.000393
Pine	10	0.89	0.000983	-0.000634	0.71	0.000711	0.000172	0.001065	-0.000597

Appendix 1: Figures

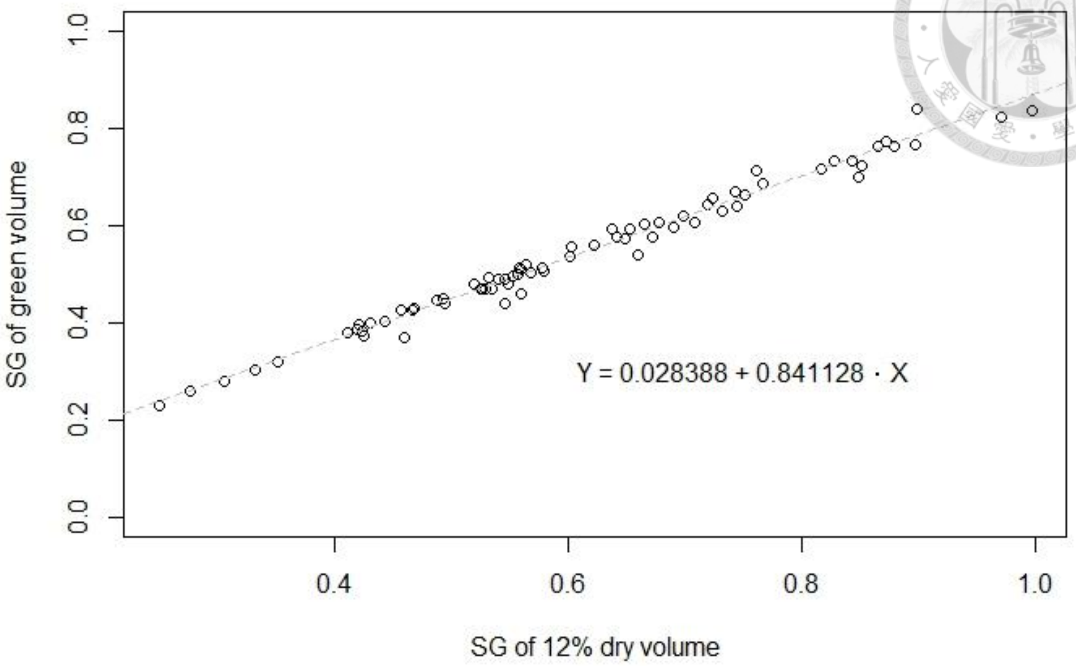

Figure A1 Conversion of specific gravity (SG) from green volume to 12% dry volume.

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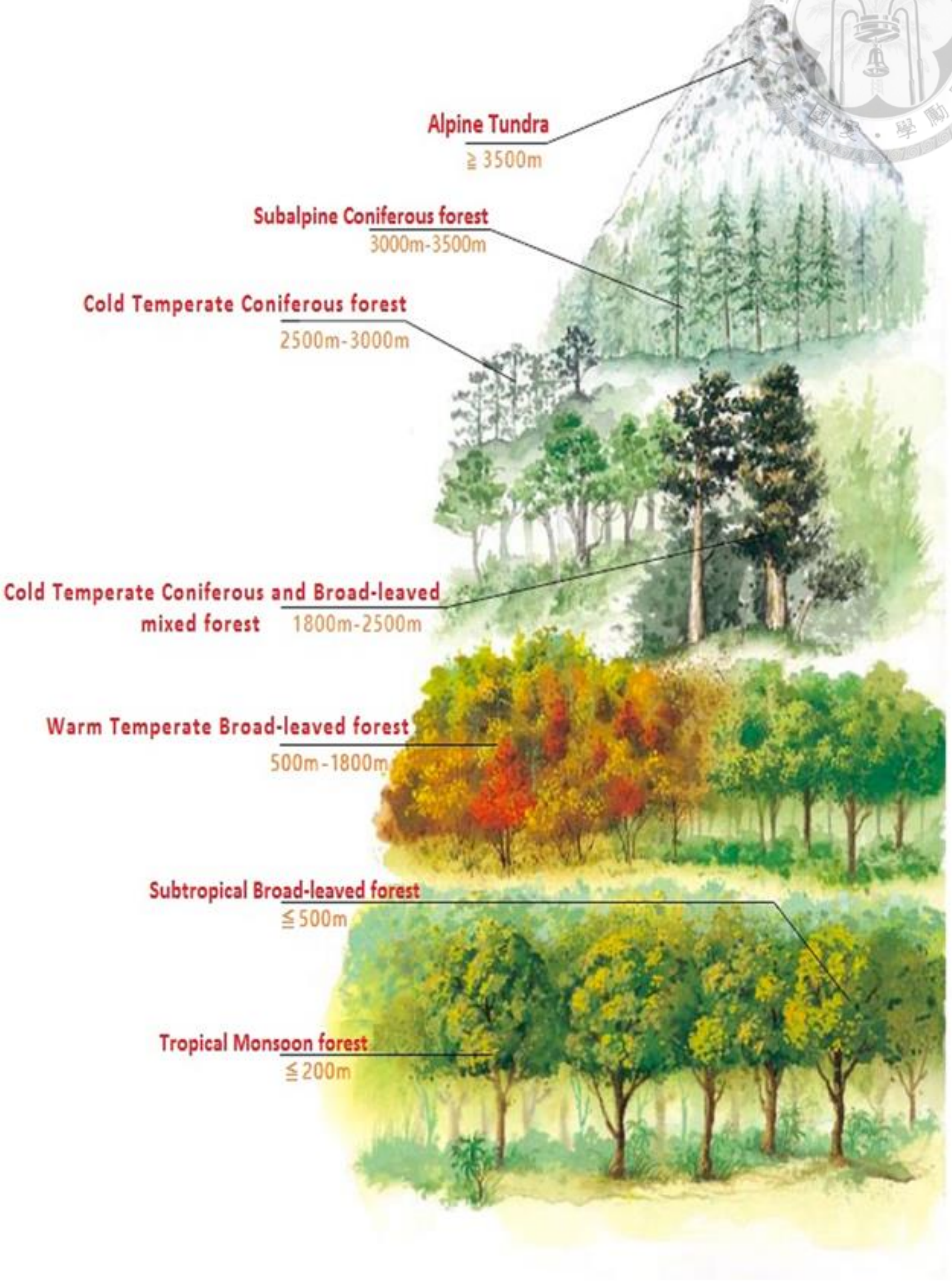

Figure A2 Seven vegetation zones are classified by climate and altitude (Taiwan Forest Bureau 2004, 2016).

