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Biomass production and distribution in mixed- species spacing trial in Central Oregon

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0. ABSTRACT

Forest management initially developed as an approach to ensuring a steady supply of timber for society’s needs. Historically, foresters in many regions have met this objective most efficiently by growing even-aged monocultures in a manner that maintained a uniform distribution of age classes in a given forest ownership, a condition referred to as a regulated forest. In the U.S. Pacific Northwest (PNW), Douglas-fir has been the major species west of the Cascades Mountains, and ponderosa pine has been the major species east of the Cascades. Due to the diversity of forest ownership, due to the increasingly complex objectives that these diverse landowners have adopted, due to natural stand dynamics that in many places make monocultures prohibitively expensive to maintain, and due to fluctuations in timber markets, foresters have never attained a regulated forest of Douglas-fir or ponderosa pine monocultures. Despite the fact that most landowners still need and want to generate timber revenue, they also have become increasinly interested in biodiversity, cultural value and recreation. Foresters have therefore been working on modifying silvicultural systems to meet this wider diversity of objectives.

Mixed species plantations may offer one way to produce economic benefits from forest management, while maintaining other important values. The dynamics and appropriate management regimes for mixed species stands are a largely unknown because the bulk of past research has focused on even-aged single-species stands. Most work in mixed stands has suggested that they produce yields that fall between the yields of pure stands of the constituent species.
Society currently demands fiber production while conserving biodiversity, landscape aesthetics, and production of other non-timber forest products (i.e. mushrooms, etc.). Because society demands a multiple-use forest, particularly on publicly owned land, mixed species stands and associated silvicultural systems are receiving more attention. Some of the benefits produced by mixed species are presumed and have yet to be scientifically tested, for example less intense intertree competition, more facilitation of one species by the other , better landscape aesthetics, greater biodiversity, and enhanced resistance to species-specific pests and diseases.

As in the PNW and other regions of the world, forestry in Spain has focused on understanding and applying silviculture techniques for growing even-aged monocultures. One typical topic is identification of the best planting density for each species, and quantifying the growth and the productivity of each species under various densities and spatial arrangements. Silvicultural practices appropriate for individual species often require for successful cultivation of mixed species stands. Due to a lack of information, the number of research studies to assess and understand the behavior of mixed species stands has increased in order to identify optimal silvilcultural practices.

Mixed-species silvicultural studies are important in the PNW because there are so few experimental plots with designed mixes of species. In eastern Oregon, the USDA-FS Pacific Northwest Research Station had the foresight to establish two initial spacing trials in with two different mixes of species, one in *Pinus ponderosa* and *Pinus contorta* and another in *Abies grandis* and *Pinus ponderosa*.

Accurate assessment of the productivity of mixed species plantations requires knowledge of the interactive effects of species composition and stand density on the allometric relationships of various biomass components in both species of the mix.
Lookout Mountain is the place where the study has been established in early 70s, with *Pinus ponderosa* and *Abies grandis* as the two species of the study plots. Since the plantation, mostly every five years the plots had been measured and remeasured. Using all this data different components at tree level and at stand level have been studied. In this case the objective of this study is to calculate the biomass of all the aboveground components (foliage mass, branch-wood mass and stem wood mass), comparing the differences between spacings and species composition.

Different models have been fitted in order to estimate the mass of foliage and branch-wood mass, a taper equation was used to estimate the stem volume and applying an average wood density value for the two species of the study the stem wood mass was calculated.

The results of this thesis show that the total foliage mass of the mixed plots always is greater than *Pinus ponderosa* (less shade tolerant) and less than *Abies grandis* (shade tolerant) foliage mass. In the case of total branch wood mixed plots have a total branch wood mass between the pure plots but, *Pinus ponderosa* pure plots have the greatest total branch-wood mass. The differences between mixed plots and pure plots in the total stem wood mass are minor than in the other cases, as the trees are older the differences are minor. So, the total biomass in mixed plots always is between the pure plots, *Pinus ponderosa* have the greatest total biomass but in the latter years of remeasurement there are less and less differences between species composition.

The results obtained in this study support the results of many researches, that mixed plots can be more productive than pure plots. Biodiversity and timber production are possible if we chose the correct species and spacing, the research in this topic have to be continued in order to find the best combination of species, phenology, ecology, soil, climate, nutrients...etc. This thesis is only one step in the research of mixed forests.

0. RESUMEN

El manejo de los bosques inicialmente se llevaba a cabo solo para satisfacer las necesidades de madera de la sociedad. Históricamente, los propietarios forestales conseguían este objetivo mediante masas monoespecíficas, manteniendo una distribución de clases uniforme. En Estados Unidos en el Pacífico Noroeste (PNW), el abeto Douglas (*Pseudotsuga menziesii*) ha sido la especie principal de estas plantaciones puras para madera al oeste de Cascades Mountains, mientras que al este de Cascades Mountains ha sido el pino ponderosa (*Pinus ponderosa*). Debido a la gran cantidad de propietarios de los terrenos forestales, al aumento de la complejidad de los objetivos de la selvicultura, a la dinámica natural de los rodales que hace que en muchos casos las masas monoespecíficas sean difíciles de mantener y debido a las fluctuaciones del precio de la madera en el mercado, es necesario cambiar el concepto de la selvicultura tradicional. A pesar de que los propietarios aun quieren seguir manteniendo las masas puras, también tienen más interés en la biodiversidad, en el valor cultural y recreativo, incluso han modificado muchas prácticas habituales de selvicultura a fin de conseguir incluir en sus masas todos estos objetivos.

Las masas mixtas pueden seguir manteniendo el objetivo principal de producir madera mientras que con la mezcla de diferentes especies se consiguen otros valores. La dinámica que siguen las masas mixtas así como el manejo más adecuado de estas masas es algo prácticamente desconocido actualmente, ya que las investigaciones se han centrado a lo largo de los años en las masas puras. La mayoría de los trabajos y estudios realizados en masas mixtas sugieren o han demostrado que la producción total en masas mixtas es mayor que la producción de las masas puras de las especies que componen la masa mixta.

La sociedad actualmente demanda producción de madera a la par que biodiversidad, paisaje, estética y producción de otros productos no maderables (ej: setas, caza…etc). Ya que la sociedad demanda múltiples usos del bosque, sobre todo en montes públicos, los bosques mixtos y su selvicultura está teniendo más y más importancia. Muchos de los beneficios de estos tipos de masas se presuponen, no están científicamente probados, algunos de ellos son: menos competición entre especies, facilitación de una especie por la otra, mejor estética del paisaje, mayor biodiversidad, mayor resistencia a plagas o enfermedades…etc.

Así como en el PNW y en otras regiones del mundo, las prácticas forestales en España también se han centrado en plantaciones monoespecíficas. Uno de los principales objetivos de las investigaciones de las masas puras, era encontrar la densidad óptima a la cual se conseguía la mayor producción del rodal. Conocer en profundidad el comportamiento de las masas puras y el comportamiento de la especie elegida, puede facilitar la comprensión de las masas mixtas. Debido a la falta de información, el número de estudios e investigaciones para entender el comportamiento de las masas mixtas está creciendo para así poder encontrar las prácticas selvícolas óptimas.

Los estudios de masas mixtas son importantes en el PNW porque hay muy pocas parcelas experimentales de masas mixtas. En el este de Oregón, el USDA-FS Pacific Northwest Research Station estableció a principios de los años 70, un estudio

experimental con la mezcla de diversas especies: *Pinus contorta* con *Pinus ponderosa* y *Pinus ponderosa* con *Abies grandis*.
Una estimación precisa de la productividad de las masas mixtas requiere un conocimiento de los efectos de la composición de especies y de la densidad de los rodales así como de la relaciones alométricas entre los diferentes componentes de los árboles que conforman los rodales mixtos.

Lookout Mountain es el lugar donde se encuentran las parcelas de estudio de este proyecto. El estudio se estableció a principios de los años 70, con *Pinus ponderosa* y *Abies grandis* como las dos especies de las parcelas. Desde la plantación, cada cinco años se han realizado medidas de las parcelas. Utilizando todos los datos recogidos a lo largo de los años, se han estudiado diferentes componentes a nivel árbol y a nivel rodal. En el caso de este proyecto el objetivo principal ha sido calcular la biomasa total de las parcelas y posteriormente extrapolarlo a nivel rodal y monte. Para la estimación total de la biomasa se han calculado por separado la masa total de follaje, la masa total de madera+corteza de las ramas, y la masa total de madera del tronco sin corteza, sumando todos estos componentes se ha obtenido la biomasa total por parcela y por hectárea.

Diversos modelos estadísticos han sido ajustados para la estimación del follaje y madera de ramas, eligiendo el que mejor se ajustaba, para el caso del cálculo del volumen de madera y masa de madera del tronco se han usado “taper equations” que fueron ajustadas para estas mismas parcelas en estudios previos.

Los resultados obtenidos en este estudio muestran que la cantidad total de follaje en las parcelas mixtas siempre es mayor que en las parcelas puras de *Pinus ponderosa* (intolerante a la sombra) y menor que las parcelas puras de *Abies grandis* (tolerante a la sombra). En el caso de la masa de madera de las ramas, la biomasa de ramas en las parcelas mixtas tiene valores comprendidos entre los valores totales de biomasa en las parcelas mixtas pero en este caso es *Pinus ponderosa* quien tiene mayores cantidades de masa de ramas. Las diferencias entre las parcelas mixtas y las parcelas puras en cuanto a cantidad de madera de tronco son menores a medida que la masa se va haciendo madura. En cuanto a la biomasa total de las parcelas que era el objetivo principal del estudio, se ha obtenido que en las parcelas mixtas la biomasa siempre alcanza valores intermedios entre las parcelas puras, pero estas diferencias cada vez se hacen menores según los árboles maduran.

Los resultados de este estudio apoyan los resultados de otros estudios realizados sobre la materia, esto es que las masas mixtas pueden ser más productivas que las masas puras. Biodiversidad y producción de madera son posibles si se elijen las especies y el espaciamiento correctos. Los estudios en masas mixtas deben continuar para afinar y poder encontrar la mejor combinación de especies, así como la mejor combinación de la fenología, ecología de las especies elegidas, las características del suelo, el clima…etc. Este estudio es solo un paso más en la investigación de las masas mixtas.

1. INTRODUCTION

The global forest area has been increasing in recent years, according to data from the FAO (2010), reaching 30% of the earth´s land surface in 2005. These numbers show us that the forests have gained importance in our society; the increase of forests probably is due to a combination of objectives, including continued supplies of wood, recognition of their potential for carbon sequestration to reduce the greenhouse effect, or aforestation policies that reflect more general and diverse values from forests.

A common practice has been cutting of native forests and replacement with plantations in order to produce more timber; however, this practice is disappearing because of restrictions on cutting native forests and aforestation of abandoned agricultural lands that can be that yield productive forest plantations, thereby helping to maintain and preserve native forests.

Most of the forest plantations on a global scale are monocultures; the species that are predominant in these kinds of plantations are from the following genera: Eucalyptus, Pinus, Acacia, Pseudotsuga, Swietenia, and Gmelina (Kelty, 2006).

The first question we must ask ourselves is, why monocultures? Until almost the 1970s, only monocultures were planted because the main objective was to obtain timber. Pure stands have the ability to maximize production of one species that usually has the desired wood qualities. In pure stands only one type of management is generally applied, and thinnings are done at the same time because we do not have to think about the different phenologies of more than one species. This type of plantation simplifies management, makingthe costs of nursery practice, planting, harvest operations, and management less that in mixed stands.

After recognizing the advantages of monocultures, a reasonable question is whether any advantages would be offered by mixed-species plantations. Some researchers have concentrated on comparing monocultures and mixed-species stands. Some commonly stated objectives of mixed species plantations include increasing stand-level productivity, allowing harvest of different products from different species on different rotations, reducing the risk of pests and diseases, and restoring degraded areas (Kelty, 2006).

One of the main intended objectives of mixed stands is to increase stand-level productivity by planting or regenerating species with complementary characteristics. The key to designing mixed species plantations to obtain high productivities is to choose species with different ecological niches, for example, shade tolerance, height growth rate, crown structure, and rooting depth. If the chosen species differ substantially in these characteristics, they will use different portions of the available resources in time and space, and use them most completely. If more of the site resources are used and/or they are used more efficiently, the stand level productivity will be greater than in monocultures. For example, all trees in monocultures are expected to have the same phenology and to use the resources at the same timeology.

Another way to increase the biomass production is through facilitacion, this means that one species facilitate access to available resources by the other species. A common expectation is that a N-fixing species will enhance nitrogen availability to the other and accelerate nitrogen cycling so that total growth will be greater.

Combining species that differ in growths rates and in rotation lengthwill reduce the length of time when products first become available. This reduction is important because the main challenge of forest plantations is carrying early investments in site preparation, plantation, and competition control until the first harvest of merchantable products. Forestry rotations are long, so many years must pass until they start to generate income. Mixing species, with different rates of development may provide earlier cash flow so we can support the costs of the management.

Another commonly stated advantage of mixed stands is resistance to pests and diseases. In pure stands, all the trees are susceptible to a species-specific pest. Even if the stand is no more resistant to a pest or disease, growing more than one species will reduce the impact of the pest because not all the trees will be affected by it. The non-susceptible species will therefore survive.

In countries like the United States (especially the West Coast) or Spain, in which one of the most important stand-replacing disturbances are forest fires, it could be helpful to have several species that differ in ecology and phenology, particularly if one species is more resistant to fire or has greater capacity for regeneration after fire.

Nowadays society expects many services from forests, including fiber production, conservation of biodiversity, landscape aesthetics, and other non-timber forest products (i.e. mushrooms, etc.). Because society demands multiple-use forests, particularly on public owned land, mixed species stands and associated silvicultural systems are receiving more attention. Some benefits of mixed species have been explained above, but most of them are presumed and have yet to be scientifically tested. For example, it is not clear whether there is less intense intertree competition, more facilitation of one species by the other , better landscape aesthetics, greater biodiversity, and enhanced resistance to species-specific pests and diseases.

Despite of the fact that society demands mixed forests, there are not too many studies about mixed plantations because land owners have traditionally grown single-species stands and may not be aware of potential advantages provided by species mixtures. The idea that monocultures are the best options is changing, and gradually there are more studies that show the benefits of the mixture of species.

Mixed species plantations have received some attention in the Pacific Northwest (PNW) of the United States, including installation of some field trials..

In eastern Oregon, the USDA-FS Pacific Northwest Research Station had the foresight to establish two initial spacing trials in with two different mixes of species, one in *Pinus ponderosa* and *Pinus contorta* and another in *Abies grandis* and *Pinus ponderosa*. Early results on these trials were reported by Seidel (1985). More recently, Garber and Maguire (2003, 2004, 2005a, b) have studied the effects of variation in species composition and initial planting density on stem form, stand productivity, size and distribution of branches, and vertical foliage distribution.

In the United States and Spain, interest is increasing in planting mixed species stands. However, this silvicultural practice is relatively new for the species involved, and there is little information on the performance of these stands over a long time-horizon, or on the best silvicultural regimes for the wide variety of possible species mixes. Fundamental research questions can be addressed by any mixed-species spacing trials, in addition to gain of site- and species-specific information on stand development. In Spain there is a study which has assessed the long-term behavior of mixed-species plantations (Condés, Del Rio, & Sterba, 2013). Condés, Del Rio, & Sterba, found that mixed species stands between *Pinus sylvestris* and *Fagus sylvatica* promote faster growth relative to their monoculture counterparts.

Accurate assessment of the productivity of mixed species plantations requires knowledge of the interactive effects of species composition and stand density on the allometric relationships of various biomass components in both species of the mix. The proposed study will assess how mixed species stand perform relative to monoculture stands in terms of biomass accumulation and it allocation among various above-ground components in Central Oregon. The study will rely on a series of experimental plots that were established in the late 1960s and have been measured seven times up to the dormant season of 2004/5.

2. BACKGROUND

2.1.PRINGLE FALLS EXPERIMENTAL FOREST

2.1.1. INTRODUCTION

Pringle Falls Experimental Forest was established in May 1931 as a center for silviculture, forest management, and insect and disease research in ponderosa pine forests east of the Oregon Cascade Range.
It was the first experimental forest to be established by the Pacific Northwest Research (PNW). In 1914 3043 ha were selected for the Pringle Butte unit of the experimental forest. The Lookout Mountain unit with 3535 acres was added in 1936. Pringle Falls Research Natural Area, within the Pringle Butte unit of the experimental forest, provided a protected area for nondestructive research.

2.1.2. OBJECTIVES

The main objectives of the Pringle Falls Experimental Forest were: to improve silvicultural methods for harvesting mature ponderosa pine stands for commercial production, to convert forests with low value into forests with higher value, to protect forests from insects and diseases, and to integrate improvement of forage resources into silviculture.

More specifically the main objective of Pringle Falls Experimental Forest was to learn about the basic silviculture and ecology of the central Oregon´s forests, and develop better methods for harvesting, managing, and protecting.

2.1.3. LOCATION

Pringle Falls Experimental Forest lies within the Deschutes National Forest in central Oregon and is about 48km southwest of Bend, OR (Figure 1). It is composed of two different areas, the Pringle Butte unit dominated by old-growth ponderosa pine (latitude 43º 43’N; longitude 121º 36’W) and the Lookout Mountain unit containing mostly young stands from two stand-replacement fires (latitude 43º48’N; longitude 121º 41’W).

Figure 1 Pringle Falls Experimental Forest in Central Oregon, with distribution of ponderosa pine (*Pinus ponderosa*) despicted by shading (Youngblood, 2011).

2.1.4. PAST RESEARCH

Between 1930 and 1993 a total of 119 research reports were published. Some of the early results of studies addressed the susceptibility of ponderosa pine to western pine beetle attack, silvicultural cutting methods with different intensities of selection, stand structure and growth for releasing suppressed ponderosa pine seedlings, and sanitation and salvage cutting of insect-susceptible ponderosa pine with the objective of fuel and fire hazard reduction.

Later studies were concentrated on determining the competitive effect of shrubs growing with ponderosa pine, soil properties, lodgepole and ponderosa pine regeneration, and other topics.

Long-term or permanent research plots were established to study the response of ponderosa pine to fertilization and to evaluate the growth of ponderosa pine at various trees densities. Periodic evaluation of these stands helped to understand the structural changes in managed stands.

Pringle Falls served as a primary research platform because of the proximity to the Bend Silvicultural Laboratory of the Pacific Northwest Research Station. This Lab closed in 1996, so, some studies were finished and others were continued by researchers of different universities.

The long-term research at Pringle Falls is important for continued understanding of the dynamics of managed and unmanaged interior northwestern forests.

Current long-term research in Pringle Falls is designed to increase understanding of the processes that regulate or influence the structure, composition, and pattern of forests and that are therefore critical for the maintenance of diverse, healthy, productive, and sustainable forest ecosystems. Specific examples include quantification of stand structure in old-growth ponderosa pine, the role of repeated fire in regulating forest structure and forest health, and the effect of species composition in overall stand production and development. (US Forest Service).

2.1.5. CLIMATE

The climate of Pringle Falls is continental, modified by proximity of the Cascade Range to the west and the Great Basin Desert to the east. Most precipitation occurs as snowfall. Annual precipitation averages 610 mm on Pringle Butte and more than 1,020 mm on Lookout Mountain. Daytime high temperatures in the summer range from 21 to 32 °C. Summer nights are cool and frosts can occur throughout the growing season (US Forest Service).

2.1.6. SOILS

Pringle Falls has low-elevation forests; the terrain is generally flat but is dotted with small volcanic peaks and cinder cones. Pringle Butte, the oldest known geologic formation in the area, is a 5-million-year-old shield volcano rising nearly 305 m above the surrounding basin. More recent deposits are sand and silt sediments of the La Pine Basin, overlain with sands and gravels deposited by glacial outwash from the Cascade Range. Lookout Mountain, the highest point in Pringle Falls Experimental Forest (1,592 m), is a 300,000-year-old shield volcano resting on La Pine sediments. Overlaying the entire area is a 0.5- to 2-m-thick layer of dacite pumice and ash resulting from the explosion of Mount Mazama (now Crater Lake) nearly 6,600 years ago. Soils derived from Mazama pumice and ash have only a thin weathered surface layer. Most of the soil profile is undeveloped, with low organic matter content, low nitrogen, sulfur, and phosphorus content, and high porosity. Daytime to nighttime temperature variation within the soil profile can be extreme.