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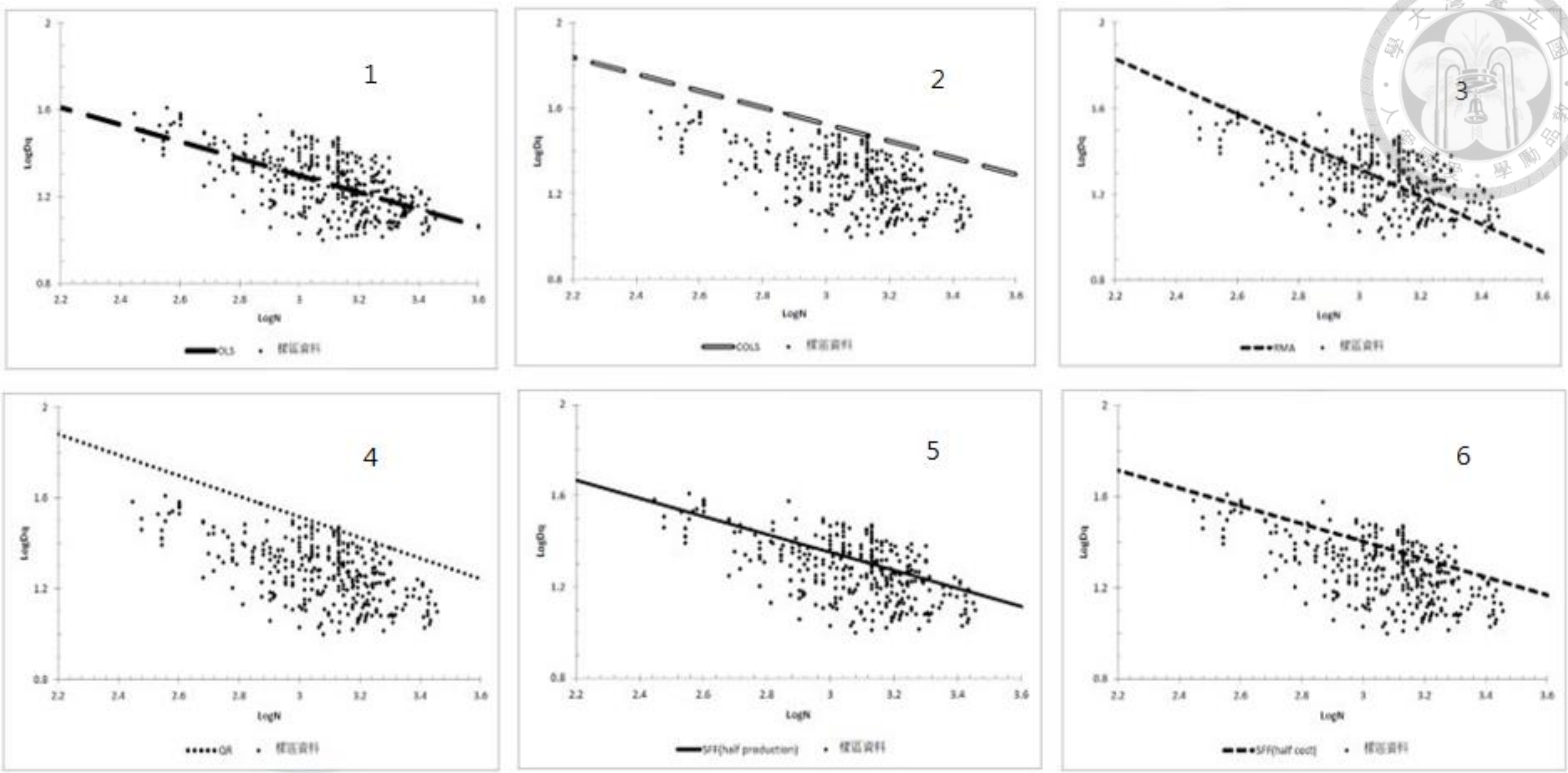

Figure A3 Su (2014) used six methods, including ordinary least squares (1), corrected ordinary least squares (2), reduced major axis (3), quantile regression (4), stochastic frontier product function (5), and stochastic frontier cost function (6), to establish self-thinning line for cypress forests.

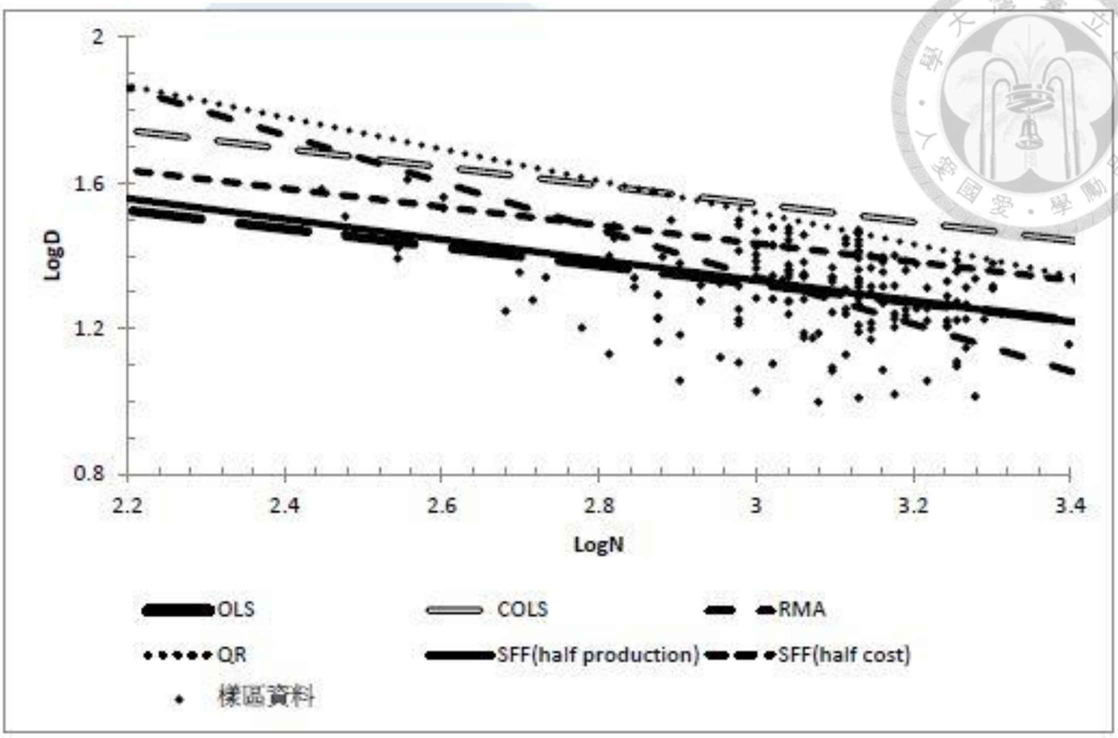

Figure A4 Su (2014) used six methods to establish self-thinning line for cypress forests by the dataset only from NFI1 to NFI3.

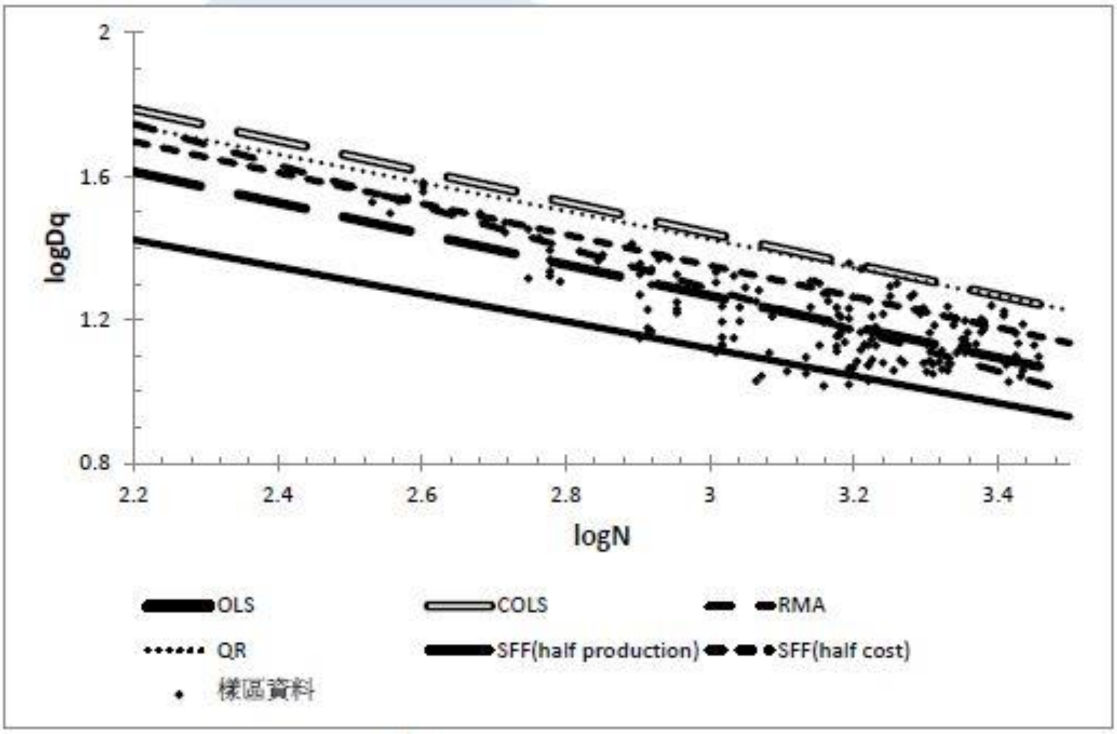

Figure A5 Su (2014) used six methods to establish self-thinning line for cypress forests by the dataset only from Qilan Mountain Forest Inventory.