2.1.7. VEGETATION

Forest communities within Pringle Falls are representative of low- and mid-elevation regional Pringle Falls Experimental Forest (Oregon) landscapes. Aspect, elevation, and past disturbance events (especially fires, insects, and disease, and more recent timber harvesting) have created a mosaic of rich biological diversity. Ponderosa pine is the dominant conifer through most of Pringle Falls. Shrub layers include antelope bitterbrush, ceanothus, greenleaf manzanita, giant chinquapin, and bearberry. A fire regime of low-intensity that burned every 7 to 20 years, coupled with infrequent large and more intense fires, was common prior to the advent of modern fire suppression.

Dense stands of lodgepole pine with antelope bitterbrush, Idaho fescue, western needlegrass, and bearberry occur on flats and basin bottoms that are slow to drain in the spring and, because of topography, are prone to frequent frosts that kill ponderosa pine seedlings. In the mixed-conifer forest type at higher elevations, stands may contain ponderosa pine, grand fir, Shasta red fir, sugar pine, western white pine, whitebark pine, and mountain hemlock.

2.2.MIXED-CONIFER STANDS OF THE DESCHUTES NATIONAL FOREST

Mixed-conifer stands can be divided into wet and dry types based on precipitation, elevation, and the understory species composition. Pinus ponderosa, Douglas fir and grand fir are in the wet zones while western larch (Larix occidentalis), lodgepole pine (Pinus contorta), and cottonwood (Populus trichocarpa) are in the dry zones. Grand fir (Abies grandis) and white fir (Abies concolor) commonly hybridize in the region covered by the Deschutes National Forest.

2.2.1. HISTORY

Native Americans managed the landscape using seasonal burning. This intentional burning with natural fires, had maintained a park-like structure and kept in-growth to a minimum (Rogan, 2012).

Settlers of central Oregon began selectively cutting large timber mainly for construction. They discovered the value of the timber in Deschutes region and began cutting ponderosa pine even before they had a way to transport the timber. Then the rail road was built and it was easier to transport the cut logs.

The landscape was originally dominated by ponderosa pine, which was the most useful species. The largest trees with highest quality logs were high-graded, greatly reducing the number of old growth trees of ponderosa pine.

The actual structure of mixed-species stands was the result of a great variety of management activities through the years. In the past the largest, “most beautiful” trees were cut, resulting in a variety of structures that differs in age, size composition, understory vegetation, and other attributes. One of the most common stand structures now is a mix of shade-intolerant Pinus ponderosa and shade-tolerant Abies grandis.

Currently, a federal policy in the Columbia River Basin, including the Deschutes National Forest, restrict the cutting trees greater than 53cm diameter at breast height to retain and restore stands with old growth characteristics.

The knowledge of the past management can help us to understand the current structure of the forest that is object of this study.

2.2.2. LOOKOUT MOUNTAIN EXPERIMENTAL SITE

Over the years, the forest research has focused mainly on spacing and thinning regimes, providing information about on the growth response of different species, and guidelines on spacing and optimal age for thinnings. This information helps manage long-term forest growth and develop models for managing stands to meet specific objectives. Considerable information is available about thinning regimes and growth responses of pure stands, but little information is available about the response of mixed species stands.

In 1974 a spacing study site in Lookout Mountain was established with seedlings of ponderosa pine (*Pinus ponderosa* Dougl. Ex Laws.), and grand fir (*Abies grandis* (Dougl. Ex D. Don) Lindl) in Central Oregon. The objective of this study was to obtain information on the productivity of mixed species stands of these species at several spacing in terms of diameter, height, basal area, an volume growth (Seidel, 1985).
The study area was a 20 acre clearcut in a mixed conifer snowbrush/chinkapin plant community. Typical ground cover in this community consists primarily of snowbrush (*Ceanothus velutinus* Dougl.ex Hook), Greenleaf Manzanita (*Arctostaphylos patula* Greene), and golden chinkapin (*Castanopsis chrysophylla* (Dougl.)A. DC.).

2.2.3. PREVIOUS RESULTS LOOKOUT MOUNTAIN (AFTER 10 YEARS)

The first results from this study site were described by Seidel (1985), covering two 5-yr growth periods comprising the first ten years of the study (first period 1974-1979 and second period 1979-1984). It was found that the most rapid rate of height growth was in pure pine plots in the second growth period at the 12-ft (3.7m) and 18-ft (5.5m) spacings, and the slowest rate was found in pure grand fir plots in the first period. Significant differences in height were found in response to initial spacing, species composition and growth periods. Growth of fir was considerably less than the pine during the second period because of freezing and animal damage.

Growth differences were greater between species composition than between spacings. Height growth at 6-foot spacing was less than at the 12 or 18-foot spacing but no significant differences were found between the 12 and 18-foot spacing.

Diameter growth was not measured these first two periods because none of the fir seedlings had reached a DBH of 0.6 inch and only 10% of the pine seedlings had reached that size.

During the first period, basal area and total cubic colume growth was very small because most of the trees were less than 4.5 feet tall, but during the second period growth increased considerably (especially for pine), more trees reached grew past breast height (4.5 ft) to have a measurable DBH.

Spacing and species composition were significantly different ($p<0.01$), for both basal area and volume growth during the second period. Growth was greater at the 6-foot spacing but there were no significant differences between the 12 and 18.foot spacing. The three species combinations were significantly different; the greatest growth was in pure pine, intermediate in mixed plots and least growth in pure fir.

The results were the typical of those found during the first years of plantation development, with greater diameter growth in wider spacings and greater plot volume growth at closer spacings. Because of the more rapid growth of pine a stratified structure was appearing in the plots.

2.2.4. OTHER RESULTS IN LOOKOUT MOUNTAIN

After Seidel (1985) reported growth responses at the Lookout Mountain mixed-species spacing trials, Garber (2002) continued measurement of a number of different responses, including vertical foliage distribution (Garber & Maguire, 2005a), stem taper differences of the two species (Garber & Maguire, 2003), and stand-level productivity (Garber & Maguire, 2004).

3. OBJECTIVES

The main objective of this study was to test the effects of spacing, species composition, and the interactdion of spacing and species composition on the biomass productivity of the plots. To meet the objective total biomass of the following above-ground tree components had to be estimated: foliage, branchwood, bolewood, and bole bark. Therefore, various branch-level and tree-level biomass equations had to be developed.

4. METHODS

4.1. STUDY SITE

The Lookout Mountain study site is located on the northeast-facing slope of Lookout Mountain at an elevation of 1550m (Figure 4.1). The geographic coordinates are 43º 49’N, 121º 41W. The slope averages 20%.

Figure 4.1. Location of the *Pinus ponderosa*/*Abies grandis* mixed species spacing trial within the Lookout Mountain Unit of Pringle Falls Experimental Forest, Oregon, USA. (Resource: Google Maps).

Figure 4.2. Aerial photograph of the Lookout Mountain *Pinus ponderosa/Abies grandis* mixed species spacing trial and the surrounding forest structure.

Summers are hot and dry with a range in average annual temperature between 21º and 32º and average annual precipitation of about 100cm, most of which falls as snow between the months of September and May. Frost can occur any time of the year.

Soils are deep, weel-drained Typic Cryorthents, developed from dacite pumice originating from the eruption of Mount Mazama, overlaying a sandy loam paleosol developed in older volcanic ash with cinders and basalt fragments (Seidel,1985; Garber & Maguire, 2005).

4.2. EXPERIMENTAL DESIGN

The spacing trial was established on a 8.1-ha unit that was clearcut in 1974.The plantation was established in the spring of 1974 by planting 2-0 bare root ponderosa pine and 2-yr-old containized grand fir (Fig. 4.2). The study was designed as a split-plot experiment with spacing as the whole-plot factor and species composition as the split-plot factor. The three spacings included 1.8, 3.7 and 5.5m (6-ft, 12-ft, and 18-ft), and the three species compositions were pure *Pinus ponderosa*, pure *Abies grandis*, and a 1:1 mix of both species planted as every other tree within and between rows (Figure 4.3). Each treatment combination was replicated three times, with plots sizes for the 1.8, 3.7 and 5.5 m spacings of 0.0086, 0.096 and 0.193-0.217ha respectively (Seidel 1985).

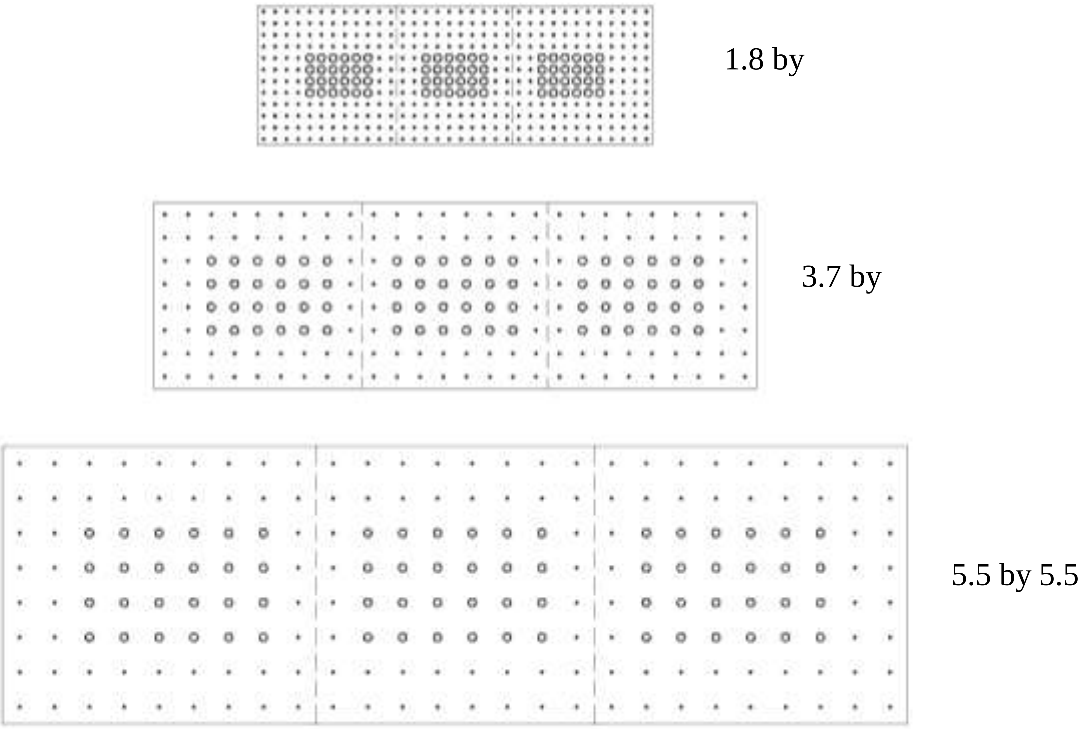

Figure 4.3 Experimental design for *Pinus ponderosa*/*Pinus contorta* mixed species spacing trials (fromSeidel (1985)).

4.3. FIELD AND LAB WORK

Total height of all trees was first measured in the spring of 1975, and remeasured in the fall of 1979 and 1984. In addition, DBH on any trees with DBH≥1.5 cm was measured to the nearest 0.2 cm. All trees were measured for both DBH and total height (nearest 0.01 m) in the spring of 1990 and 1995, and all trees were measured for DBH, total height, and height to crown base (HLB, height to lowest live branch; nearest 0.01 m) in the fall of 1999.

In 2001, some trees inside the study plots were climbed and all branches were measured up to the height where the stem became approximately 10 cm in diameter (Garber and Maguire 2005). In addition to tree DBH, HT, and HLB, the basal diameter (nearest 1mm) and height of attachment (nearest 0.01m) of each live branch were recorded. The last measurements included in this analysis were taken in 2004 when the total plantation age was 30 years.

Also in 2001 a total of 48 trees outside but adjacent to the experimental plots were selected for destructive sampling (Garber and Maguire 2005). The following variables were recorded: DBH, diameter outside bark at breast height (1.37m); HT, total height; HLB, height to the lowest living branch; and height and basal diameter of all live branches. Two live whorl branches were randomly sampled for biomass estimation from each crown third of each felled tree of both species, and in *Abies grandis* an interwhorl branch was also randomly sampled from each crown third.

The sample branches were removed from the felled trees, oven-dried, separated into foliage and wood+bark, and then weighed (Garber and Maguire 2005).

The dbh range was slightly more narrow for *A. grandis* than for *P. ponderosa*, ranging from 2.5 to 26.8 cm versus 5.0 to 41.7 cm, respectively (Table 1). In contrast, the range in total height was quite similar for both species, ranging from 2.2 to 15.7 m for *A. grandis* and from 3.3 to 15.6 for *P. ponderosa*. Average branch diameter was almost three times greater in *P. ponderosa* compared to *A. grandis*, i.e., 26 versus 9 mm (Table 1).

Table 1. Means and ranges for attributes of individual branches and trees sampled in 2001 at the Lookout Mountain *Pinus ponderosa-Abies grandis* mixed-species spacing trial.

	Variable	Units	Mean	SD	Minimun	Maximun
Abies grandis	**Branches**					
	BD	mm	9.188	5.8291	1	32
	BH	mm	4.26	2.8955	0.24	12.52
	BLM	g	49.211	86.8284	0.05	727.131
	BWM	g	36.001	66.7483	0.22	513.31
	Trees					
	DBH	cm	15.71	6.6587	2.5	26.8
	HT	m	9.846	3.3253	2.16	15.68
	CL	m	9.35	3.3928	1.79	14.95
	CFM	Kg	16.64	12.9996	0.56	44.92
	CWM	Kg	9.0375	11.5494	0.2815	40.0931
Pinus ponderosa	**Branches**					
	BD	mm	26.08	14.4087	3	61
	BH	mm	6.031	2.6472	1.67	13.16
	BLM	g	205.3947	262.7308	0.8503	1165.5852
	BWM	g	437.88	689.1766	0.36	3831.88
	Trees					
	DBH	cm	23.69	8.0795	5	41.7
	HT	m	3.26	2.3381	3.26	15.6
	CL	m	8.046	2.3082	2.02	13.07
	CFM	Kg	16.431	13.1746	0.4274	43.686
	CWM	Kg	33.8158	30.6696	0.4804	106.4451

4.4. BIOMASS ESTIMATION

To estimate total aboveground biomass at the time of each remeasurement, the following procedure had to be followed for each species:

- Fit branch-level foliage and branchwood mass equations as a function of branch diameter, relative height in the crown, and/or relative height on the tree.
- Estimate total sample-tree foliage and branchwood mass by applying branch-level equations to all measured branches on the felled and climbed sample trees
- Estimate stem wood volume at the tree level by numerically integrating diameter-inside-bark taper equations developed by Garber and Maguire (2003).
- Convert from stem wood volume to stem wood mass by apply average wood.
- Estimate individual-tree allometric relationships between the following biomass components and tree dbh, total height, and/or crown length:
    - Stem wood

  - Branchwood (wood + bark)
  - Foliage
- Estimate biomass per hectare for each biomass component (foliage, branchwood, and stem wood) by applying tree-level allometric equations to the tree list and expanding to a per-ha basis by mulitiplying by the reciprocal of plot size.
- Estimate total biomass per per hectare by adding all above-ground biomass components.

4.5. STATISTICAL ANALYSIS

The biomass response variables were initially tested by traditional analysis of variance, recognizing the split-plot design of the experiment with initial spacing forming the whole-plot factor and species composition forming the split-plot factor. The latter includes three levels: pure *P. ponderosa*, pure *A. grandis*, and a 1:1 mix of these same species (planted as every other tree within and between rows). Measurement date was analyzed as a second split-plot factor in a split-split plot analysis of variance, or as a repeated measures split-plot design.

The null hypotheses were:

1. Cumulative productivity of the following stand-level biomass components did not differ significantly by spacing, species composition, or their interaction
   a. Stem wood
   b. Branchwood
   c. Foliage
   d. Total above-ground biomass

2. The relative allocation of biomass productivity among above-ground components over time does not differ significantly by spacing, species composition, or their interaction.

4.6. BRANCH LEAF MASS AND BRANCH WOODY MASS EQUATIONS

Alternative branch-level foliage mass models were fitted by nonlinear regression in R (R Core Team 2013) to the branch-level foliage mass data (Table 1) to estimate foliage and branchwood mass on individual branches of *Abies grandis* and *Pinus ponderosa*. Models errors were assumed to be additive, random, and normally distributed. All models were weighted by BD^{-m}, where $m \geq 0$. Final models were chosen on the basis of residual analysis and Furnival's Index of fit (Furnival, 1961).

4.7. TOTAL FOLIAGE AND BRANCH WOODY MASS

The branch-level equations were applied to all live branches measured on each felled and standing sample tree to estimate crown foliage mass, CFM (Kg). Different nonlinear models for estimating tree-level biomass were then fitted with weights equal to the reciprocal of Y^{-m}, where Y was the predicted value and $m \geq 0$. As in the case of branch level equations final models were chosen on the basis of residual analysis and Furnival's Index of fit (Furnival, 1961).

Total height was the only dimension measured on the trees during the first several measurements, so alternative models were developed for estimating tree-level biomass based on only total height at the start of the experiment and for the first two remeasurements.

4.8. TOTAL FOLIAGE AND BRANCHWOOD MASS PER PLOT AND PER HECTARE

The –tree-level equations for foliage and branchwood mass were applied to all the trees in each plot to estimate total foliage and branchwood mass per plot. Plot-level estimates were multiplied by the reciprocal of the corresponding plot size (ha) to expand the estimated to total mass per ha to facilitate comparison to other studies of forest productivity.

4.9.TOTAL STEM VOLUME AND STEM MASS

The diameter inside bark (dib) was calculated by numerical integration of the following taper equations ([1] and [2]) presented by Garber & Maguire (2003):
Abies grandis

[1] $dib = \alpha_{11} DBH^{\alpha_{12}} X^{\alpha_{13} \operatorname{asin}(Q) + \alpha_{14} Q^2 + \alpha_{15} \ln(X) + \alpha_{16} X^2 + \alpha_{17} \operatorname{asin}(Z) + \alpha_{18} \exp\left({}^{DBH}/_{HT}\right)} + \varepsilon_1$

Pinus ponderosa

[2] $dib = \alpha_{21} DBH^{\alpha_{12}} X^{\alpha_{13} \mathrm{Z}^2 + \alpha_{14} \ln(X) + \alpha_{15} \mathrm{Z}^{-0.5} + \alpha_{16} \cos(Z) + \alpha_{17} \mathrm{DBH}^{\mathrm{X}} + \alpha_{18} \mathrm{Z} \cdot \exp\left({}^{-DBH}/_{HT}\right)} + \varepsilon_2$

where DBH was tree diameter at breast height (cm), HT was total tree height (m), Z was relative height on the tree (h/HT, where $0 \leq h \leq HT$), Q was $1-\sqrt{Z}$, p was 1.37/HT, and X was $(Q/(1-\sqrt{p}))$.

Each tree was divided into 100 height sections, dib at the bottom and the top of each section was estimated by the taper equation, and the volume (V) of each section was computeed as:

[3] $V = \left(\frac{A1+A2}{2}\right) \cdot L$

where; L is length of the section (m), A1 is the cross-sectional area at the bottom of the segment (m^2), and A2 is the cross-sectional area at the top of the segment (m^2). The total stem volume of the tree was the sum of all segment volumes.

Total tree stem was converted into biomass by applying average wood density value obtained from the literature. Wood density was assumed to be 380kg/m^3 for *Pinus ponderos*a and 350kg/m^3 for *Abies grandis* (Miles & Smith, 2009).

4.10. TOTAL BIOMASS PER HECTARE

After calculating the total foliage mass per hectare, total branch-wood mass per hectare total stem bark per hectare, and total stem wood per hectare, total live above-ground biomass was calculated as the sum of foliage + branch-wood+ stem wood.

5. RESULTS

5.1. BRANCH LEAF MASS

The models chosen to estimate the branch leaf mass were:

Abies grandis:

[4] $BLM=10.72349\ (BD)^{2.20606}\ (RELDINC^{2.16875})\ \exp(-4.12983(RELDINC))+\varepsilon_1$

Pinus ponderosa:

[5] $BLM=1.40101\ (BD)^{2.28308}\ (RELDINC^{1.04337})\ \exp(-3.60867(RELDINC))+\varepsilon_2$

where BLM was estimated branch foliage mass (kg), BD was branch diameter (mm) and RELDINC was relative depth into crown (proportion). Both models were weighted by $BD^{-3.8}$ to correct for heteroskedasticity. All parameter estimates were significantly different from 0 and 1 at $\alpha=0.05$. As would be expected, foliage mass for a given branch increased with branch diameter and up to about 53% of relative depth into crown for *Abies grandis* and up to about 29% of relative depth into crown for *Pinus ponderosa*; below these relative distances from the tree tip the foliage mass on a branch of given diameter started to decrease with increasing depth into crown (Fig. 5.1).

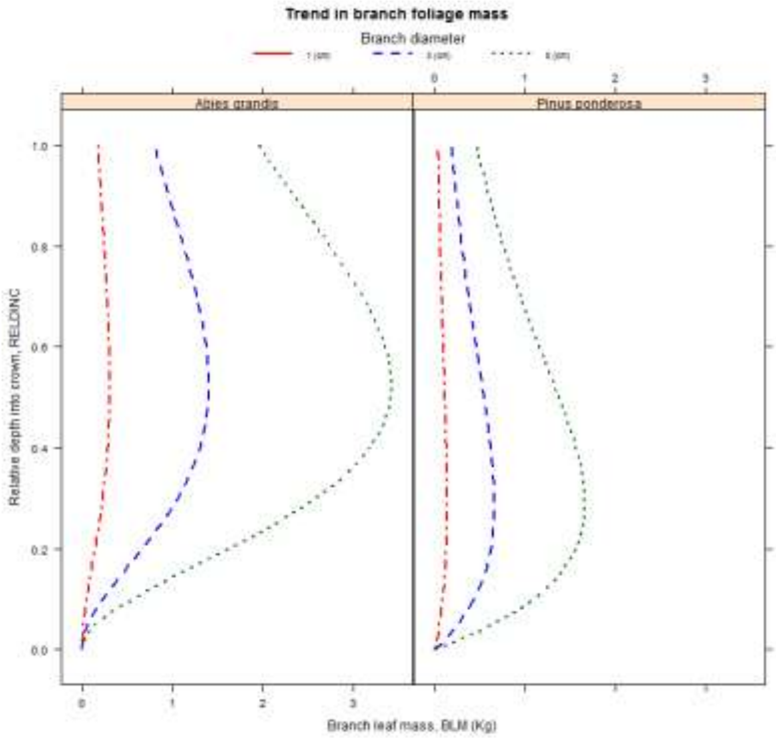

Figure 5.1. Trend in branch foliage mass (BLM) by relative depth into crown (RDINC) and branch diameter (BD) for: (a) *Abies grandis*; and (b) *Pinus ponderosa* (estimates from equations [4] and [5]).

5.2. BRANCH WOODY MASS

The best equations for estimating the branch woody mass (wood + bark) were:

Abies grandis

[6] $BWM= 0.073398 (BD^{2.624537}) (RELDINC^{0.456194})$

Pinus ponderosa

[7] $BWM= 0.031659 (BD^{2.769183}) (RELDINC^{0.296713})$

where BWM was estimated branch woody mass (kg) and BD and RELDINC were as defined above. All parameter estimates were significantly different from 0 and 1 at $\alpha=0.05$. The model for *Abies grandis* was weighted by BD^{-4} and the model for *Pinus ponderosa* by BD^{-6} to correct for heteroscedasticity.

As would be expected, woody mass for a given branch increased with branch diameter (Figure 5.2).

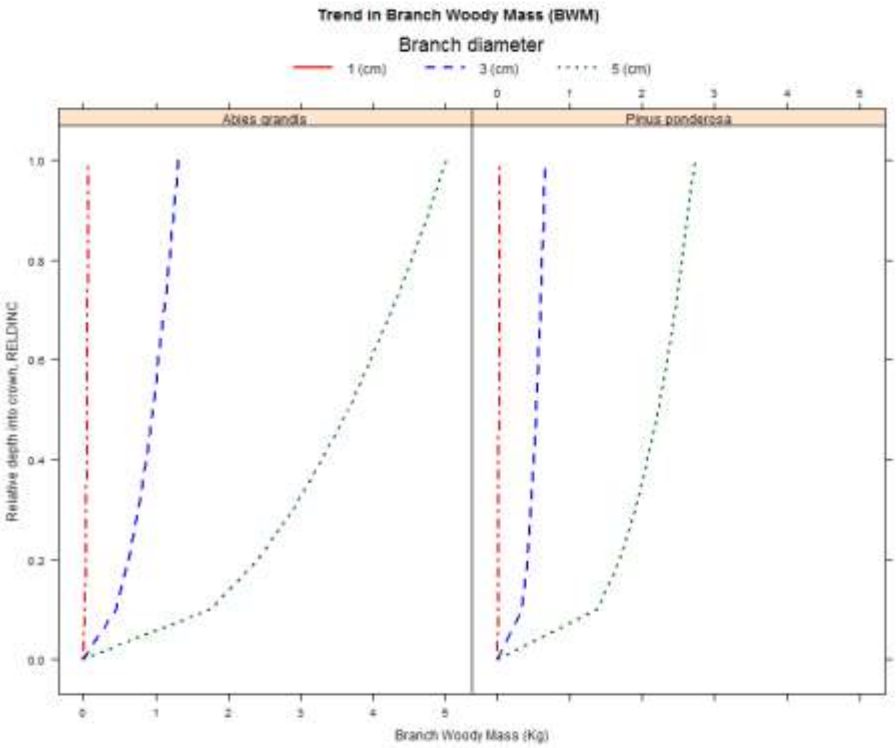

Figure 5.2. Trend in branch woody mass (BWM) by relative depth into crown (RELDINC) and branch diameter (BD) for: (a) *Abies grandis*; and (b) *Pinus ponderosa* (estimates from equations [6] and [7]).

5.3.TOTAL LEAF MASS

Equations [4] and [5] were applied to all live branches measured on each climbed and felled tree to estimate the total crown foliage mass, CFM (Kg). Because the top branches on the climbed trees could not be reached safely, models were fitted to the data for the combined felled and standing samples trees (Table 4.1), separately for each species. The final models were:

Abies grandis

[8] $TFM=0.0791\ DBH^{2.47633}\ HT^{-0.9275}\ (CL^{0.25387\ (mcl/cl)})$

Pinus ponderosa

[9] $TFM=0.003453\ DBH^{2.260311}\ (CL^{0.605171\ (mcl/cl)})$

where TFM was estimated total tree foliage mass (kg), CL was live crown length (m), MCL was crown length over which live branches were measured (m), and all other variables are defined above. Both equations were weighted by the reciprocal of the predicted value raised to the 1.5 power to correct for heteroskedasticity. . All parameter estimates were significantly different from 0 and 1 at α=0.05.This model form allowed both felled and standing trees to contribute to estimates of the final equation for estimating total foliage mass on trees (TFM, kg), which would then be derived simply by setting MCL/CL equal to one.

As expected, total tree foliage mass increased with both DBH and CL (Fig. 5.3).

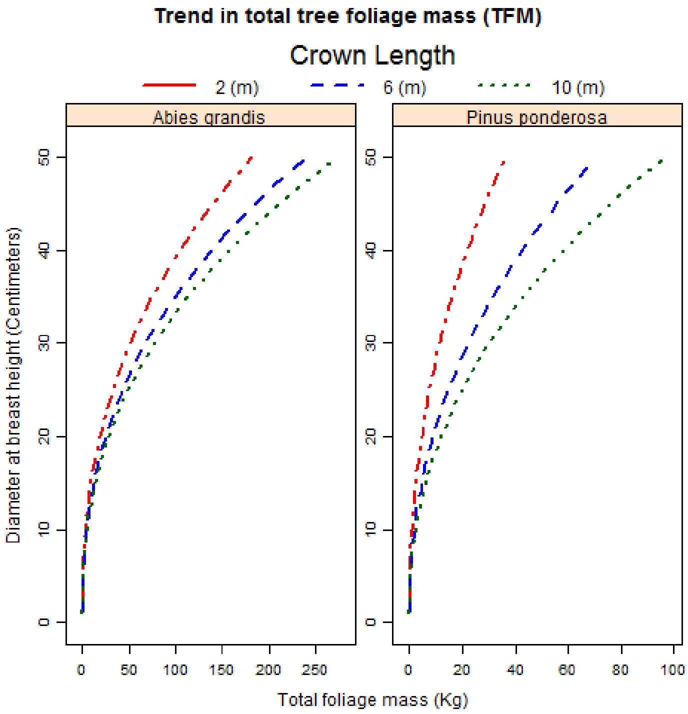

Figure 5.3 Trend in total tree foliage mass (TFM) by DBH and crown length (CL) for: (a) *Abies grandis*; and (b) *Pinus ponderosa* (estimates from equations [8] and [9]).

Because trees were measured for only height when the plantation was very young, the following set of equations was developed to estimate foliage biomass from only tree height:

Abies grandis

[10] $TFM=0.08601\ HT^{2.23904}$

Pinus ponderosa

[11] $TFM=0.011358\ HT^{2.950587}$

In equation [11], the first parameter estimate, 0.011358, was not significantly different from zero, but the parameter on HT, 2.950587, was significant. This model was applied for only the first two years of measurement (1975 and 1979).

After the trees grew to a height greater than 1.3 m, DBH was also measured (nearest 0.02mm, but height to crown based was not measured because the large majority of trees had not yet experienced any crown recession. The following models were developed to estimate total tree foliage biomass on those trees measured for DBH and HT:

Abies grandis

[12] $TFM=0.08451\ DBH^{2.56894}\ HT^{-0.85539}$

Pinus ponderosa

[13] $TFM=0.008135\ DBH^{2.996661}\ HT^{-0.8633415}$

5.4. TOTAL WOODY MASS

The same process applied to estimate total tree foliage mass was used to estimate total tree branchwood mass. Equations [6] and [7] were applied to all the live branches of each climbed and felled tree, and these estimates were summed for total crown branchwood mass, CWM (Kg). The following models were then developed to estimate total tree branchwood mass:

Abies grandis

[14] $TWM=0.0300823\ DBH^{2.88033}\ HT^{-1.180678}\ (CL^{0.305888\ (mcl/cl)})$

Pinus ponderosa

[15] $TWM= 0.0015457\ DBH^{2.8491391}\ (CL^{0.3707963\ (mcl/cl)})$

where TWM was total tree branchwood mass (kg) and all other variables are as defined above. Both equations were weighted by the reciprocal of the predicted value raised to the 1.5 power to correct for heteroskedasticity. All parameter estimates were significantly different from 0 and 1 at α=0.05. As expected, total tree foliage mass increased with both DBH and CL (Fig. 5.4), although the effect of crown length was less in *Pinus ponderosa*.

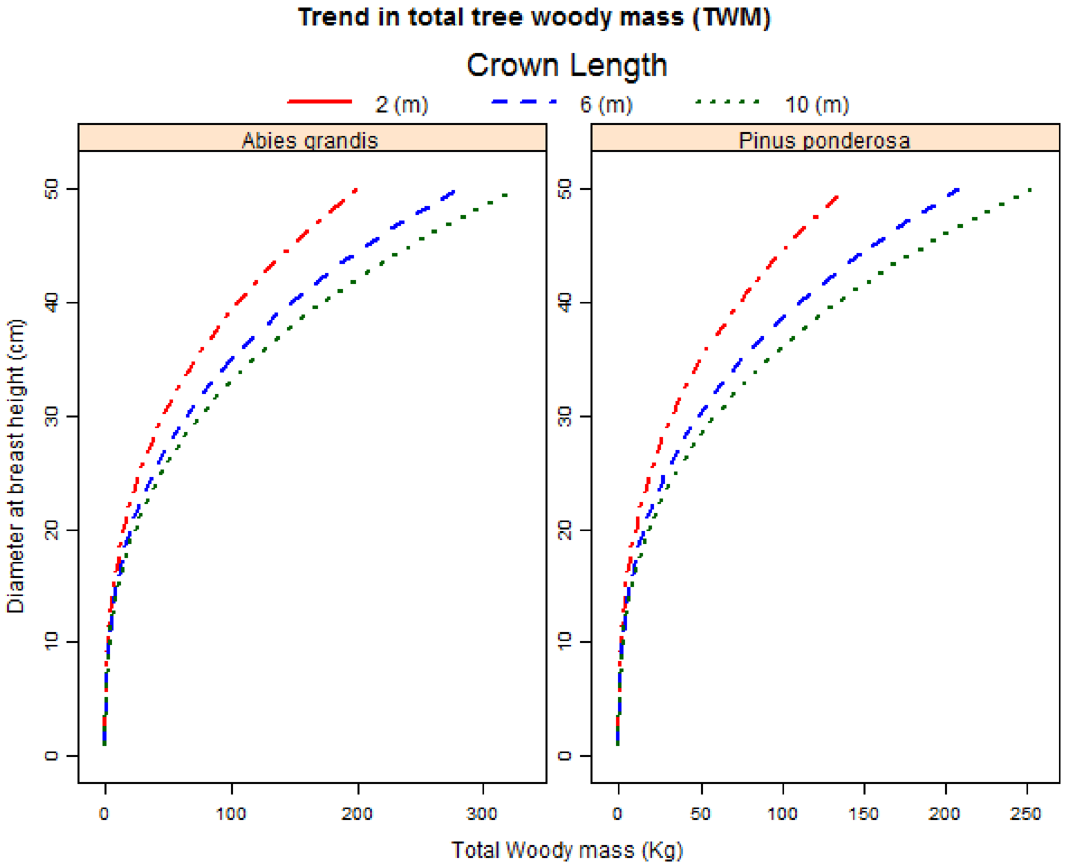

Figure 5.4 Trend in total tree branch-wood mass (TWM) by DBH and crown length (CL) for: (a) *Abies grandis*; and (b) *Pinus ponderosa* (estimates from equations [14] and [15]).

Again because trees were measured for only height when the plantation was very young, the following set of equations was developed to estimate tree branchwood biomass from only tree height:

Abies grandis

[16] $TWM=0.03448\ HT^{2.5133}$

Pinus ponderosa

[17] $TWM=0.003958\ HT^{3.66074}$

In equation [17], the first parameter estimate is not significantly different from zero (see Appendix), but the second parameter estimate was significant. This model was applied only for the first two years of measurement (1975 and 1979).

After the trees grew to a height greater than 1.3 m, DBH was also measured (nearest 0.02mm, but height to crown based was not measured because the large majority of trees had not yet experienced any crown recession. The following models were developed to estimate total tree branchwood biomass on those trees measured for DBH and HT:

Abies grandis

[18] $TWM=0.034672\ DBH^{3.026752}\ HT^{-1.152963}$

Pinus ponderosa

[19] $TWM=0.004772\ DBH^{3.447856}\ HT^{-0.973793}$

where all variables are defined as above.

5.5. TOTAL LEAF MASS PER HECTARE

Equations [8] -[13] were applied to all live trees within each plot to estimate total foliage mass per plot. This plot-level estimate was then expanded to a full hectare by muliplying by the reciprocal of the plot size in ha (Fig.5.5 and Table 5.1)

Table 5.1 Means and ranges for total foliage mass (Kg/ha) by year.

	Total Foliage Kg/ha			
	Mean	**SD**	**Minimun**	**Maximun**
1975	0.84942	1.042178	0.02916	3.63465
1979	45.209	45.49818	4.587	144.175
1984	804.44	668.1176	80.29	2321.28
1990	3483.4	2028.163	742.6	8255
1995	6562	2906.045	2185	11938
1999	11027	4422.024	5391	22339
2004	15213	4517.718	8642	25232
2014	20842	4681.26	14869	29963

Treatment effects of spacing, species composition and their interaction were tested by analysis of variance, ANOVA (Table 5.2).

Table 5.2. Summary from Analyses of Variance (ANOVAs) for testing treatment effects on total foliage mass per hectare.

	p-value		
	Spacing	**Species composition**	**Interaction**
1975	<<0.05	<<0.05	<<0.05
1979	<<0.05	<0.05	0.051
1984	<<0.05	<0.05	0.148
1990	<<0.05	<<0.05	0.065
1995	<<0.05	0.278	0.02
1999	<<0.05	<<0.05	<<0.05
2004	<<0.05	<<0.05	<<0.05
2014	<<0.05	<<0.05	<<0.05

During the early years of plantation development the interaction between spacing and species composition had no significant effect on total foliage mass per ha, but as the plantation aged the interaction became more significant (Table 5.2).

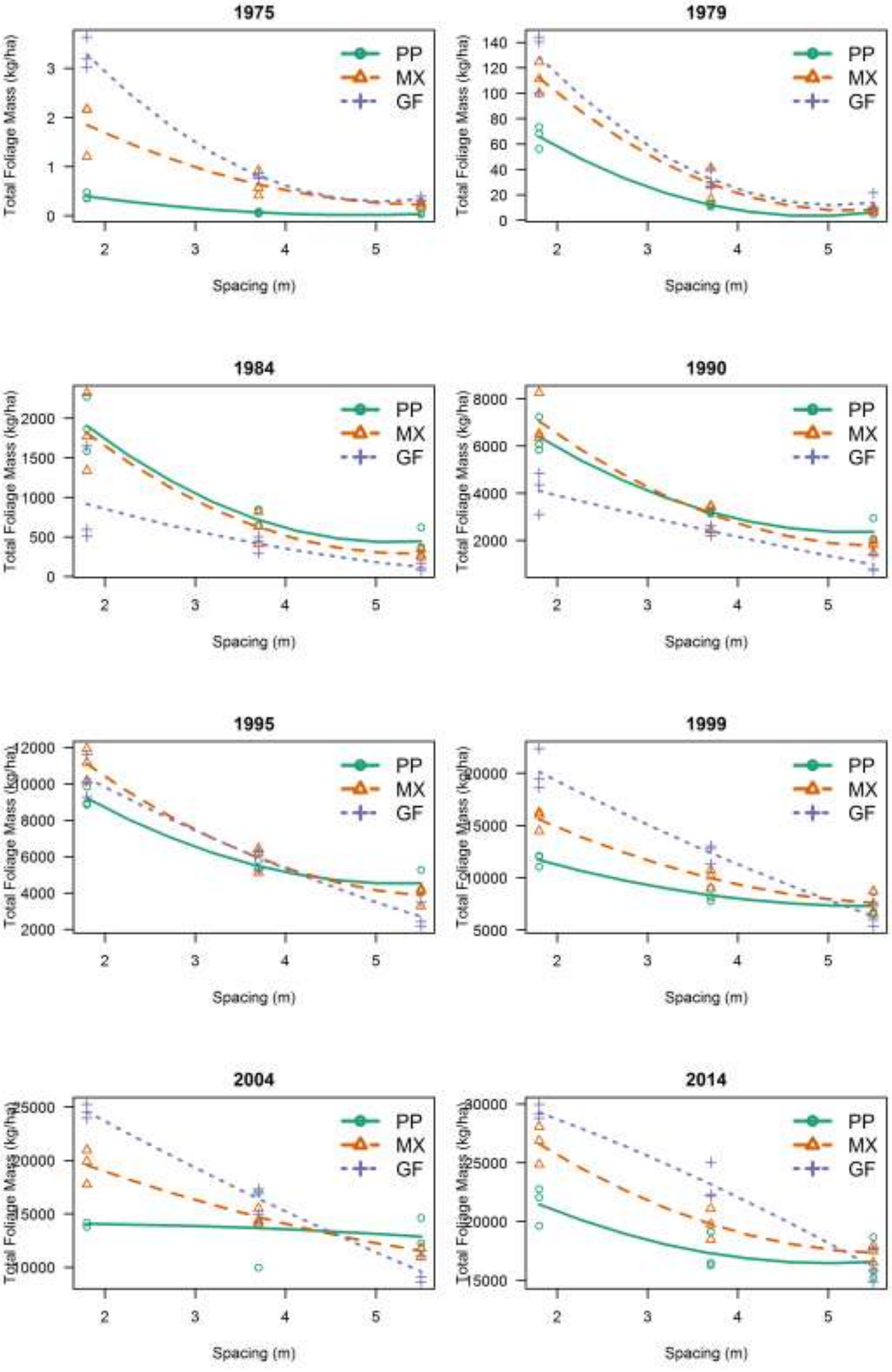

Figure 5.5 Trend in total foliage mass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

5.6. TOTAL WOODY MASS PER HECTARE

The process for estimating foliage mass per ha was repeated for estimating total branchwood mass per ha. Total branchwood mass per plot was estimated by apply equations [14]-[19] to all the trees within each plot, and then plot-level estimates were expanded to branchwood mass per ha by multiplying with the reciprocal of plot size (Table 5.3). An ANOVA was computed to test for treatment effects of spacing, species composition and their interaction (Table 5.4).

Table 5 .3 Means and ranges for Total woody mass per hectare by year.