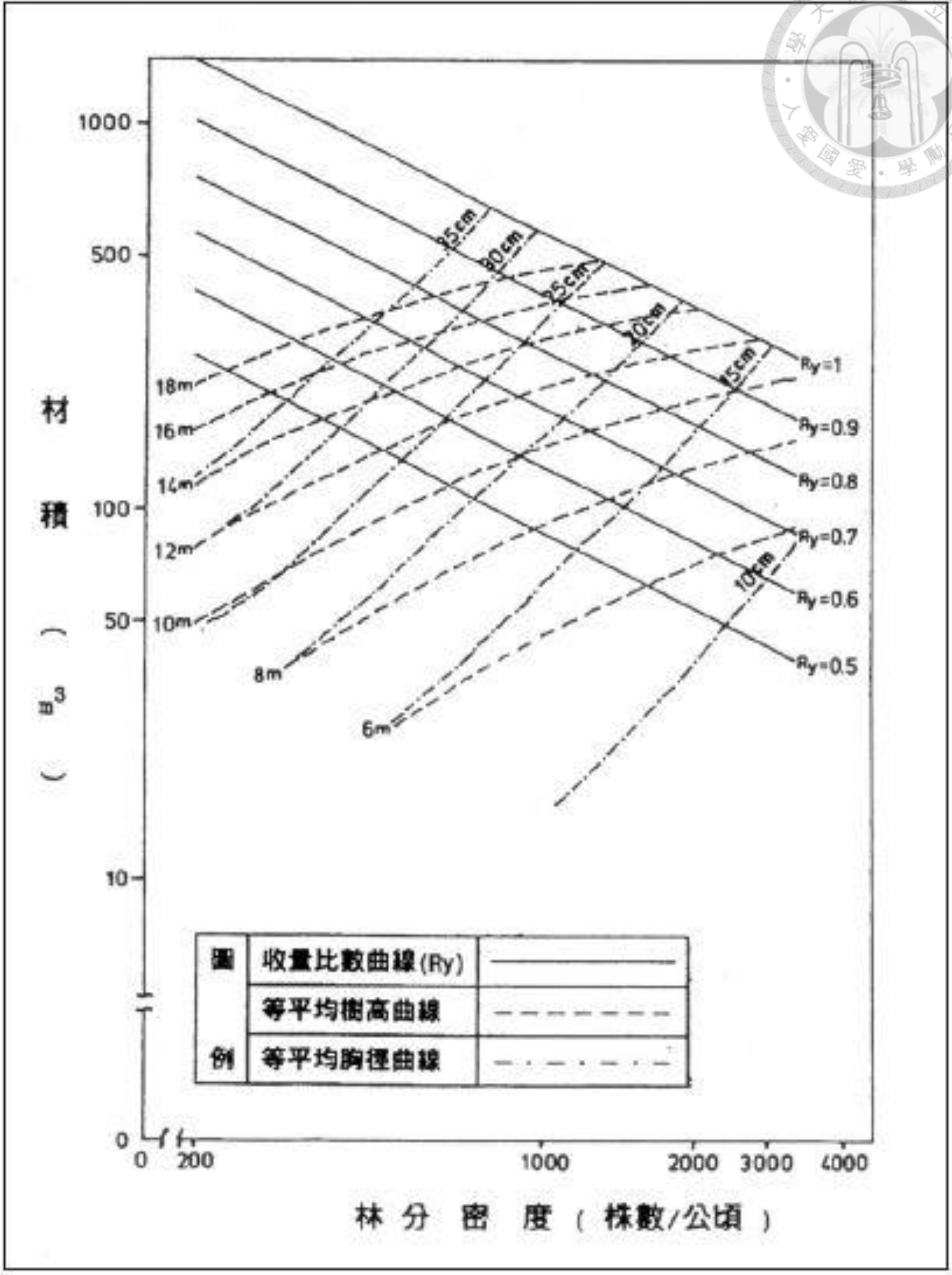

Figure A6 Stand density management diagram for cypress plantations in Taiwan (Yen 2002)

Appendix 2: Tables

Table A1. The number of plot and volume of main tree species for each forest stand (Taiwan Forest Bureau 2016).

Forest stand	Number of plot	Volume(m3/ha)
Nature forest		
Coniferous forest	241	499.65
Hemlock	67	606.86
Fir	47	426.94
Spruce	13	657.48
Cypress	37	746.63
Pine	70	271.04
Others	7	379.48
Mixed coniferous and broad-leaved forest	113	486.28
Broad-leaved forest	2073	198.95
Plantation forest		
Coniferous forest	153	318.05
Cypress	26	320.43
Incense Cedar	4	86.18
Pine	29	296.31
Chinese Fir	17	222.57
Japanese Cedar	72	388.89
Taiwan Cedar	3	258.11
Others	2	230.71
Mixed coniferous and broad-leaved forest	75	287.77
Broad-leaved forest	135	147.66
Taiwan Zelkova	7	193.15
Camphor Tree	5	76.60
Taiwan Acacia	65	171.06
Ash	7	147.35
Others	51	146.20

Table A2. Specific gravity (SG) by species including source information. SG is based on weight when ovendry and volume are at 12% moisture content.

Family	Genus	Species	SG	Range	Source
Aceraceae	Acer	taitonmontanum	0.745	0.64-0.85	b,c
Aceraceae	Acer	morrisonense	0.745	0.64-0.85	b,c
Aceraceae	Acer	oblongum	0.745	0.64-0.85	b,c
Aceraceae	Acer	palmatum	0.745	0.64-0.85	b,c
Aceraceae	Acer	serrulatum	0.745	0.64-0.85	b,c
Anacardiaceae	Pistacia	chinensis	0.630	0.51-0.76	b,d
Anacardiaceae	Rhus	ambigua	0.630	0.51-0.76	b,c
Anacardiaceae	Rhus	javanica	0.620	-	b
Anacardiaceae	Rhus	succedanea	0.760	-	b
Aquifoliaceae	Ilex	aquifolimm	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	bioritsensis	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	ficoidea	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	formosana	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	goshiensis	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	hakkuensis	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	hayataiana	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	lanceolata	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	lonicerifolia	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	matsudae	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	micrococca	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	pedunculosa	0.820	-	b
Aquifoliaceae	Ilex	rotunda	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	sugerokii	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	tugitakayamensis	0.742	0.64-0.90	b,c
Aquifoliaceae	Ilex	yunnanensis	0.742	0.64-0.90	b,c
Araliaceae	Aralia	armata	0.534	0.45-0.60	b,d
Araliaceae	Aralia	glauca	0.534	0.45-0.60	b,d
Araliaceae	Aralia	spinosa	0.534	0.45-0.60	b,d
Araliaceae	Dendropanax	dentiger	0.495	0.45-0.53	a,b,d
Araliaceae	Fatsia	japonica	0.495	0.45-0.53	a,b,d