	Total Woody Kg/ha			
	Mean	**SD**	**Minimun**	**Maximun**
1975	0.196876	0.2531088	0.003594	0.8765
1979	18.146	18.07361	1.887	55.281
1984	840.94	807.3831	37.55	2802.87
1990	4543.2	3200.785	480.9	11981.7
1995	7986	3941.537	1541	16038
1999	13449	4538.73	4305	22654
2004	19229	6053.478	7200	29511
2014	27972	8320.744	13000	41421

Table 5.4 Summary from ANOVAs for testing effects of spacing, species composition and their interaction on total branchwood mass per ha.

	p-value		
	Spacing	**Species composition**	**Interaction**
1975	<<0.05	<<0.05	<<0.05
1979	<<0.05	<0.05	0.13286
1984	<<0.05	<<0.05	<0.05
1990	<<0.05	<<0.05	<0.05
1995	<<0.05	<<0.05	0.05
1999	<<0.05	<<0.05	<0.05
2004	<<0.05	<<0.05	<0.05
2014	<<0.05	<<0.05	0.05

Spacing, species composition and their interaction had a significant effect on total branchwood biomass in all years.

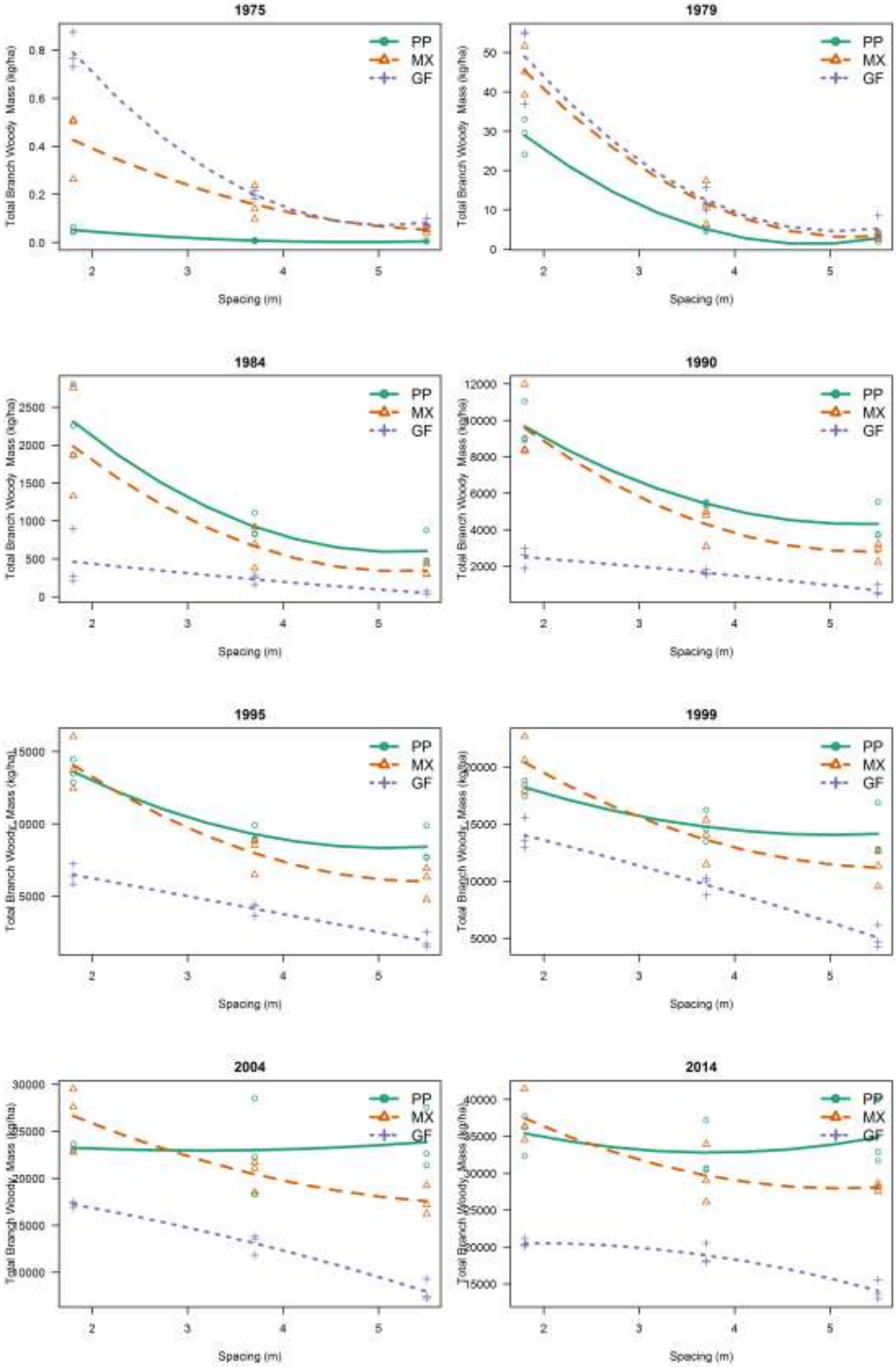

Figure 5.6 Trend in total branchwood mass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

5.7. TOTAL STEM WOOD PER HECTARE

Total stemwood volume was calculated by numerical integration of the taper equations Eq. [1] and [2] for all the trees measured in the plots. To facilitate comparison of wood volume per hectare to biomass, Table 5.5 shows the average volumes in m^3/ha. The first two years of measurement (1975 and 1979) do not have stem wood volume because the trees were very small reaching only a few centimeters in height, total biomass above-ground was composed of almost only foliage and branchwood mass.

Table 5.5 Summary of Total wood volume per hectare by years.

	Volume m3/ha			
	Mean	**SD**	**Minimun**	**Maximun**
1984	4.93102	5.6446	0.06632	18.6572
1990	50.684	40.04386	6.109	140.078
1995	70.3	44.3223	13.31	158.44
1999	97.57	52.40188	26.68	194.98
2004	115.11	56.27594	40.95	217.13
2014	151.73	61.719	72.68	258.18

The total biomass per hectare was calculated from volume by assuming wood densities of 380kg/m^3 for *Pinus ponderos*a and 350kg/m^3 for *Abies grandis*.

Table 5.6 Average and range for total stem mass (Kg/ha) by year.

	Total Stem mass Kg/ha			
	Mean	**SD**	**Minimun**	**Maximun**
1984	1864.32	2147.529	23.21	7089.74
1990	18956	15275.92	2138	53229
1995	26147	16894.11	4657	60208
1999	36100	19882.24	9338	74091
2004	42488	21303.44	14334	82511
2014	55798	23273.89	25438	98108

The trend of the total stemwood mass is shown in Figure 5.7. Treatment effects of spacing, species composition and their interaction were tested by ANOVA (Table 5.7) as in the previous analysis of total foliage mass and total branchwoody. As the plots and trees became older the interaction between spacing and species composition become insignificant.

Table 5.7 ANOVA of the total stem wood mass by years.

	p-value		
	Spacing	**Species composition**	**Interaction**
1984	<<0.05	<<0.05	<<0.05
1990	<<0.05	<<0.05	<<0.05
1995	<<0.05	<<0.05	<0.05
1999	<<0.05	<<0.05	0.1
2004	<<0.05	<<0.05	0.116
2014	<<0.05	<0.05	0.193

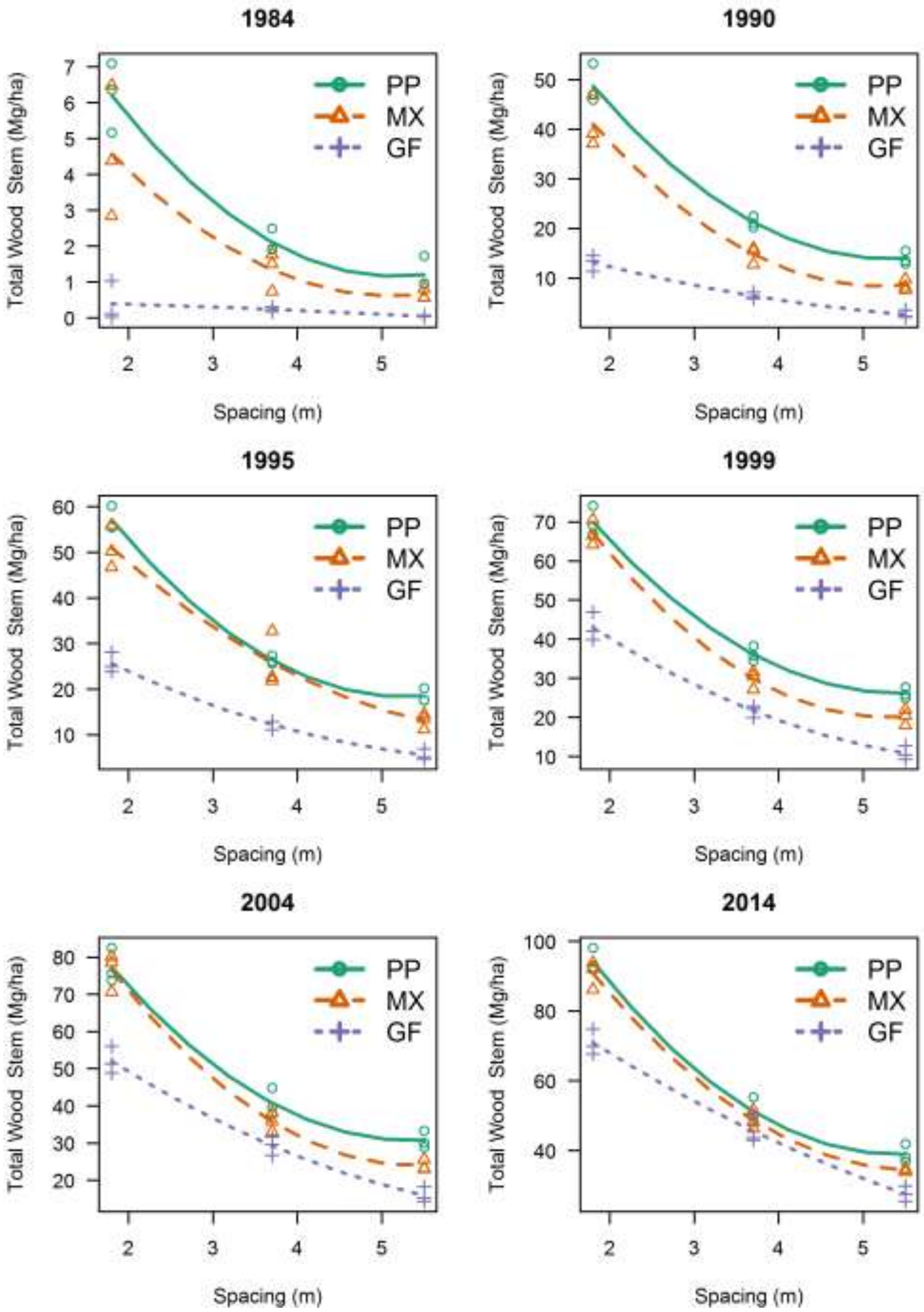

Figure 5.7 Trend in total stem-wood mass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

5.8. TOTAL BIOMASS PER HECTARE

Total biomass per hectare has been calculated as the sum of: total foliage mass per hectare, total branch-wood mass per hectare and the total stem wood per hectare, except in 1979 and 1984 where the total biomass per hectare is the sum of total foliage mass per hectare and total branch-wood per hectare. A summary of the results is shown in Figure 5.8.

Table 5.8 Average and range for total biomass (Kg/ha in the first three years, Mg/ha the rest of years) by year.

	Total Biomass				
	Mean	**SD**	**Minimun**	**Maximun**	
1975	1.0463	1.2949	0.03275	4.5111	Kg/ha
1979	63.355	63.5369	6.474	199.456	
1984	3.5097	3.5757	0.1502	12.1627	Mg/ha
1990	26.983	20.2857	3.462	71.516	
1995	40.695	22.9406	8.383	84.532	
1999	60.58	26.7681	19.03	109.14	
2004	76.93	28.3749	30.18	129.56	
2014	104.61	31.4694	53.31	163.33	

An ANOVA (Table 5.9) was performed to compare the differences between spacing, species composition and their interaction.

Table 5.9 ANOVA of the total biomass by years.

	p-value		
	Spacing	**Species composition**	**Interaction**
1975	<<0.05	<<0.05	<<0.05
1979	<<0.05	<0.05	0.06
1984	<<0.05	<<0.05	<<0.05
1990	<<0.05	<<0.05	<<0.05
1995	<<0.05	<<0.05	<0.05
1999	<<0.05	<<0.05	0.43
2004	<<0.05	<<0.05	0.11
2014	<<0.05	<<0.05	0.43

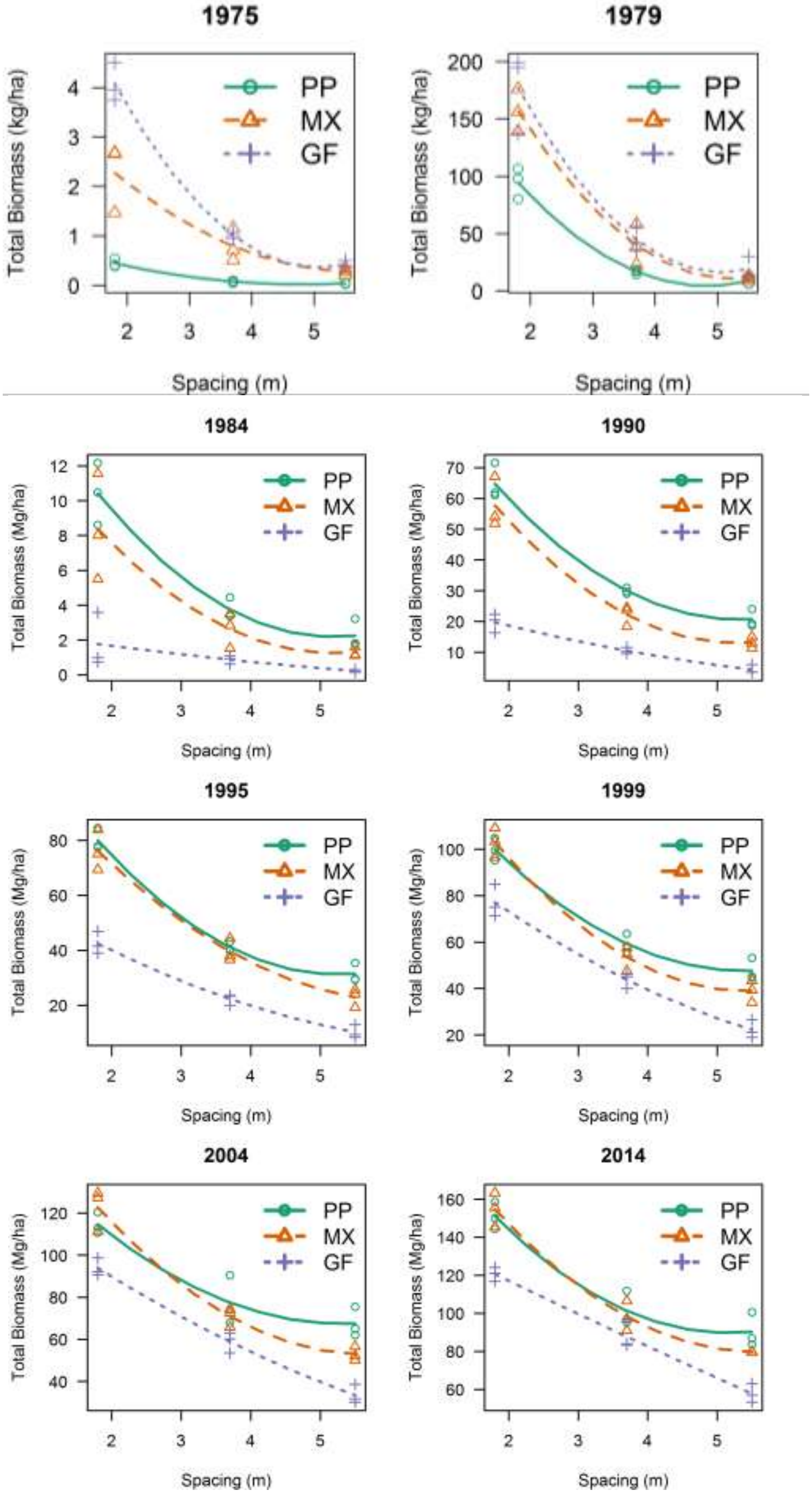

Figure 5.8 Trend in total biomass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

6. DISCUSSION

Increasing stand productivity has traditionally be a primary goal of silviculture. The relative productivity of pure versus mixed species stands had long been debated in forestry, with some studies allegedly demonstrating that mixed stands can have more productivity if the best combination of species is selected. Mixed forests are often presumed to be more efficient and more productive based largely on the idea of optimal use of site resources and the prevalence of niche separation with respect to resource use. Some experiments have shown that mixed stands have greater yields than monocultures of both the shade intolerant species and the shade tolerant species (Kelty,1992), but this is not the most common situation.

Mixed species stands have many advantages over single species stands, regardless of their relative productivity. Where the objective is to grow mixed species stands, it is important to understand the relative morphology and growth rates of the target species to ensure successful establishment and maintenance of both species and, ultimately, the desired stand structure. Species with complementary characteristics are usually a good option for many stand management objective; for example, species with different degrees of shade tolerance, like *Abies grandis* (shade tolerant) and *Pinus ponderosa* (shade intolerant) in the Lookout Mountain mixed species spacing trials. These two species use the resources slightly differently and at different rates at different stages of stand development. Ponderosa pine, like many shade intolerant species, grows rapidly in height, allocates more growth to stem and branches, and has crowns with lower leaf area density; in contrast, grand fir, like many shade tolerant species, forms a lower stratum with greater leaf area density (Kelty, 2006). However, degree of stratification has been shown to be dependent on spacing, decreasing with increasing spacing (Garber & Maguire, 2005a).

6.1.FOLIAGE MASS

Different studies have shown that branch leaf area depends on branch diameter and its position within the crown (Garber & Maguire, 2005a; Weiskittel & Maguire, 2006). If a branch of the same diameter is in a lower position near the base of the crown, foliage mass decreases. Lookout Mountain species differ in their shade tolerance; therefore the peaks of maximum branch foliage mass within the crown are different. Figure 5.1 shows that *Abies grandi*s branch foliage mass peaks near the middle of the crown (50% of depth into the crown), but in the case of *Pinus ponderosa*, branch foliage mass peaks closer to the top of the tree (30% of depth into the crown). For a given branch diameter branch foliage mass decreases as depth into the crown increases.

In species in a dominant position, the foliage in the upper crown is influenced by many environmental factors like temperature and vapor pressure deficit, while foliage in lower crown positions is influenced more by the light intensity (Garber & Maguire, 2005a). *Pinus ponderosa* is less shade tolerant and, in narrower spacing, grows faster in height. Maximum branch foliage mass therefore may be located closer to the top of the tree, because faster height growth favors faster self pruning and the branches at crown base die due to the lack of light. As a result, less foliage survives in the lower branches, and more of the foliage is concentrated close to the top.

In the other hand, *Abies grandis* is more shade tolerant with apical dominance decreasing with increasing shade. Therefore, it needs less light to survive and maintains significantly longer crowns (Garber & Maguire, 2003). The shade tolerance of A. grandis foliage allow foliage to live longer than in *P.ponderosa*, so more foliage mass is located around the middle of the crown.

Trees cannot always be cut in long-term silvicultural experiments to measure all the variables necessary for the estimation of foliage. It is therefore necessary to create equations that depend on allometric relationships among variables that are relatively easy to measure nondestructively in the field. With the equations that have been developed in this study, it is possible to estimate the total tree foliage mass from variables such as DBH, CL, and HT. The trend in total foliage biomass for three crown lengths (2m, 6m and 10m) as implied by the equations conform to biological expectations (Fig. 5.3). In both species total foliage mass increases with the DBH, but in the case of *Abies grandis* the total foliage mass does not differ as much within the different crown lengths, while in *Pinus ponderosa* the differences between crown lengths are greater.

An ANOVA has been calculated to estimate if there are differences between spacing, species composition and their interaction. In the first few years after the plantation was established, the three factors included in the ANOVA were significant ($P<0.05$), so there are strong treatment effects of spacing, species composition, and their interaction. Until 1990 the interaction between spacing and species composition was not significant ($P>0.05$). Surprisingly, in 1995 species composition and the interaction effect are not statistically significant, suggesting that whether the plots are pure or mixed there are no differences and the total foliage mass was similar. No data are available to know what happened in that year, for example with respect to the weather or the season of measurement. However in the last 15 years (the plots are currently 40 years old), the trees are mature, and the treatment effects of spacing, species composition and their interaction are stronger (Table 5.2).