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Araliaceae	Fatsia	polycarpa	0.495	0.45-0.53	a,b,d
Araliaceae	Schefflera	arboricola	0.457	-	a,c
Araliaceae	Schefflera	octophylla	0.457	-	a
Araliaceae	Schefflera	taiwaniana	0.457	-	a,c
Araliaceae	Sinopanax	formosana	0.495	0.45-0.53	a,b,d
Araliaceae	Tetrapanax	papyriferus	0.495	0.45-0.53	a,b,d
Berberidaceae	Berberis	kawakamii	0.668	-	e
Betulaceae	Alnus	formosana	0.419	-	a
Betulaceae	Carpinus	cordata	0.750	-	b
Betulaceae	Carpinus	hebestroma	0.741	0.734-0.75	a,b,c
Betulaceae	Carpinus	kawakamii	0.732	-	a
Boraginaceae	Ehretia	dicksonii	0.700	-	b,c
Buxaceae	Buxus	sinica	0.700	-	b,c
Cannabaceae	Celtis	sinensis	0.678	-	a,f
Caprifoliaceae	Viburnum	arboricolum	0.730	-	b,c
Caprifoliaceae	Viburnum	betulifolium	0.730	-	b,c
Caprifoliaceae	Viburnum	dilatatum	0.730	-	b,c
Caprifoliaceae	Viburnum	formosanum	0.730	-	b,c
Caprifoliaceae	Viburnum	integrifolium	0.730	-	b,c
Caprifoliaceae	Viburnum	luzonicum	0.730	-	b,c
Caprifoliaceae	Viburnum	parvifolium	0.730	-	b,c
Caprifoliaceae	Viburnum	propinquum	0.730	-	b,c
Caprifoliaceae	Viburnum	rectangulatum	0.730	-	b,c
Caprifoliaceae	Viburnum	sympodiale	0.730	-	b,c
Caprifoliaceae	Viburnum	taitoense	0.730	-	b,c
Celastraceae	Euonymus	acanthocarpus	0.550	-	b,c
Celastraceae	Euonymus	tashiroi	0.550	-	b,c
Celastraceae	Microtropis	fokienensis	0.550	-	b,d
Celastraceae	Perrottetia	arisanensis	0.550	-	b,d
Cephalotaxaceae	Cephalotaxus	wilsoniana	0.631	-	a
Compositae	Hieracium	morii	0.668	-	e
Cornaceae	Swida	controversa	0.668	-	e
Cornaceae	Swida	macrophylla	0.668	-	e

Cupressaceae	Calocedrus	formosana	0.540	-	a
Cupressaceae	Chamaecyparis	formosensis	0.354	-	a
Cupressaceae	Chamaecyparis	obtusa	0.445	-	a
Cupressaceae	Cryptomeria	japonica	0.326	-	a
Cupressaceae	Cunninghamia	lanceolata	0.364	-	a
Cupressaceae	Cunninghamia	konishii	0.396	-	a
Cupressaceae	Juniperus	formosana	0.730	-	b,c
Cupressaceae	Juniperus	squamata	0.730	-	b,c
Cupressaceae	Taiwania	cryptomerioides	0.397	-	a
Daphniphyllaceae	Daphniphyllum	himalaense	0.660	-	b,c
Daphniphyllaceae	Daphniphyllum	oldhami	0.660	-	b,c
Ebenaceae	Diospyros	morrisiana	0.796	0.74-0.85	a,b,c
Ebenaceae	Diospyros	oldhamii	0.796	0.74-0.85	a,b,c
Elaeagnaceae	Elaeagnus	formosana	0.668	-	e
Elaeagnaceae	Elaeagnus	grandifolia	0.668	-	e
Elaeocarpaceae	Elaeocarpus	japonicus	0.579	-	a
Elaeocarpaceae	Elaeocarpus	obovata	0.554	0.53-0.58	a,c
Elaeocarpaceae	Elaeocarpus	sylvestris	0.529	-	a
Elaeagnaceae	Elaeagnus	thunbergii	0.668	-	e
Elaeocarpaceae	Sloanea	dasycarpa	0.554	0.53-0.58	a,d
Ericaceae	Lyonia	ovalifolia	0.740	-	b,d
Ericaceae	Lyonia	lanceolata	0.740	-	b,d
Ericaceae	Pieris	taiwanensis	0.740	-	b,d
Ericaceae	Rhododendron	ellipticum	0.740	-	b,d
Ericaceae	Rhododendron	formosanum	0.740	-	b,d
Ericaceae	Rhododendron	lapponicum	0.740	-	b,d
Ericaceae	Rhododendron	morii	0.740	-	b,d
Ericaceae	Rhododendron	oldhamii	0.740	-	b,d
Ericaceae	Rhododendron	ovatum	0.740	-	b,d
Ericaceae	Rhododendron	rubropilosum	0.740	-	b,d
Ericaceae	Rhododendron	sasakii	0.740	-	b,d
Ericaceae	Vaccinium	bracteatum	0.740	-	b,d
Ericaceae	Vaccinium	randaiense	0.740	-	b,d