Figure 5.5 shows the development of total foliage per hectare over time. In all years, total foliage mass in the mixed plots is between the pure plots; however, in the first ten years of the field trial, pure *Abies grandis* plots have more foliage in all the spacings than pure plots of *Pinus ponderosa*. Conversely, in the next decade of the field trial, *P.ponderosa* foliage mass was greater than that of *A. grandis*, primarily because in the first years of plantation development the height growth of *P.ponderosa* was two times the height growth of *A.grandis* (Seidel,1985). Slower growth of *A. grandis* is attributable in part topoor resistance to frost and animal damages. At the subsequent years of measurement, until 2014, the total foliage mass per hectare in pure plots of fir was greater than that in pine pure plots, primarily because fir maintains a lower stratum, with longer crowns, more branches, and in consequence greater foliage mass. In all the plots (pure or mixed), the total foliage mass decreases as spacing increases.

Spacing affects total foliage mass, but also interacts with social position and shade tolerance. With more spacing, there is more light and less competition for the resources.

6.2.BRANCH WOODY MASS

Branches support foliage necessary for photosynthesis, and are related to production efficiency. Larger trees with larger crowns normally produce thicker and longer branches.

Branch foliage mass is less in the lower branches of the crown or almost inexistent, but older branches with greater diameters are near to the crown base (Garber & Maguire, 2005b); hence, branch woody mass in the lower part of the crown is greater than in the top of the crown. Branch wood mass is dependent on the same variables as the branch foliage mass, that is, branch diameter (BD) and relative depth into the crown (RELDINC). As we expected branch woody mass increases with both branch diameter and depth into the crown (Fig. 5.2), with lower branches having more mass and greater diameter.

From tree tip to about a 10% of the depth into crown, branch woody mass increases slowly, but from that height to the crown base the mass increases exponentially (Fig. 5.2). In the case of *Abies grandis,* branch woody mass increases rapidly with branch diameter and reaches higher values than in *Pinus ponderosa*.

As is the case forfoliage mass, it is generally not possible to destructively sample branches for woody mass in long-term silvicultural field trials, so it is necessary to fit different models that allow estimation of the total foliage mass or total branch woody mass from variables that are easy to measure in the field, most usually DBH, CL and HT.

In the case of *Abies grandis* total branch-wood mass is slightly greater than in *P.ponderosa*, but in both cases branch wood mass increases with tree size. Until tree DBH reaches approximately 20cm branch-wood mass is very small, but from that size it starts to increase rapidly.

Another ANOVA was performed to test for treatment effects of spacing, species composition, and their interaction. Plantation age was significant ($P<0.05$), indicating that the treatment effects changed over time. Except for 1979,1995 and 2014, all treatment effects are significant ($P<0.05$), except for the interaction between spacing and species composition. The response of branch-wood mass to spacing and species composition was more significant than to the interaction of these two factors (Table 5.4).

Figure 5.6 shows the development of branch-wood mass by spacing, species composition, and their interaction. As in total foliage mass, total branch woody mass of mixed plots was between the amount in the two pure plots. In the first five years of the plantation, fir had more branch wood mass, probably due to the greater number of branches than pines, but as the trees grew pines rapidly developed more branch wood mass. Since plantation reached 20 years old, mixed plots have more branch woody mass than pure plots in narrower spacing, but as the spacing increased pure ponderosa pine (shade intolerant) plots had more branch-wood mass.

Garber & Maguire (2005b) found that there was dramatically less response in branch size for *A.grandis* at spacings greater than 3.7m. The same situation was found in this study, with total branch wood mass for grand fir reaching small values as spacing increases, while ponderosa pine branch-wood decreases with increasing spacing, reaching a low (about a spacing of 4m) that starts increasing again. In 2004 and 2014, *Pinus ponderosa* had greater branch-woody mass in wider spacing than in narrower spacing. Branch wood continued increasing, because ponderosa pine is not shade tolerant and in wider spacing received more light that allowed fuller development of the crown. *Abies grandis* is a shade tolerant species, so in wider spacing with more light its development is less, the crown is minor and in consequence the branch wood mass is minor.

In both cases (total foliage mass and total branch wood mass), the hypothesis that mixed stands are more productive than pure stands does not seem supported by the trends in foliage and branch wood mass; rather , mixed plots contain quantities of biomass that are between pure plots. Combining species with complementary characteristics (Kelty, 2006) promotes production of biomass, branches or foliage between production of pure plots of the same species.

6.3.STEM WOOD BIOMASS

Several studies in northern Europe suggest that stem wood production in mixtures can exceed production of pure stands of the least shade-tolerant component (Assman 1970). However, this is not the case at the Lookout Mountain mixed species spacing trials up to age 40 years, because the less shade tolerant is *Pinus ponderosa* and it is the most productive species, the mixed stands have less stem wood mass than the pure pine stands. This result emphasizes the risk of general statements and the importance of considering the growth patterns of the species (e.g., juvenile vs. mature growth), the relative shade tolerance, relative morphology and associated growing space, and many other factors.

Total stem wood volume inside bark has been calculated with the taper equations that Garber & Maguire(2003) fitted in the same plots of this study. Applying densities of 380kg/m^3 for *Pinus ponderosa* and 350kg/m^3 for *Abies grandis* (Wilson, Funck, & Avery, 1987), total stem wood mass inside bark has been estimated.

Treatment effects of spacing, species composition, and their interaction were tested by ANOVA. Results indicated that as the trees became older the interaction became insignificant. Standing stem wood mass increases significantly with age but the effects of spacing, species composition and their interaction change over time from 1984 to 1995 (Table 5.7). When the trees are between 15 and 25 years old, spacing, species composition and their interaction are significant ($P<0.05$). However, since 1999 through 2014, the interaction is not significant ($P>0.05$).

Figure 5.7 shows the development of the stem wood mass through plantation development. *Abies grandis* in early years (1984 and 1990) had a very small quantity of total stem wood because the canopy of the upper stratum had not closed yet, primarily due to its relatively slow juvenile height growth rate. Once the trees get larger and the canopy is closed enough ameliorate the microclimate for firs, productivity of *Abies grandis* increased, reachinglevels of stem wood mass in 2014 that are very similar to those of pure *Pinus ponderosa* plots and the mixed plots.

In all the years the ponderosa pine pure plots have more mass than the others plots, but as the trees get older the differences between the pure plots (both *Abies grandis* and *Pinus ponderosa* pure plots) and the mixed plots became minor. The largest standing stem wood mass was found in the narrowest plots and decreased when the spacing increased but at a spacing of 5m the production stabilized.

Kelty (2006) suggested that greater productivity of mixtures could result from different options, competition reduction, facilitation or complementary characteristics. In the case of the present study, combining *Abies grandis* (shade tolerant) with *Pinus ponderosa* (shade intolerant), we obtain a mixture of species that can use the light in different levels, creating two stratums that can grow with different levels of light and at least maintain the total productivity of the stand.

6.4.TOTAL BIOMASS PER HECTARE

Total biomass was calculated as the sum of: total foliage mass per hectare, total branch-wood mass per hectare and total stem wood mass per hectare.

In all the years the total biomass decreased as the spacing increased (Figure 5.8). In 1975 and 1979 *Abies grandis* pure plots have more total biomass per hectare than *Pinus ponderosa* pure plots, and in 1979 the total biomass in mixed plots was less than in fir plots and greater than in pine plots.In 1979, fir plots were more productive than pine plots, but the mixed plots were closer to the fir plots than in the year before. Probably in this first two years of measurement *Abies grandis* had more total biomass than *Pinus ponderosa*, because the biomass is only composed of foliage and branch-wood mass, and as we have shown before, *Abies grandis* had more branches and more foliage in early years.

Since 1984 *Pinus ponderosa* plots had more total foliage mass per hectare than *Abies grandis*. In 1984 and1990 the trend of total biomass in mixed plots was almost parallel to the *Pinus ponderosa* total biomass trend.

When the trees became older the interaction between spacing and species composition become insignificant (Table 5.9, $P>0.05$); that is, the mixed plots had a total biomass equal to the *Pinus ponderosa* plots in narrower spacing. However, in wider spacings, pine plots were more productive. Also, as the trees became older, total biomass production of *Abies grandis* was getting close to the mixed plots, little difference was evident in the production of fir and mixed plots in 2004 and 2014 (Figure 5.8).

Analyzing the different components of the total biomass, it is shown that in early years almost everything is foliage with little quantity of branch wood mass (Figure 6.1). When the height and diameter growth start, most of the total biomass becomes mostly stem wood mass (Figure 6.2). As the trees age, the total foliage mass stabilizes, because the crown does not experience changes as in the early years of development.

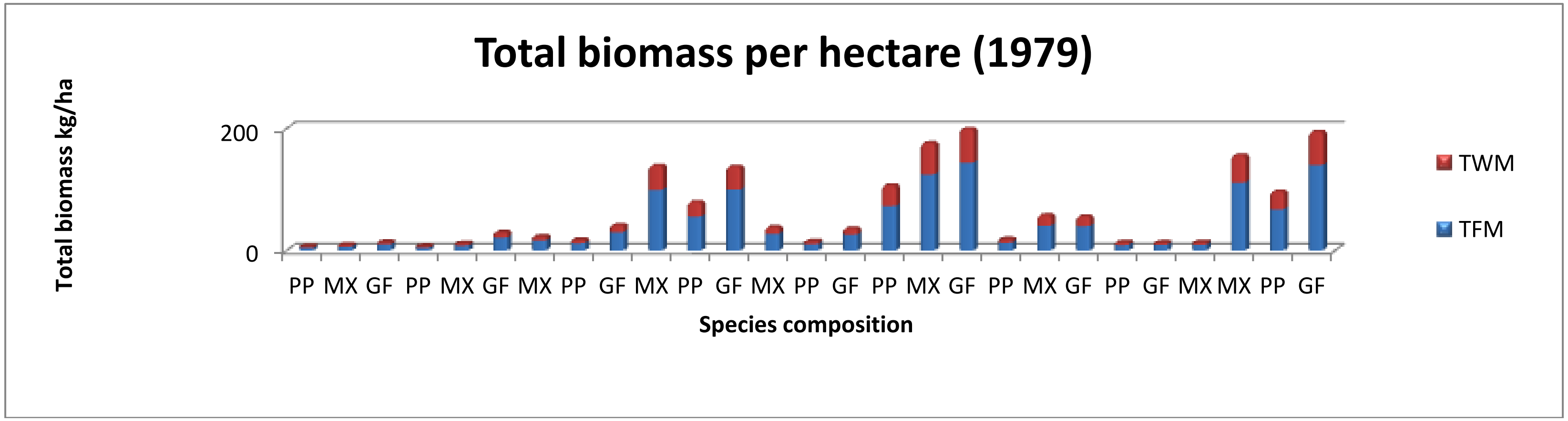

Figure 6.1 Total Biomass distribution by components (foliage, branch-wood and stem wood mass) in 1979.

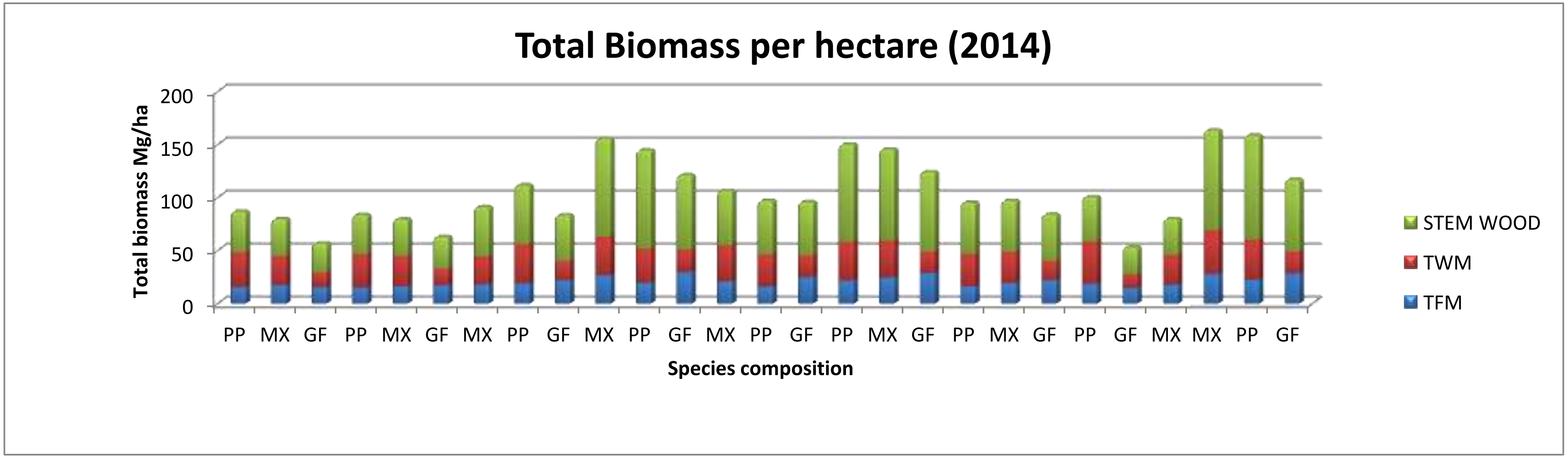

Figure 6.2 Biomass distribution by components (foliage, branch-wood and stem wood mass) in 2014.

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APPENDIX

APPENDIX

1. BRANCH LEVEL EQUATIONS

1.1. BRANCH LEAF MASS

Different models were fitted (Table 1), the model with lower Furnival Index (FI), (Furnival, 1961) was chosen.

Table 2. Models fitted to estimate branch leaf mass for Grand fir and Ponderosa pine.

Model number	Model	Grand fir		Ponderosa pine	
		Optimal weight	FI	Optimal weight	FI
1	β1*BD^β2	BD-3.9	10.5541	BD-4.0	42.1571
2	**BLM=β1*BD^β2 * RELDINC^β3*EXP(-β4*RELDINC)**	**BD-3.8**	**8.7681**	**BD-3.8**	**30.68**
3	BLM=β1*BD^β2*DINC^β3*EXP(-β4*DINC)	BD-3.9	9.4111	BD-3.8	37.9547
4	BLM=β1*BD^β2*DINC^β3*EXP(-β4*RELDINC)	BD-3.9	9.3694	BD-3.9	33.1336
5	BLM=β1*BD^β2*RELDINC^β3*EXP(-β4*DINC)	BD-4.0	10.0421	BD-3.9	38.9801
6	BLM=β1*BD^β2 * RELHC^β3*EXP(-β4*RELHC)	BD-3.8	9.0726	BD-3.9	31.26699
7	BLM=β1*BD^β2*HC^β3*EXP(-β4*HC)	BD-3.6	9.71291	BD-3.9	31.89815
8	BLM=β1*BD^β2*HC^β3*EXP(-β4*RELHC)	BD-3.7	8.7076	BD-3.8	33.65406
9	BLM=β1*BD^β2*RELHC^β3*EXP(-β4*HC)	BD-3.8	10.32552	BD-3.8	32.62724

The best model was model 2, $BLM=\beta1*BD^{\beta2} * RELDINC^{\beta3}e^{(-\beta4\ RELDINC)}$, with a weights of BD$^{-3.8}$ for both species to correct for heteroskedasticity it was chosen because it has in both species the lower FI. The residuals distribution after applying the weights and the Qqplots are shown in Figure 1 and 2.

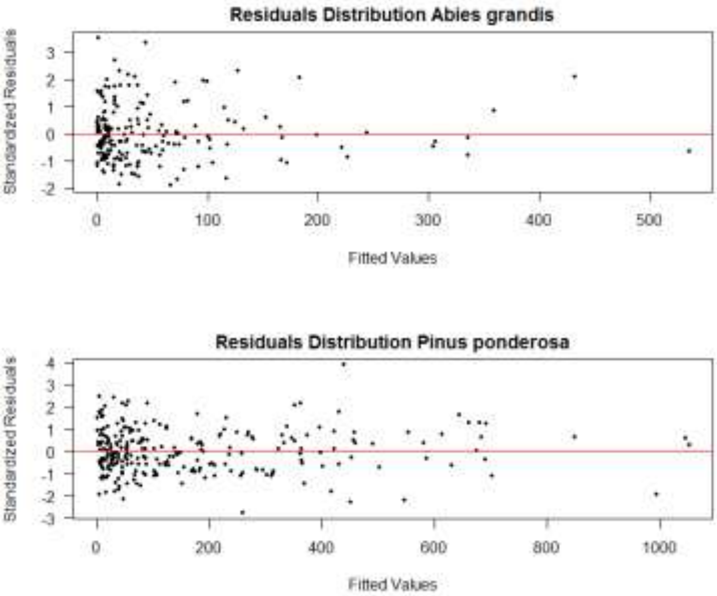
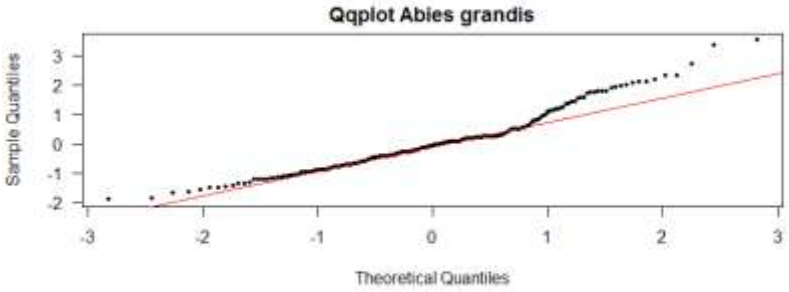


Figure 2. Residuals distribution of both species, for branch leaf mass model 2.



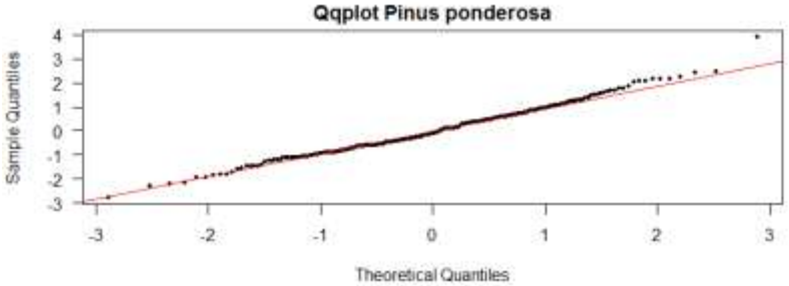


Figure 3. Qqplot of both species for branch leaf mass, model 2.

Table 3. Parameter estimates and standard error of model 2, estimation of branch leaf mass for *Abies grandis* and *Pinus ponderosa*.

Parameter	Estimate value	S.E	p-value
Abies grandis			
β1	10.72349	5.84236	6.79E-02
β2	2.20606	0.04703	2.00E-16
β3	2.16875	0.30468	1.85E-11
β4	4.12983	0.60229	8.29E-11
Pinus ponderosa			
β1	1.40101	0.42778	1.20E-03
β2	2.28308	0.04312	2.00E-16
β3	1.04337	0.12778	1.50E-14
β4	3.60867	0.32566	2.00E-16

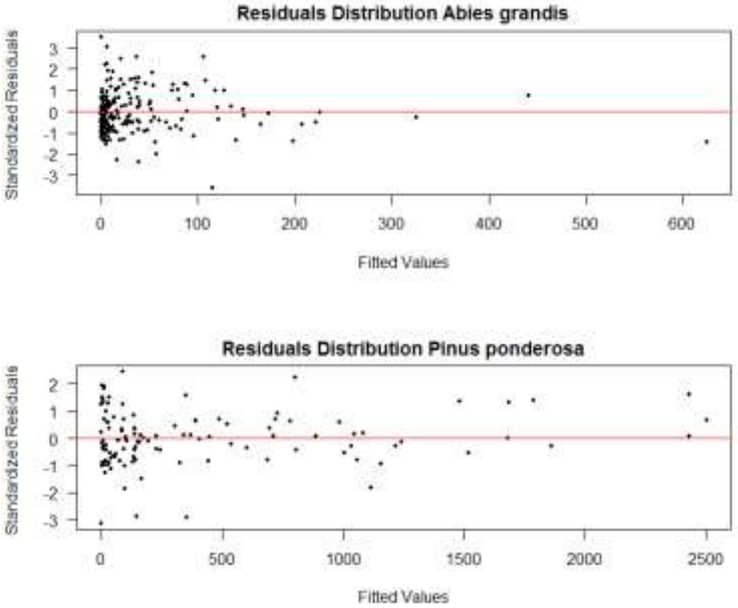
1.2. BRANCH WOODY MASS

As in the case of branch leaf mass Different models were fitted (Table 3), the model with lower Furnival Index (FI), (Furnival, 1961) was chosen.

Table 4. Models fitted for Branch woody mass for Grand fir and Ponderosa pine.