Ericaceae	Vaccinium	wrightii	0.740	-	b,d
Euphorbiaceae	Bridelia	monoica	0.605	0.59-0.62	a,b,d
Euphorbiaceae	Glochidion	acuminatum	0.620	-	a,c
Euphorbiaceae	Glochidion	rubrum	0.620	-	a,c
Euphorbiaceae	Glochidion	zeylanicum	0.620	-	a,c
Euphorbiaceae	Mallotus	japonicus	0.590	-	b
Euphorbiaceae	Mallotus	paniculatus	0.590	-	b,c
Euphorbiaceae	Mallotus	phillipinensis	0.590	-	b,c
Euphorbiaceae	Mallotus	phillppicum	0.590	-	b,c
Fabaceae	Acacia	confusa	0.668	-	e
Fabaceae	Ormosia	formosana	0.668	-	e
Fagaceae	Castanopsis	carlesii	0.559	-	a,f
Fagaceae	Castanopsis	eyrei	0.732	0.559-0.997	a,c
Fagaceae	Castanopsis	fabri	0.732	0.559-0.997	a,c
Fagaceae	Castanopsis	fargesii	0.732	0.559-0.997	a,c
Fagaceae	Castanopsis	formosana	0.732	0.559-0.997	a,c
Fagaceae	Cyclobalanopsis	longinux	0.897	-	a
Fagaceae	Cyclobalanopsis	morri	0.879	-	a
Fagaceae	Cyclobalanopsis	pachyloma	0.864	0.817-0.897	a,c
Fagaceae	Cyclobalanopsis	sessilifolia	0.864	0.817-0.897	a,c
Fagaceae	Cyclobalanopsis	stenophylloides	0.817	-	a
Fagaceae	Lithocarpus	amygdalifolius	0.843	-	a
Fagaceae	Lithocarpus	brevicaudatus	0.752	0.69-0.843	a,c
Fagaceae	Lithocarpus	corneus	0.752	0.69-0.843	a,c
Fagaceae	Lithocarpus	formosanus	0.752	0.69-0.843	a,c
Fagaceae	Lithocarpus	hancei	0.752	0.69-0.843	a,c
Fagaceae	Lithocarpus	kawakamii	0.752	0.69-0.843	a,c
Fagaceae	Lithocarpus	lepidocarpus	0.752	0.69-0.843	a,c
Fagaceae	Lithocarpus	synbalanos	0.752	0.69-0.843	a,c
Fagaceae	Quercus	gilva	0.872	-	a
Fagaceae	Quercus	glauca	0.971	-	a
Fagaceae	Quercus	globosa	0.903	0.865-0.971	a,c
Fagaceae	Quercus	harlandii	0.903	0.865-0.971	a,c

Fagaceae	Quercus	konishii	0.903	0.865-0.971	a,c
Fagaceae	Quercus	semecarpifolia	0.903	0.865-0.971	a,c
Fagaceae	Quercus	stenophylla	0.903	0.865-0.971	a,c
Fagaceae	Quercus	tarokoensis	0.903	0.865-0.971	a,c
Fagaceae	Quercus	tatakaensis	0.903	0.865-0.971	a,c
Fagaceae	Quercus	variabilis	0.865	-	a
Flacourtiaceae	Idesia	polycarpa	0.668	-	e
Hamamelidaceae	Liquidambar	formosana	0.670	-	a,f
Hamamelidaceae	Sycopsis	sinensis	0.670	-	a,d
Illiciaceae	Illicium	anisatum	0.549	-	a,c
Illiciaceae	Illicium	arborescens	0.549	-	a,c
Juglandaceae	Engelhardtia	roxburghiana	0.602	-	a,c
Juglandaceae	Juglans	cathayensis	0.600	-	b,c
Juglandaceae	Platycarya	strobilacea	0.720	-	b
Lauraceae	Actinodaphne	nantoensis	0.548	0.494-0.601	a,c
Lauraceae	Actinodaphne	pedicellata	0.548	0.494-0.601	a,c
Lauraceae	Beilschmiedia	erythrophloia	0.538	0.561-0.66	a,d
Lauraceae	Cinnamomum	camphora	0.420	-	a
Lauraceae	Cinnamomum	kanehirai	0.461	0.41-0.552	a,c
Lauraceae	Cinnamomum	macrostemon	0.461	0.41-0.552	a,c
Lauraceae	Cinnamomum	mushaensis	0.461	0.41-0.552	a,c
Lauraceae	Cinnamomum	osmophloeum	0.461	0.41-0.552	a,c
Lauraceae	Cinnamomum	philippinense	0.461	0.41-0.552	a,c
Lauraceae	Cinnamomum	randaiense	0.552	-	a
Lauraceae	Cryptocarya	chinensis	0.545	-	a
Lauraceae	Lindera	communis	0.660	-	a,c
Lauraceae	Lindera	erythrocarpa	0.660	-	a,c
Lauraceae	Lindera	megaphylla	0.660	-	a,c
Lauraceae	Litsea	acuminata	0.600	-	b,c
Lauraceae	Litsea	acutivena	0.600	-	b,c
Lauraceae	Litsea	akoensis	0.600	-	b,c
Lauraceae	Litsea	coreana	0.600	-	b,c
Lauraceae	Litsea	cubeba	0.600	-	b,c

Lauraceae	Litsea	elongata	0.600	-	b,c
Lauraceae	Litsea	kostermansii	0.600	-	b,c
Lauraceae	Litsea	lii	0.600	-	b,c
Lauraceae	Litsea	morrisonensis	0.600	-	b,c
Lauraceae	Litsea	nakaii	0.600	-	b,c
Lauraceae	Litsea	oblongifolia	0.600	-	b,c
Lauraceae	Machilus	japonica	0.490	0.487-0.493	a,c
Lauraceae	Machilus	kusanoi	0.490	0.487-0.493	a,c
Lauraceae	Machilus	thunbergii	0.493	-	a
Lauraceae	Machilus	zuihoensis	0.487	-	a,f
Lauraceae	Neolitsea	acuminatissima	0.538	0.42-0.66	a,d
Lauraceae	Neolitsea	konishii	0.538	0.42-0.66	a,d
Lauraceae	Neolitsea	parvigemma	0.538	0.42-0.66	a,d
Lauraceae	Neolitsea	sericea	0.538	0.42-0.66	a,d
Lauraceae	Neolitsea	variabillima	0.538	0.42-0.66	a,d
Lauraceae	Phoebe	formosana	0.538	0.42-0.66	a,d
Lauraceae	Phoebe	zhennan	0.538	0.42-0.66	a,d
Lauraceae	Sassafras	randaiense	0.467	-	a
Leguminosea	Moringa	olifera	0.668	-	e
Lythraceae	Lagerstroemia	subcostata	0.648	-	a,f
Magnoliaceae	Michelia	compressa	0.532	-	a
Malvaceae	Hibiscus	taiwanensis	0.668	-	e
Meliaceae	Dysoxylum	hongkongense	0.442	-	a,c
Meliaceae	Melia	azedarach	0.442	-	a
Mimosaceae	Leucaena	leucocephala	0.668	-	e
Moraceae	Ficus	caulocarpa	0.305	-	a,c
Moraceae	Ficus	erecta	0.305	-	a,c
Moraceae	Ficus	nervosa	0.305	-	a,c
Moraceae	Maclura	cochinchinensis	0.305	-	a,d
Moraceae	Morus	australis	0.305	-	a,d
Myrsinaceae	Ardisia	quinquegona	0.545	-	a,c
Myrsinaceae	Ardisia	sieboldii	0.545	-	a,f
Myricaceae	Myrica	rubra	0.520	-	b