Model number	Model	Grand fir		Ponderosa pine	
		Optimal weight	FI	Optimal weight	FI
1	**BWM = β1 * (BD^β2) * (RELDINC^β3)**	**BD^{-4}**	**4.1228**	**BD^{-6}**	**40.8940**
2	BWM =β1 * (BD^β2) * exp(-β3*RELDINC)	BD^{-4}	4.2338	BD^{-5}	42.694
3	BWM =β1 * (BD^β2) * (RELDINC^β3)*exp(-β4*RELDINC)	BD^{-4}	4.127	BD^{-6}	40.603

The best model was model 1, BWM = β1 * (BD$^{\beta 2}$) * (RELDINC$^{\beta 3}$), with a weights of BD $^{-4}$ to correct for heteroskedasticity it was chosen because it has in both species the lower FI. The residuals distribution after applying the weights and the Qqplots are shown in Figure 1 and 2.


Residuals Distribution Abies grandis

Residuals Distribution Pinus ponderosa

Figure 4. Residuals distribution of both species, for branch woody mass model.

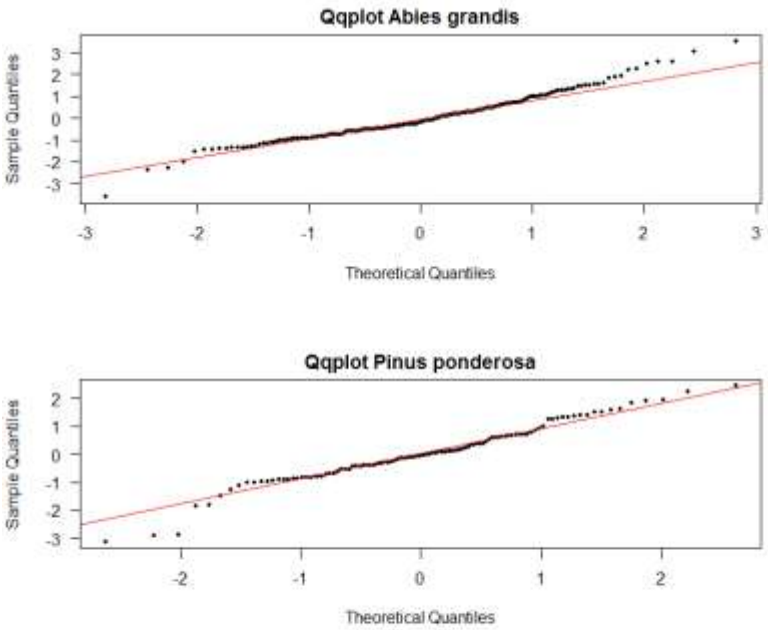


Figure 5. Qqplot of both species for branch woody mass, model 1.

Table 5. Parameter estimates and standard error of model 1, estimation of branch woody mass for Abies grandis and Pinus ponderosa.

Parameter	**Estimate value**	**S.E**	**p-value**
Abies grandis			
β1	0.073397	0.008449	1.21E-15
β2	2.624544	0.04281	2.00E-16
β3	0.456196	0.048216	2.00E-16
Pinus ponderosa			
β1	0.031659	0.005443	5.87E-08
β2	2.769182	0.050309	2.00E-16
β3	0.296715	0.0528	1.44E-07

2. TREE LEVEL EQUATIONS

2.1. TOTAL LEAF MASS

There were a lot of difficulties to find the optimal models to estimate the total foliage mass, many models were fitted but any of them satisfied all the requirements (Table 5).

Table 6 . Different models fitted to estimate the Total foliage mass (TFM).

Model number	Model	Grand fir			Ponderosa pine		
		Optimal weight	**FI**	**Comments**	**Optimal weight**	**FI**	**Comments**
1	TFM =β1 * (DBH^β2) * (CL^β3) * ((MCL/CL)^β4)	DBH^{-3}	2.428	No sig	$DBH^{-3.7}$	2.543	Sig
1	TFM =β1 * (DBH^β2) * (CL^β3) * ((MCL/CL)^β4)	$CL^{-3.5}$	2.865	no sig	$CL^{-3.8}$	2.880	Sig
2	TFM =β1 * exp(β2 * DBH)	DBH^{-2}	3.852	sig	DBH^{-3}	4.731	No sig
3	TFM =β1 * exp(β2 *DBH) * (CL^β3)	DBH^{-3}	3.529	sig	DBH^{-5}	3.038	sig
4	TFM =β1 * exp(β2 * DBH) * ((MCL/CL)^β3)	DBH^{-2}	3.885	No sig	DBH^{-3}	4.783	No sig
5	TFM=β1 * exp(β2 *DBH) * (CL^β3) * ((MCL/CL)^β4)	$DBH^{-3.5}$	3.548	No sig	DBH^{-5}	2.908	Sig
5	TFM =β1 * exp(β2 * DBH) * (CL^β3) * ((MCL/CL)^β4)	$CL^{-3.5}$	4.087	No sig	CL^{-4}	3.437	Sig
6	TFM =β1 * (DBH^β2) * exp(β3 * DBH) * (CL^β4)	$DBH^{-3.5}$	2.453	No sig	DBH^{-3}	2.689	No sig
6	TFM =β1 * (DBH^β2) * exp(β3 * DBH) * (CL^β4)	$CL^{-3.5}$	2.956	No sig	CL^{-3}	2.989	No sig
7	TFM=β1 * (DBH^β2) * exp(β3 * DBH) * ((MCL/CL)^β4)	$DBH^{-3.5}$	2.492	No sig	DBH^{-5}	3.073	No sig
8	TFM=β1 * (DBH^β2) * exp(β3 * DBH) * (CL^β4) * ((MCL/CL)^β5)	$DBH^{-3.5}$	2.442	No sig	$DBH^{-3.5}$	2.504	No sig
9	TFM= exp(β1) * exp(β2 * DBH) * (DBH^(β3 + β4 *PCL))	$DBH^{-3.5}$	2.493	No sig	DBH^{-4}	3.100	No sig

Where :
MCL= measured crown length
CL= crown length
DBH= diameter breast height
HT=Total height
PCL= MCL/CL

Finally the model chosen was:

Abies grandis

$$TFM = \beta 1 \; DBH^{\beta 2} \; HT^{\beta 3} \; CL^{(\beta 4 * (MCL/CL))}$$

Pinus ponderosa

$$TFM= \beta 1 \; DBH^{\beta 2} \; CL^{(\beta 3 * (MCL/CL))}$$

Both models were weighted by the reciprocal of the predicted value, Figure .. and … show the residuals distribution and the Qqplots.

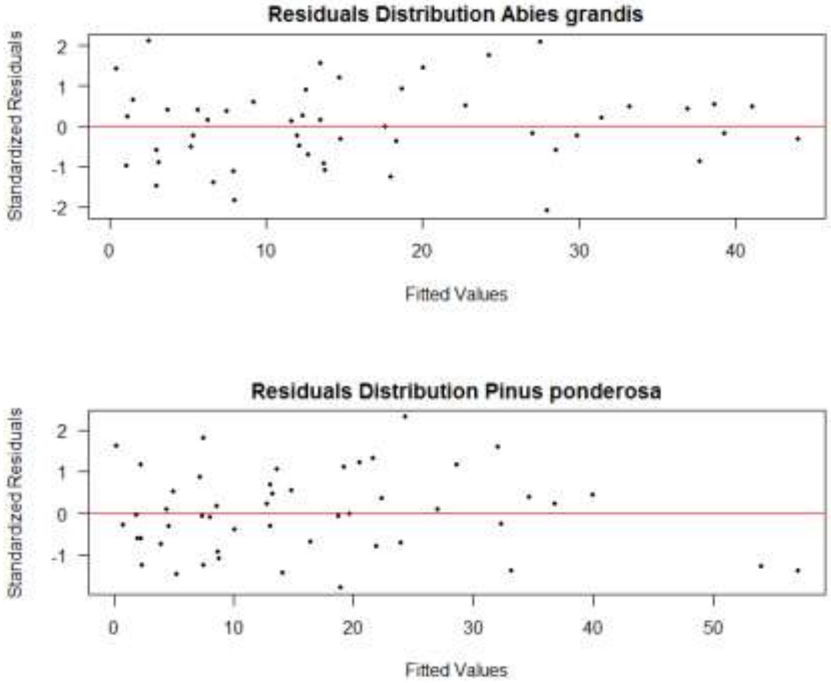


Figure 6. Residuals distribution of the model to estimate the total foliage mass for both species.

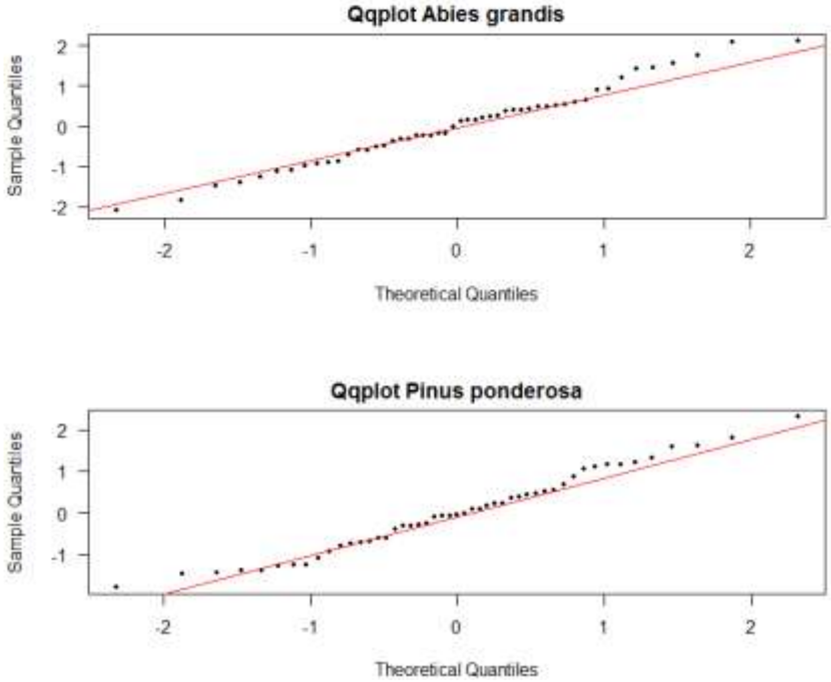


Figure 7. Qplot of all the felled and climbed trees used in the model of total foliage mass**.**

Table 7 . Parameter estimation and standard error of the model of TFM.

$TFM = \beta1\ DBH^{\beta2}\ HT^{\beta3}\ CL^{(\beta4 * (MCL/CL))}$			
Abies grandis			
Parameter	**Estimate value**	**S.E**	**p-value**
β1	0.0791	0.01246	8.69E-08
β2	2.47633	0.17339	2.00E-16
β3	-0.92748	0.2258	1.62E-04
β4	0.25387	0.09767	1.25E-02
$TFM = \beta1\ DBH^{\beta2}\ CL^{(\beta3 * (MCL/CL))}$			
Pinus ponderosa			
β1	0.003453	0.001284	9.94E-03
β2	2.260311	0.135864	2.00E-16
β3	0.605171	0.112548	2.46E-06

If only total height is available the model will be: $TFM = \beta1\ HT^{\beta2}$

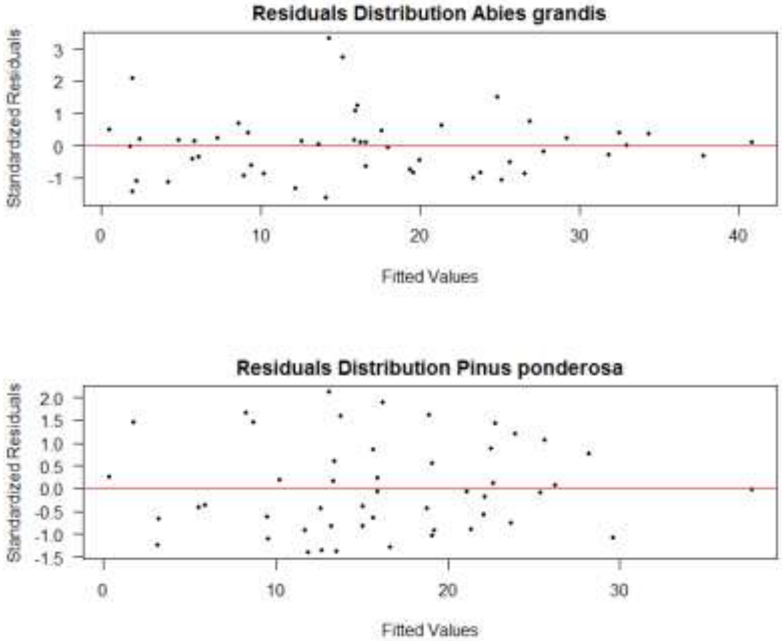


Figure 8. Residuals distribution of the model with only HT.

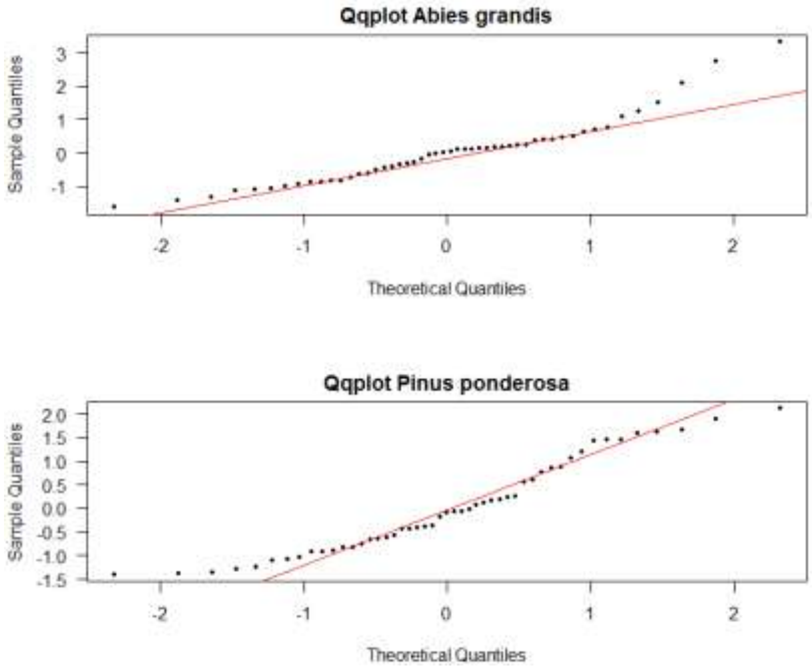


Figure 9. QQplot of the model with only HT.

The parameter estimated and the standard error of the model with only HT are shown in Table 8.

Table 8. Parameter estimates and standar error of the model with only HT.

$TFM = \beta 1 \; HT^{\beta 2}$			
Abies grandis			
Parameter	**Estimate value**	**S.E**	**p-value**
β1	0.08601	0.02666	2.26E-04
β2	2.23904	0.14344	2.00E-16
Pinus ponderosa			
β1	0.011358	0.009085	2.17E-01
β2	2.950587	0.332603	1.32E-11

After 1979 most of the trees reached the minimum diameter to measure so, since that year at least it was measured the total height and the diameter at breast height, so different models for this cases were fitted.

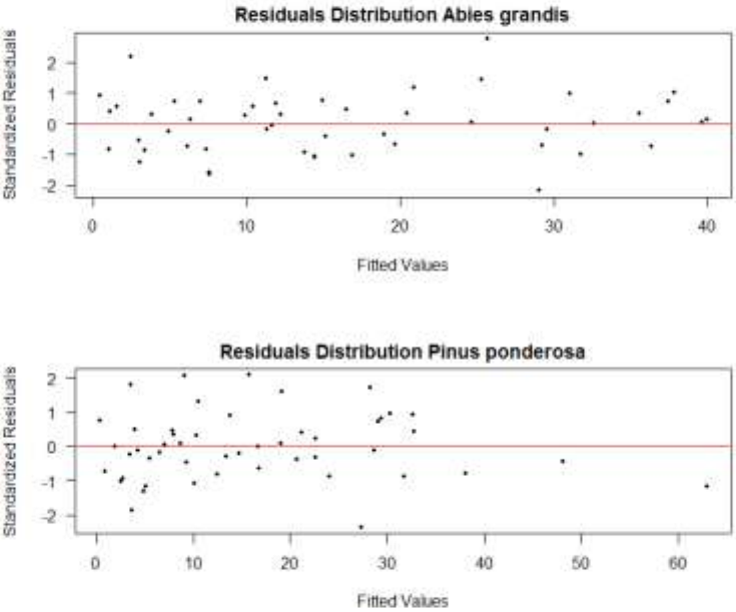


Figure 10 . Residuals distribution of the model with only DBH and HT to estimate TFM.

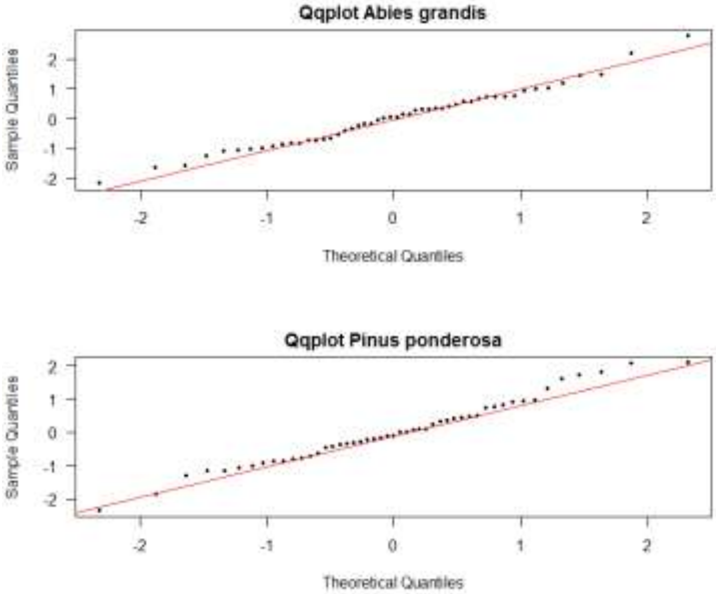


Figure 11. Qqplot of the model with only DBH and HT to estimate TFM**.**

Table 9. Parameter estimates and standard error of the model with only DBH and HT.

$$TFM = \beta 1\ DBH^{\beta 2}\ HT^{\beta 3}$$

Parameter	Estimate value	S.E	p-value
Abies grandis			
β1	0.08451	0.01463	5.90E-07
β2	2.56894	0.18602	2.00E-16
β3	-0.85539	0.23862	7.99E-04
Pinus ponderosa			
β1	0.008135	0.002642	3.50E-03
β2	2.996661	0.193732	2.00E-16
β3	-0.8633415	0.279784	3.43E-03

2.2. TOTAL WOODY MASS

As in the case of total foliage mass many difficulties were found while looking for the best model, the Table… shows the different options of models for estimating the total woody mass.

Table 10. Different models fitted to find the best model for estimating the Total Woody Mass (TWM).

Model number	Model	Grand fir			Ponderosa pine		
		Optimal weight	FI	Comments	Optimal weight	FI	Comments
1	TWM= β1 * (DBH^β2) * (CL^β3) * (PCL^β4)	CL-4	2.969	sig	CL-5	8.788	no sig
1	TWM =β1 * (DBH^β2) * (CL^β3) * (PCL^β4)	DBH-3.8	2.403	no sig	DBH-5	7.124	sig
2	TWM =β1 * exp(β2 * DBH)	DBH-3	3.566	sig	DBH-3	13.77	sig
3	TWM = β1 * exp(β2 * DBH) * (CL^β3)	DBH-3.9	3.232	sig	DBH-4	10.292	sig
4	TWM =β1 * exp(β2 * DBH) * (PCL^β3)	DBH-3	3.584	no sig	DBH-3.6	12.145	sig
5	TWM= β1 * exp(β2 * DBH) * (CL^β3) * (PCL^β4)	DBH-3.9	3.253	no sig	DBH-6	8.724	sig
5	TWM = β1 * exp(β2 * DBH) * (CL^β3) * (PCL^β4)	CL-4	3.959	no sig	CL-4	10.73	sig
6	TWM=β1 * exp(β2 * DBH) * (DBH^β3) * (CL^β4)	DBH-4	2.408	no sig	DBH-4	8.682	no sig
6	TWM =β1 * exp(β2 * DBH) * (DBH^β3) * (CL^β4)	CL-4	3.058	no sig	CL-4	9.437	no sig
7	TWM = β1 * (DBH^β2) * exp(β3 *DBH) * (PCL^β4)	DBH-4	2.479	no sig	DBH-5	7.493	no sig

Any of the models shown in Table 10, satisfied all the requirements so it was fitted another one, which was the definitive.