Myrsinaceae	Myrsine	neriifolia	0.668	-	e
Myrtaceae	Syzygium	formosanum	0.668	-	e
Myrtaceae	Syzygium	somai	0.668	-	e
Oleaceae	Fraxinus	griffithii	0.743	-	a,c
Oleaceae	Fraxinus	insularis	0.743	-	a,c
Oleaceae	Ligustrum	japonicum	0.860	-	b,c
Oleaceae	Ligustrum	matsudae	0.860	-	b,c
Oleaceae	Ligustrum	morrisonense	0.860	-	b,c
Oleaceae	Ligustrum	pricei	0.860	-	b,c
Oleaceae	Osmanthus	enervis	0.930	-	b,c
Oleaceae	Osmanthus	heterophyllus	0.930	-	b,c
Oleaceae	Osmanthus	lanceolatus	0.930	-	b,c
Oleaceae	Osmanthus	marginatus	0.930	-	b,c
Oleaceae	Osmanthus	matsumuranus	0.930	-	b,c
Oleaceae	Osmanthus	kaoi	0.930	-	b,c
Pinaceae	Abies	kawakamii	0.382	-	a
Pinaceae	Picea	morrisonicola	0.472	-	a
Pinaceae	Pinus	armandii	0.468	-	a
Pinaceae	Pinus	morrisonicola	0.536	-	a
Pinaceae	Pinus	taiwanensis	0.514	-	a
Pinaceae	Pseudotsuga	wilsoniana	0.462	-	a
Pinaceae	Tsuga	chinensis	0.548	-	a
Pittosporaceae	Pittosporum	illicioides	0.668	-	e
Pittosporaceae	Pittosporum	tenuifolium	0.668	-	e
Podocarpaceae	Podocarpus	neriifolius	0.730	-	b,c
Portulaceace	Portulaca	oleracea	0.668	-	e
Proteaceae	Helicia	formosana	0.524	-	a,f
Rhamnaceae	Rhamnus	crenata	0.668	-	e
Rhamnaceae	Rhamnus	davurica	0.668	-	e
Rhamnaceae	Rhamnus	formosana	0.668	-	e
Rhamnaceae	Rhamnus	nakaharae	0.668	-	e
Rosaceae	Eriobotrya	deflexa	0.731	0.68-0.8	b,d
Rosaceae	Laurocerasus	spinulosa	0.731	0.68-0.8	b,d

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Rosaceae	Malus	doumeri	0.731	0.68-0.8	b,d
Rosaceae	Photinia	lasiopetala	0.731	0.68-0.8	b,d
Rosaceae	Photinia	niitakayamensis	0.731	0.68-0.8	b,d
Rosaceae	Photinia	serrulata	0.731	0.68-0.8	b,d
Rosaceae	Pourthiaea	notabilis	0.731	0.68-0.8	b,d
Rosaceae	Prinsepia	utilis	0.731	0.68-0.8	b,d
Rosaceae	Prunus	campanulata	0.712	0.6-0.9	b,c
Rosaceae	Prunus	obtusata	0.712	0.6-0.9	b,c
Rosaceae	Prunus	phaeosticta	0.712	0.6-0.9	b,c
Rosaceae	Prunus	taiwaniana	0.712	0.6-0.9	b,c
Rosaceae	Rhaphiolepis	indica	0.731	0.068-0.8	b,d
Rosaceae	Sorbus	randaiensis	0.800	-	b,c
Rubiaceae	Gardenia	florida	0.668	-	e
Rubiaceae	Tricalysia	dubia	0.668	-	e
Rubiaceae	Wendlandia	uvariifolia	0.668	-	e
Rutaceae	Citrus	reticulata	0.668	-	e
Rutaceae	Glycosmis	cochinchinensis	0.668	-	e
Rutaceae	Phellodendron	wilsonii	0.668	-	e
Rutaceae	Skimmia	reevesiana	0.668	-	e
Rutaceae	Tetradium	meliaefolia	0.668	-	e
Rutaceae	Tetradium	ruticarpum	0.668	-	e
Rutaceae	Zanthoxylum	pistaciiflorum	0.668	-	e
Rutaceae	Zanthoxylum	schinifolium	0.668	-	e
Sabiaceae	Meliosma	callicarpifolia	0.555	0.459-0.65	a,b,c
Sabiaceae	Meliosma	rhoifolia	0.459	-	a,f
Sabiaceae	Meliosma	squimulata	0.555	0.459-0.65	a,b,c
Salicaceae	Salix	fulvopubescens	0.450	-	b,c
Salicaceae	Salix	lanifera	0.450	-	b,c
Salicaceae	Salix	morii	0.450	-	b,c
Sapindaceae	Sapindus	mukorossi	0.622	-	a,f
Saxifragaceae	Deutzia	cordatula	0.668	-	e
Saxifragaceae	Deutzia	grandiflora	0.668	-	e
Saxifragaceae	Deutzia	taiwanensis	0.668	-	e