Abies grandis

$TWM=\beta 1\ DBH^{\beta 2}\ HT^{\beta 3}\ (CL^{\beta 4 * (mcl/cl)})+\varepsilon_3$

Pinus ponderosa

$TWM= \beta 1\ DBH^{\beta 2}\ (CL^{\beta 3 * (mcl/cl)})+\varepsilon_4$

Both models were weighted by the reciprocal of the predicted value, Figure 12 and 13 show the residuals distribution and the Qqplots.

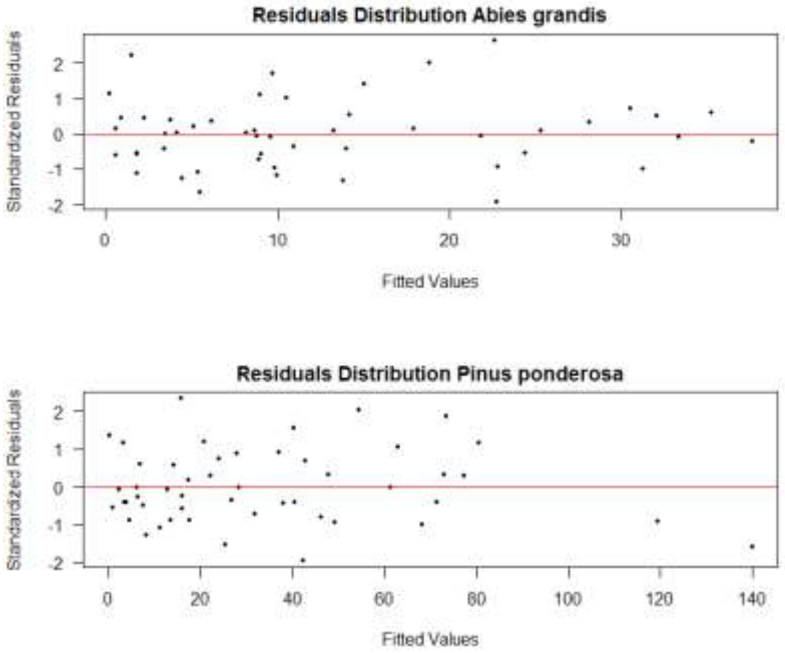


Figure 12 Residuals Distribution of the model of TWM.

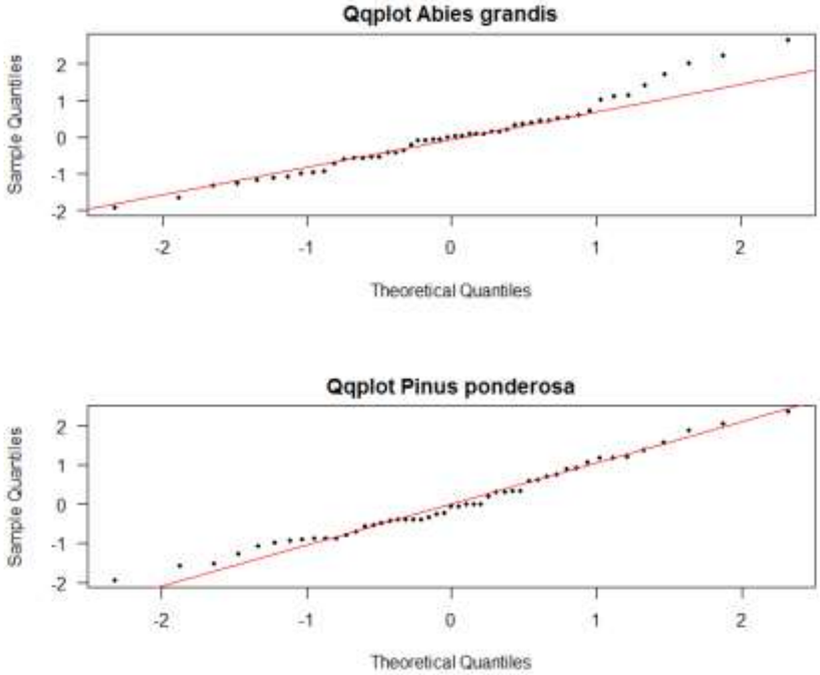


Figure 13. QQplots model estimation TWM.

Table 11. Parameters estimates and standard error of the model for TWM.

TWM ~ β1 * (DBH^β2) * (HT^β3) * (CL^(β4 * (MCL/CL)))			
Abies grandis			
Parameter	**Estimate value**	**S.E**	**p-value**
β1	0.030826	0.006895	5.07E-05
β2	2.88033	0.233113	3.23E-16
β3	-1.180678	0.303539	3.21E-04
β4	0.305888	0.128823	2.18E-02
TWM~β1 * (DBH^β2) * (CL^(β3 * (MCL/CL)))			
Pinus ponderosa			
β1	0.0015457	0.0007733	5.15E-02
β2	2.8491391	0.1818362	2.00E-16
β3	0.3707963	0.1464155	1.48E-02

In the case that there is only HT measurements: $TWM = \beta 1\ HT^{\beta 2}$

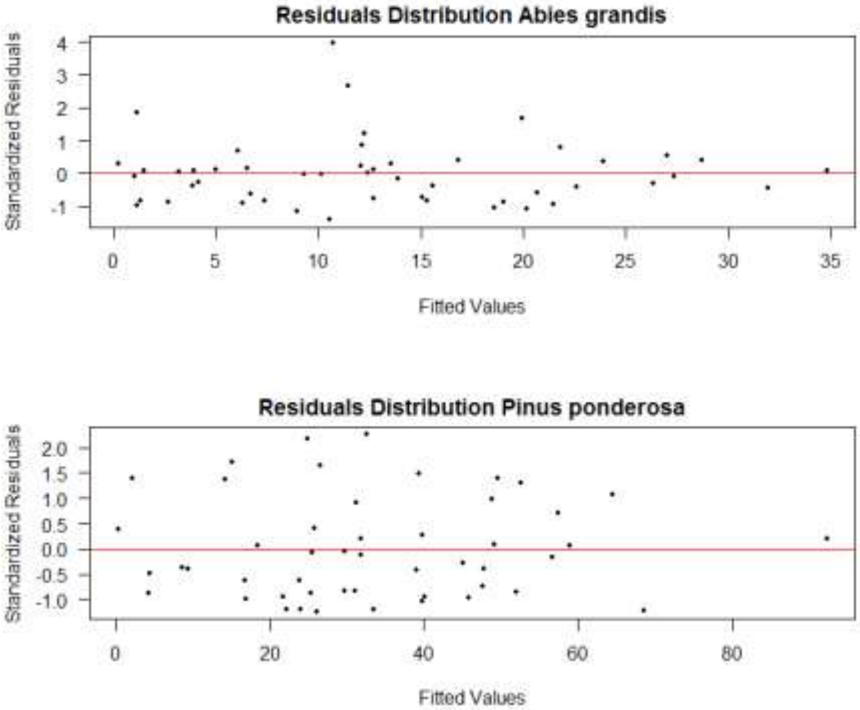


Figure 14. Residuals distribution of the model of TWM with only HT.

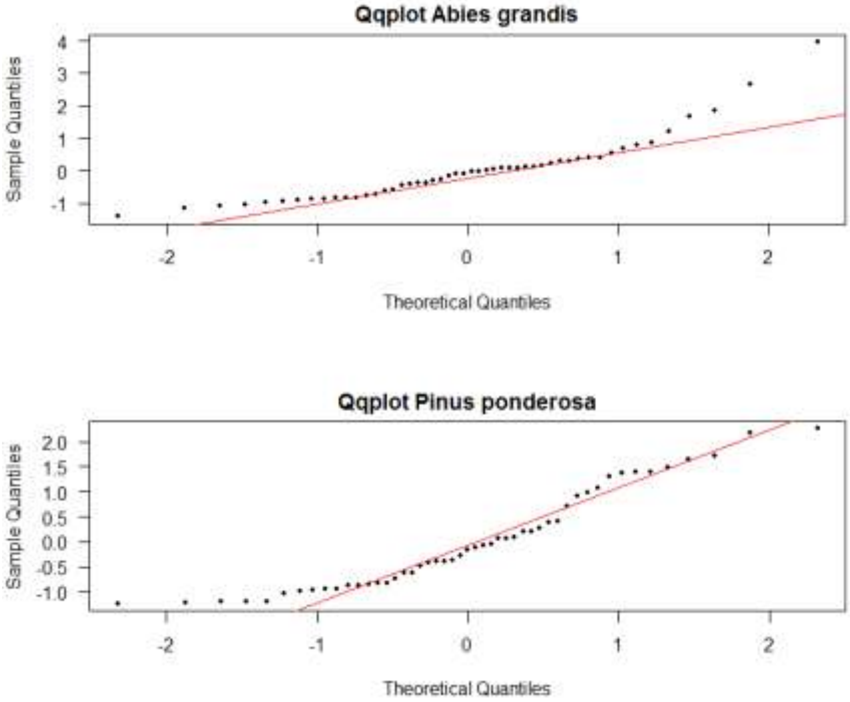


Figure 15. Qqplot of model for TWM with only HT.

Table 12 .Parameters estimated of TWM model with only HT.

TWM= β1 HT $^{\beta2}$			
Abies grandis			
Parameter	**Estimate value**	**S.E**	**p-value**
β1	0.03448	0.01615	3.79E-02
β2	2.5133	0.20759	3.38E-16
Pinus ponderosa			
β1	0.003958	0.005325	4.61E-01
β2	3.66074	0.545096	2.21E-08

When we only have DBH and HT we use the other model: TWM = β 1 DBH $^{\beta2}$ HT $^{\beta3}$

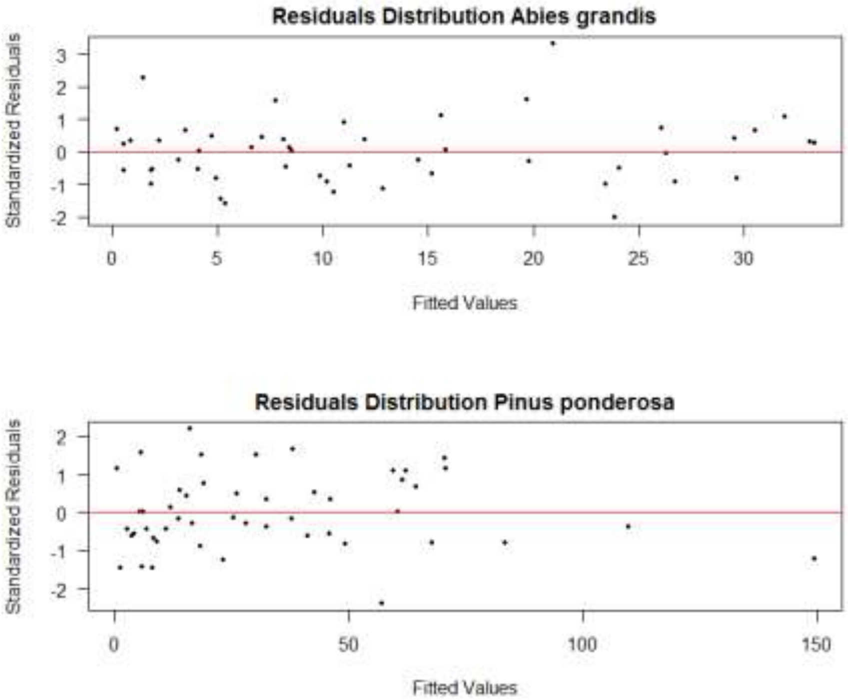


Figure 16. Residuals distribution model for TWM with DBH and HT.

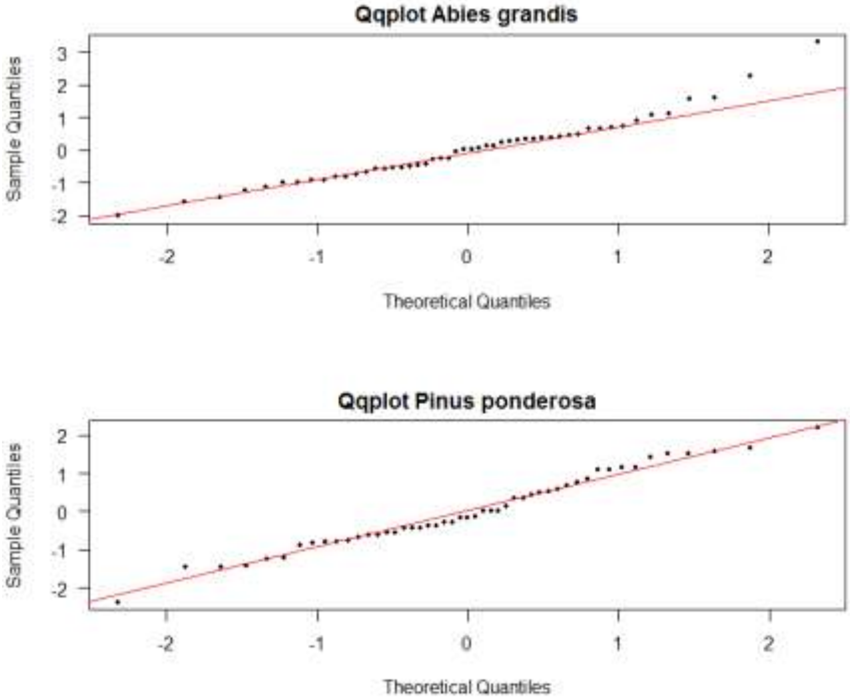


Figure 17. Qqplot model for TWM with DBH and HT.

Table 13. Parameters estimated of TWM model with DBH and HT

TWM =β 1 DBH^ β 2 HTβ 3			
	Abies grandis		
Parameter	**Estimate value**	**S.E**	**p-value**
β1	0.034672	0.008276	1.22E-04
β2	3.026752	0.259186	1.70E-15
β3	-1.152963	0.33268	1.14E-03
	Pinus ponderosa		
β1	0.004772	0.001515	2.88E-03
β2	3.447856	0.215803	2.00E-16
β3	-0.973793	0.302732	2.38E-03

3. PLOT LEVEL AND BIOMASS PER HECTARE

3.1 TOTAL FOLIAGE MASS PER HECTARE

Once we have the total foliage mass equations, they are applied to all the measured trees in the plots, in order to obtain the total foliage mass per plot and per hectare (Figure 17). An ANOVA was calculated to study if there are differences between spacing, species composition and their interaction. Each year was calculated an ANOVA (Table 14).

Table 14. Analysis of Variance of total foliage mass per hectare of each year of measurement. Comparison between spacing, species composition and their interaction.

1975	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	12.2559	12.2559	81.944	1.0750E-08	***
sp composition	2	7.7701	3.885	25.976	2.0960E-06	***
interaction	2	5.0727	2.5363	16.958	4.1340E-05	***
residuals	21	3.1408	0.1496			

1979	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	39124	39124	105.1649	1.2440E-09	***
sp composition	2	4328	2164	5.8164	9.7710E-03	**
interaction	2	2558	1279	3.4386	5.1072E-02	.
residuals	21	7812	372			

1984	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	7207724	7207724	61.5834	1.1200E-07	***
sp composition	2	1450491	725245	6.1966	7.6720E-03	**
interaction	2	489853	244926	2.0927	1.4834E-01	
residuals	21	2457842	117040			

1990	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	77930407	77930407	134.454	1.3670E-10	***
sp composition	2	13248422	6624211	11.4288	4.3840E-04	***
interaction	2	3598960	1799480	3.1047	6.5882E-02	.
residuals	21	1217174	579607			

1995	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	192616633	192616633	236.3993	6.6740E-13	***
sp composition	2	2159224	1079612	1.325	2.8712E-01	
interaction	2	7686030	3843015	4.7166	2.0330E-02	*
residuals	21	17110667	814794			

Table 14. (Cont.) Analysis of Variance of total foliage mass per hectare of each year of measurement. Comparison between spacing, species composition and their interaction.

1999	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	344901033	344901033	240.231	5.7120E-13	***
sp composition	2	66268657	33134328	23.079	4.9980E-06	***
interaction	2	67092232	33546116	23.366	4.5710E-06	***
residuals	21	30149777	1435704			

2004	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	292465264	292465264	134.336	1.3780E-10	***
sp composition	2	49902949	24951474	11.461	4.3170E-04	***
interaction	2	142566595	71283297	32.742	3.5110E-07	***
residuals	21	45719391	2177114			

2014	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	376937166	376937166	152.514	4.2790E-11	***
sp composition	2	89731218	44865609	18.153	2.6430E-05	***
interaction	2	51199630	5599815	10.358	7.4150E-04	***
residuals	21	51901176	2471485			

Table 15 . Summary of ANOVA of total foliage mass by years.

	p-value		
	Spacing	**Species composition**	**Interaction**
1975	<<0.05	<<0.05	<<0.05
1979	<<0.05	<0.05	0.051
1984	<<0.05	<0.05	0.148
1990	<<0.05	<<0.05	0.065
1995	<<0.05	0.278	0.02
1999	<<0.05	<<0.05	<<0.05
2004	<<0.05	<<0.05	<<0.05
2014	<<0.05	<<0.05	<<0.05

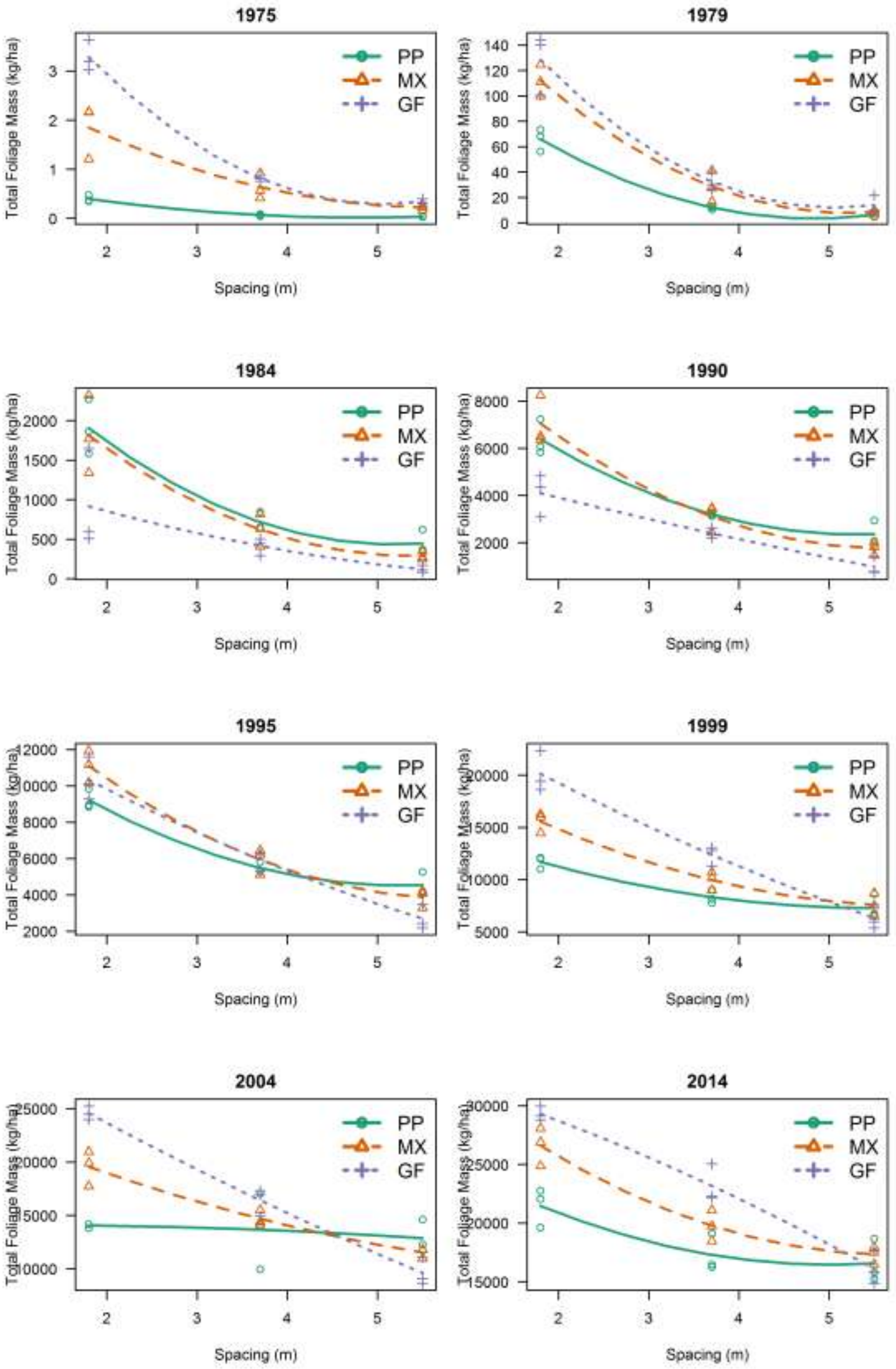


Figure 18. Trend in total foliage mass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials..