Saxifragaceae	Hydrangea	angustipetala	0.668	-	e
Saxifragaceae	Hydrangea	chinensis	0.668	-	e
Saxifragaceae	Itea	parviflora	0.668	-	e
Stachyuraceae	Stachyurus	himalaicus	0.668	-	e
Staphyleaceae	Turpinia	arguta	0.668	-	e
Staphyleaceae	Turpinia	ternata	0.668	-	e
Styracaceae	Alniphyllum	pterospermum	0.425	-	a,f
Styracaceae	Styrax	formosana	0.600	-	b,c
Styracaceae	Styrax	suberifolia	0.600	-	b,c
Symplocaceae	Symplocos	arisanensis	0.668	-	e
Symplocaceae	Symplocos	caudata	0.668	-	e
Symplocaceae	Symplocos	divaricativena	0.668	-	e
Symplocaceae	Symplocos	glauca	0.668	-	e
Symplocaceae	Symplocos	konishii	0.668	-	e
Symplocaceae	Symplocos	lucida	0.668	-	e
Symplocaceae	Symplocos	migoi	0.668	-	e
Symplocaceae	Symplocos	modesta	0.668	-	e
Symplocaceae	Symplocos	morrisonicola	0.668	-	e
Symplocaceae	Symplocos	nokoensis	0.668	-	e
Symplocaceae	Symplocos	setchuensis	0.668	-	e
Symplocaceae	Symplocos	sonoharae	0.668	-	e
Symplocaceae	Symplocos	stellaris	0.668	-	e
Symplocaceae	Symplocos	theophrastifolia	0.668	-	e
Symplocaceae	Symplocos	wikstroemiifolia	0.668	-	e
Taxaceae	Taxus	mairei	0.725	-	a
Theaceae	Adinandra	formosana	0.702	0.577-0.81	a,b,d
Theaceae	Adinandra	lasiostyla	0.702	0.577-0.81	a,b,d
Theaceae	Camellia	brevistyla	0.810	-	b,c
Theaceae	Camellia	tenuifolia	0.810	-	b,c
Theaceae	Camellia	transnokoensis	0.810	-	b,c
Theaceae	Cleyera	japonica	0.700	-	b,c
Theaceae	Cleyera	morii	0.700	-	b,c
Theaceae	Cleyera	taipinensis	0.700	-	b,c

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Theaceae	Cleyera	longicarpa	0.700	-	b,c
Theaceae	Eurya	acuminata	0.750	-	b,c
Theaceae	Eurya	chinensis	0.750	-	b,c
Theaceae	Eurya	crenatifolia	0.750	-	b,c
Theaceae	Eurya	glaberrima	0.750	-	b,c
Theaceae	Eurya	gnaphalocarpa	0.750	-	b,c
Theaceae	Eurya	hayatae	0.750	-	b,c
Theaceae	Eurya	japonica	0.750	-	b
Theaceae	Eurya	leptophylla	0.750	-	b,c
Theaceae	Eurya	nitida	0.750	-	b,c
Theaceae	Eurya	strigillosa	0.750	-	b,c
Theaceae	Gordonia	axillaris	0.702	0.577-0.81	a,b,d
Theaceae	Pyrenaria	shinkoensis	0.702	0.577-0.81	a,b,d
Theaceae	Schima	superba	0.577	-	a
Theaceae	Ternstroemia	gymnanthera	0.672	-	a
Trochodendraceae	Trochodendron	aralioides	0.526	-	a
Ulmaceae	Ulmus	parvifolia	0.899	-	a
Ulmaceae	Ulmus	uyematsui	0.899	-	a,c
Ulmaceae	Trema	orientalis	0.833	0.767-0.899	a,d
Ulmaceae	Zelkova	serrata	0.767	-	a
Urticaceae	Boehmeria	densiflora	0.662	0.305-0.899	a,d
Urticaceae	Boehmeria	nivea	0.662	0.305-0.899	a,d
Urticaceae	Oreocnide	pedunculata	0.662	0.305-0.899	a,d
Verbenaceae	Callicarpa	formosana	0.668	-	e
Verbenaceae	Callicarpa	kochiana	0.668	-	e
Verbenaceae	Clerodendrum	trichotomum	0.668	-	e
Verbenaceae	Vitex	quinata	0.668	-	e

[a] Taiwan Forestry Research Institute (1992)
[b] Ryōzō Kanehira (1926)
[c] Specific gravity based on the same genus
[d] Specific gravity based on the same family
[e] Specific gravity based on an average value of hardwoods
[f] Specific gravity converted from green volume to 12% dry

Table A3 Classification of seven vegetation zones in Taiwan (Taiwan Forest Bureau 2004)

Vegetation Zone	Altitude (m)	Annual Average Temperature (℃)	Annual Average Rainfall (mm)	Presentative Species
Alpine Tundra	≧3500	≦5	2800	*Juniperus morrisonicola* *Rhododendron pseudochrysanthum* *Juniperus communis*
Subalpine Coniferous forest	3000-3500	8~11	2800	*Abies kawakamii* *Yushania niitakayamensis*
Cold Temperate Coniferous forest	2500-3000	15~18	3500	*Tsuga chinensis* *Picea asperata* *Pinus armandii* *Pinus taiwanensis*
Cold Temperate Coniferous and Broad-leaved mixed forest	1800-2500	10~20	3000-4200	*Chamaecyparis formosensis* *Chamaecyparis taiwanensis* *Castanopsis carlesii* *Machilus thunbergii* *Alnus formosana*
Warm Temperate Broad-leaved forest	500-1800	17~23	--	Evergreen broad-leaved trees are mainly composed of *Lauraceae* (*Machilus*), *Theaceae* and *Fagaceae* (*Castanopsis*).

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Subtropical Broad-leaved forest	≦500	≧23	1000~4000	The compositions of plants are dominated by *Moraceae*(*Ficus*) and *Lauraceae* (*Machilus*).
Tropical Monsoon forest	≦200	≧25	3000	*Ficus benjamina* *Cerbera manghas* *Pandanus tectorius* *Calophyllum Inophyllum*

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