3.2 TOTAL WOODY MASS PER HECTARE

Once we have the total woody mass equations, they are applied to all the measured trees in the plots, in order to obtain the total branch-wood mass per plot and per hectare (Figure 18).
An ANOVA was calculated to study if there are differences between spacing, species composition and their interaction. Each year was calculated an ANOVA (Table 15).

Table 15. Analysis of Variance of total branch- wood mass per hectare of each year of measurement. Comparison between spacing, species composition and their interaction.

1975	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	0.64294	0.64294	74.593	2.3640E-08	***
sp composition	2	0.51004	0.25502	29.587	7.7800E-07	***
interaction	2	0.33167	0.16584	19.24	1.7880E-05	***
residuals	21	0.18101	0.00862			

1979	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	6364	6364	99.3698	2.0840E-09	***
sp composition	2	499.1	249.6	3.8967	3.6370E-02	*
interaction	2	285.1	142.5	2.2256	1.3286E-01	
residuals	21	1344.9	64			

1984	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	7128449	7128449	48.5049	7.0480E-07	***
sp composition	2	5120308	2560154	17.4203	3.4700E-05	***
interaction	2	1613563	806782	5.4897	1.2080E-02	*
residuals	21	3086233	146963			

1990	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	98093893	98093893	72.8541	2.8700E-08	***
sp composition	2	120323394	60161697	44.6819	2.7140E-08	***
interaction	2	19678062	9839031	7.3074	3.9010E-03	**
residuals	21	28275307	1346443			

1995	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	159864179	159864179	102.3242	1.5840E-09	***
sp composition	2	200724841	100362420	64.2386	1.1230E-09	***
interaction	2	10530525	5265262	3.3701	5.3780E-02	.
residuals	21	32808938	1562330			

Table 15. (Cont)**Analysis of Variance of total branch- wood mass per hectare of each year of measurement. Comparison between spacing, species composition and their interaction.**

1999	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	248698606	248698606	88.434	5.6200E-09	***
sp composition	2	202661910	101330955	36.032	1.6260E-07	***
interaction	2	25183960	12591980	4.4775	2.4010E-02	*
residuals	21	59057292	2812252			

2004	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	157951522	157951522	27.5332	3.3510E-05	***
sp composition	2	579073621	289536811	50.4704	9.5220E-09	***
interaction	2	95262363	47631182	8.3028	2.2040E-03	**
residuals	21	120472139	536769			

2014	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	135196005	135196005	15.374	7.8470E-04	***
sp composition	2	1419731795	709865897	80.7236	1.3850E-10	***
interaction	2	60507110	30253555	3.4403	5.1006E-02	.
residuals	21	184669494	8793785			

Table 16. Summary of ANOVA branch-wood mass by years.

	p-value		
	Spacing	Species composition	Interaction
1975	<<0.05	<<0.05	<<0.05
1979	<<0.05	<0.05	0.13286
1984	<<0.05	<<0.05	<0.05
1990	<<0.05	<<0.05	<0.05
1995	<<0.05	<<0.05	0.05
1999	<<0.05	<<0.05	<0.05
2004	<<0.05	<<0.05	<0.05
2014	<<0.05	<<0.05	0.05

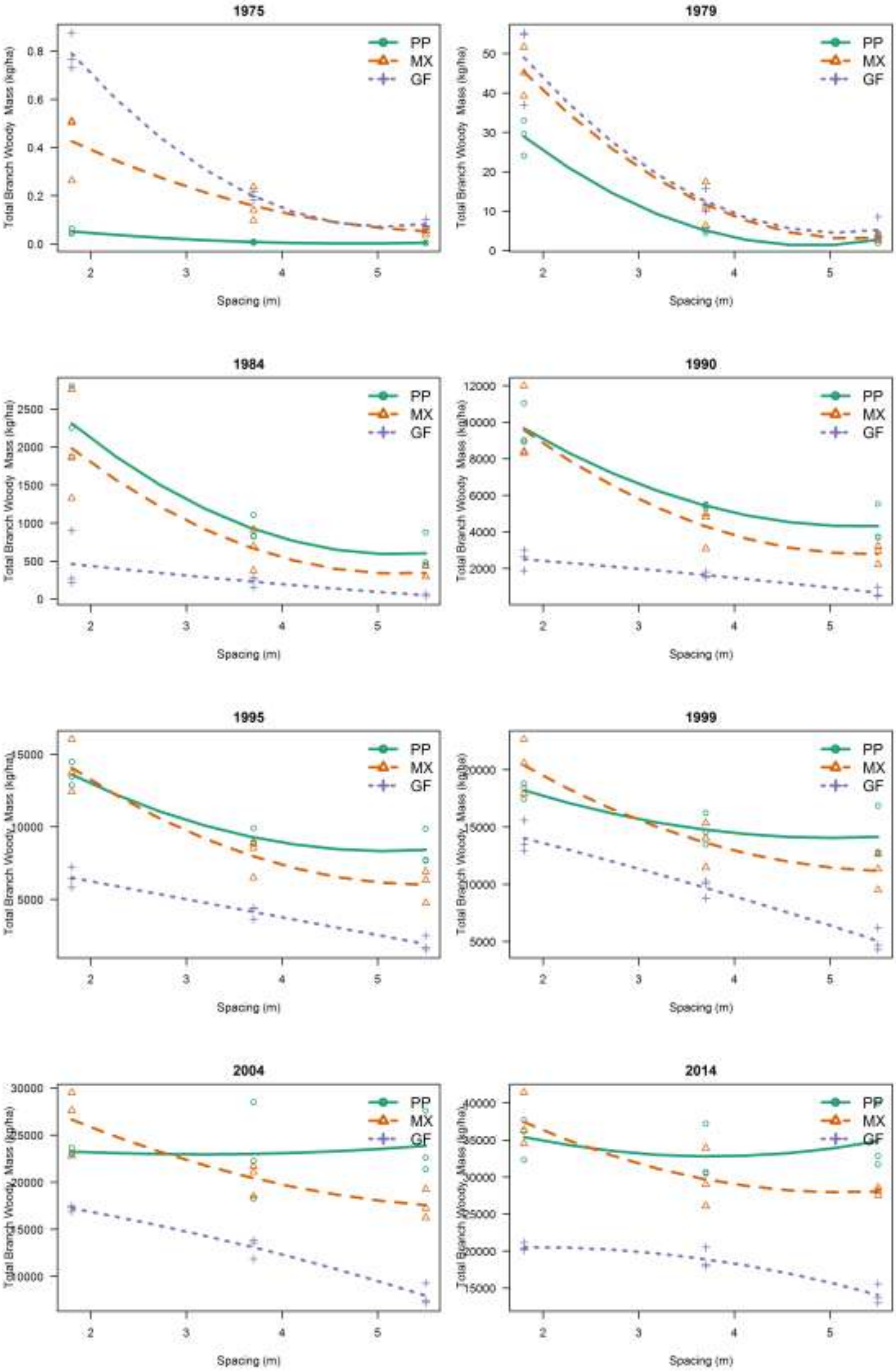


Figure 19. Trend in total branch-wood mass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

3.3 TOTAL STEM WOOD PER HECTARE

3.3.1 TAPER EQUATIONS

The stem shape was modeled with a variable exponent (Garber & Maguire, 2003)

[1] $$\frac{dib}{DIB} = X^{C}$$

Where:
dib= predicted diameter inside bark at some height h.
DIB= diameter inside bark at reference height p.
$X= [1-(Z)^{0.5}]/[1-(p)^{0.5}]$
Z=h/HT
C=f (Z and other three variables).
p=1.37/HT
Diameter inside bark was modeled as a nonlinear function of DBH:

[2]
$$\widehat{DIB} = a1\ DBH^{a1}$$

Where a1 and a2 are the parameters estimated from the data. Substituting $\widehat{DIB}$ from eq. [1] for DIB in Eq[2] we obtain:

$$dib = a1DBH^{a2}\,X^{c}$$

Finally we obtain for each species, Table 17:

Abies grandis

[1] $\mathrm{dib}=\alpha 11\ \mathrm{DBH}^{\alpha 12}\ (X)^{\alpha 13\ \mathrm{asin}(Q)+(\alpha 14+\delta 14)Q2+\ \alpha 15\ \log(X)+\ \alpha 16\ X2+\ \alpha 17\ \mathrm{asin}\ (Z)+(\ \alpha 18+\ \delta 18)\ \mathrm{e\ DBH/HT}}\ +\varepsilon$

Pinus ponderosa

[2] $\mathrm{dib}=\alpha 31\ \mathrm{DBH}^{\alpha 32}\ (X)^{\alpha 33Z2+\ \alpha 34\log(X)+\ \alpha 35\ Z\text{-}1/2\ +(\ \alpha\ 36+\ \delta\ 36)\ \cos(Z)+(\ \alpha\ 37+\ \delta\ 37)\ DBH\ \mathrm{X}+\ \alpha 38\ Z\ \mathrm{e\ DBH/HT}}$ $+\varepsilon$

Table 17. Parameter estimates and asymptotic standard errors of the best Kozak variable exponent taper model for A. grandis, P. ponderosa.

Abies grandis			***Pinus ponderosa***		
Parameter	**Estimated value**	**S.E.**	**Parameter**	**Estimated value**	**S.E.**
α11	0.8875	0.0228	α31	0.8167	0.0189
α12	1.0145	0.0098	α32	1.0155	0.0082
α13	-0.5035	0.1434	α33	1.0191	0.0364
α14	1.3749	0.1953	α34	0.1153	0.0072
α15	0.2626	0.0362	α35	-0.0491	0.0137
α16	-0.0491	0.016	α36	0.5841	0.0212
α17	1.2042	0.0942	α37	0.0077	0.0015
α18	0.035	0.0083	α38	-1.2134	0.1645
S.D. (δ14)	0.2945	0.2448	S.D. (δ36)	0.056	0.2583
S.D. (δ18)	0.01	0.3965	S.D. (δ37)	0.0015	0.2452
Cor(δ14,δ18)	-0.5102		Cor(δ36,δ37)	-0.5668	
S.D. (ε)	0.4214	0.0929	S.D. (ε)	0.3728	0.0942
φ	0.3955		φ	0.7105	

After calculating the volume of the trees, we needed to find the best density for both species. The densities chosen are 380kg/m^3 for *Pinus ponderos*a and 350kg/m^3 for *Abies grandis* (Miles & Smith, 2009).

Applying the densities to the volume of the trees we obtain the stem wood mass without bark of the trees, the total stem wood mass per plot and then per hectare.
The first two years of measurement (1975 and 1979) do not have stem wood volume because there were small tress with just few centimeters of height, in that years the total biomass above ground will be composed only by foliage and branch woody mass. Te taper equations works really bad at small trees, so in 1984 in which the trees were very small was impossible to use the taper equation, because it overestimates the volume per tree. Different approaches were used, for example V= BA*HT*0.35, but the volume was also overestimated. The other approach was to calculate the stem volume up to breast height (BH) as a cylinder, and from BH to the top of the tree as a cone. Finally this method was used for 1984.

$$\text{Volume cylinder} \quad V_1 = BA * 1.37$$

$$\text{Volume cone} \quad V_2 = \frac{1}{3} BA * (HT - 1.37)$$

$$V_{tree} = V_1 + V_2$$

Finally an ANOVA was calculated to see if there are differences or not between spacing, species composition and their interaction.

Table 18. Analysis of Variance of total stem wood mass per hectare of each year of measurement. Comparison between spacing, species composition and their interaction.

1984	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	43272224	43272224	50.278	5.3840E-07	***
sp composition	2	40593848	20296924	23.583	4.2740E-06	***
interaction	2	17968990	8984495	10.439	7.1190E-04	***
residuals	21	18073862	860660			

1990	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	3048828721	3048828721	133.927	1.4170E-10	***
sp composition	2	1991942719	995971359	43.75	3.2450E-08	***
interaction	2	548365242	274182621	12.044	3.2780E-04	***
residuals	21	478063536	22764930			

1995	**Df**	**Sum sq**	**Mean sq**	**F value**	**p-value**	
spacing	1	4699336993	4699336993	204.8747	2.6460E-12	***
sp composition	2	1903731485	951865742	41.498	5.0660E-08	***
interaction	2	335928163	167964082	7.3226	3.8660E-03	**
residuals	21	481690018	22937620			

Table 18 (Cont.)Analysis of Variance of total stem wood mass per hectare of each year of measurement. Comparison between spacing, species composition and their interaction

1999	**Df**	**Sum sq**	**Mean sq**	**F value**	**p-value**	
spacing	1	7601690686	7601690686	208.7677	2.2100E-12	***
sp composition	2	1726044356	863022178	23.7015	4.1210E-06	***
interaction	2	185498540	92749270	2.5472	1.0220E-01	
residuals	21	764656274	36412204			

2004	**Df**	**Sum sq**	**Mean sq**	**F value**	**p-value**	
spacing	1	9215979908	9215979908	208.4109	2.2460E-12	***
sp composition	2	1443796304	721898152	16.3251	5.2820E-05	***
interaction	2	211354496	105677248	2.3898	1.1610E-01	
residuals	21	928624988	44220238			

2014	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	135196005	135196005	15.374	7.8470E-04	***
sp composition	2	1419731795	709865897	80.7236	1.3850E-10	***
interaction	2	60507110	30253555	3.4403	5.1006E-02	.
residuals	21	184669494	8793785			

Table 19. Summary of ANOVA total stem wood mass by years.

	p-value		
	Spacing	**Species composition**	**Interaction**
1984	<<0.05	<<0.05	<<0.05
1990	<<0.05	<<0.05	<<0.05
1995	<<0.05	<<0.05	<0.05
1999	<<0.05	<<0.05	0.1
2004	<<0.05	<<0.05	0.116
2014	<<0.05	<<0.05	0.05

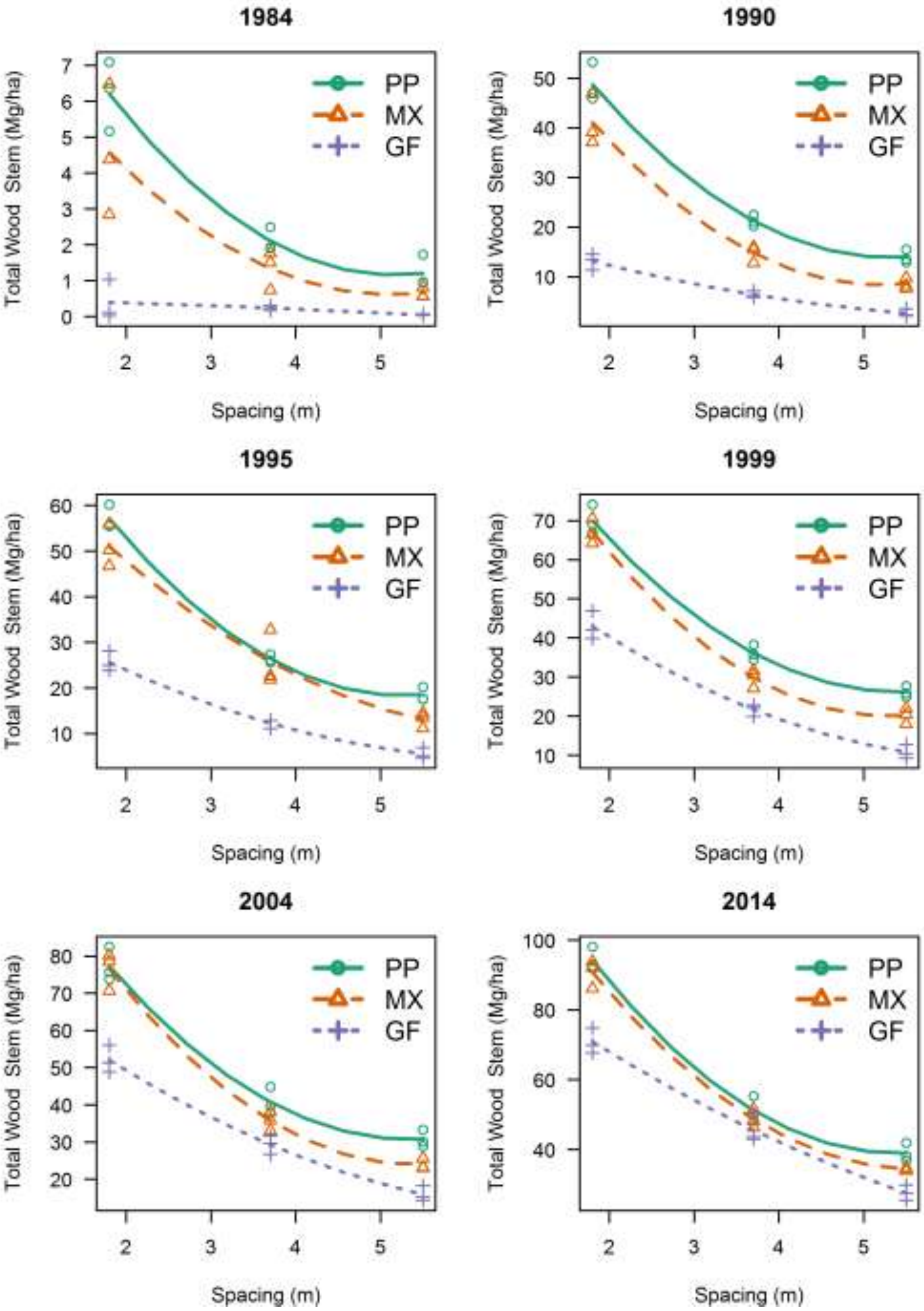


Figure 20. Trend in total stem wood mass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

3.4 TOTAL BIOMASS PER HECTARE

Total biomass per hectare has been calculated as the sum of: total foliage mass per hectare, total branch-wood mass per hectare and the total stem wood per hectare, except in 1979 and 1984 where the total biomass per hectare is the sum of total foliage mass per hectare and total branch-wood per hectare. An ANOVA was performed to evaluate the differences between spacing, species composition and their interaction.

Table 20. Analysis of Variance od the total biomass per hectare.

1975	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	18.5131	18.5131	80.589	1.2380E-08	***
sp composition	2	12.2614	6.1307	26.688	1.7110E-06	***
interaction	2	7.9985	3.9993	17.409	3.4850E-05	***
residuals	21	4.8241	0.2297			

1979	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	77046	77046	103.6192	1.4180E-09	***
sp composition	2	7758	3879	5.2168	1.4480E-02	*
interaction	2	4542	2271	3.0545	6.8000E-02	.
residuals	21	15615	744			

1984	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	142391685	142391685	54.0275	3.1100E-07	***
sp composition	2	96591169	48295584	18.3247	2.4830E-05	***
interaction	2	38111176	19055588	7.2302	4.0830E-03	**
residuals	21	55346402	2635543			

1990	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	5468.3	5468.3	127.9061	2.1540E-10	***
sp composition	2	3483.2	1741.6	40.7365	5.9140E-08	***
interaction	2	849.9	425	9.9402	9.1710E-04	***
residuals	21	897.8	42.8			

1995	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	9039.1	9039.1	220.8175	1.2890E-12	***
sp composition	2	3418.2	1709.1	41.752	4.8100E-08	***
interaction	2	366.2	183.1	4.4724	2.4100E-02	*
residuals	21	859.6	40.9			

1999	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	14769.4	14769.4	214.9325	1.6720E-12	***
sp composition	2	2298.9	1149.4	16.7272	4.5180E-05	***
interaction	2	118.6	59.3	0.8631	4.3630E-01	
residuals	21	1443	68.7			

Table 20 (Cont.)Analysis of Variance od the total biomass per hectare

2004	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	15792.8	15792.8	196.366	3.6700E-12	***
sp composition	2	3068.6	1534.3	19.0772	1.8940E-05	***
interaction	2	383.2	191.6	2.3824	1.1680E-01	
residuals	21	1688.9	80.4			

2014	Df	Sum sq	Mean sq	F value	p-value	
spacing	1	19869.2	19869.2	187.5938	6.1270E-12	***
sp composition	2	3473.7	1736.9	16.3984	5.1330E-05	***
interaction	2	181.3	90.6	0.8557	4.3930E-01	
residuals	21	2224.2	105.9			

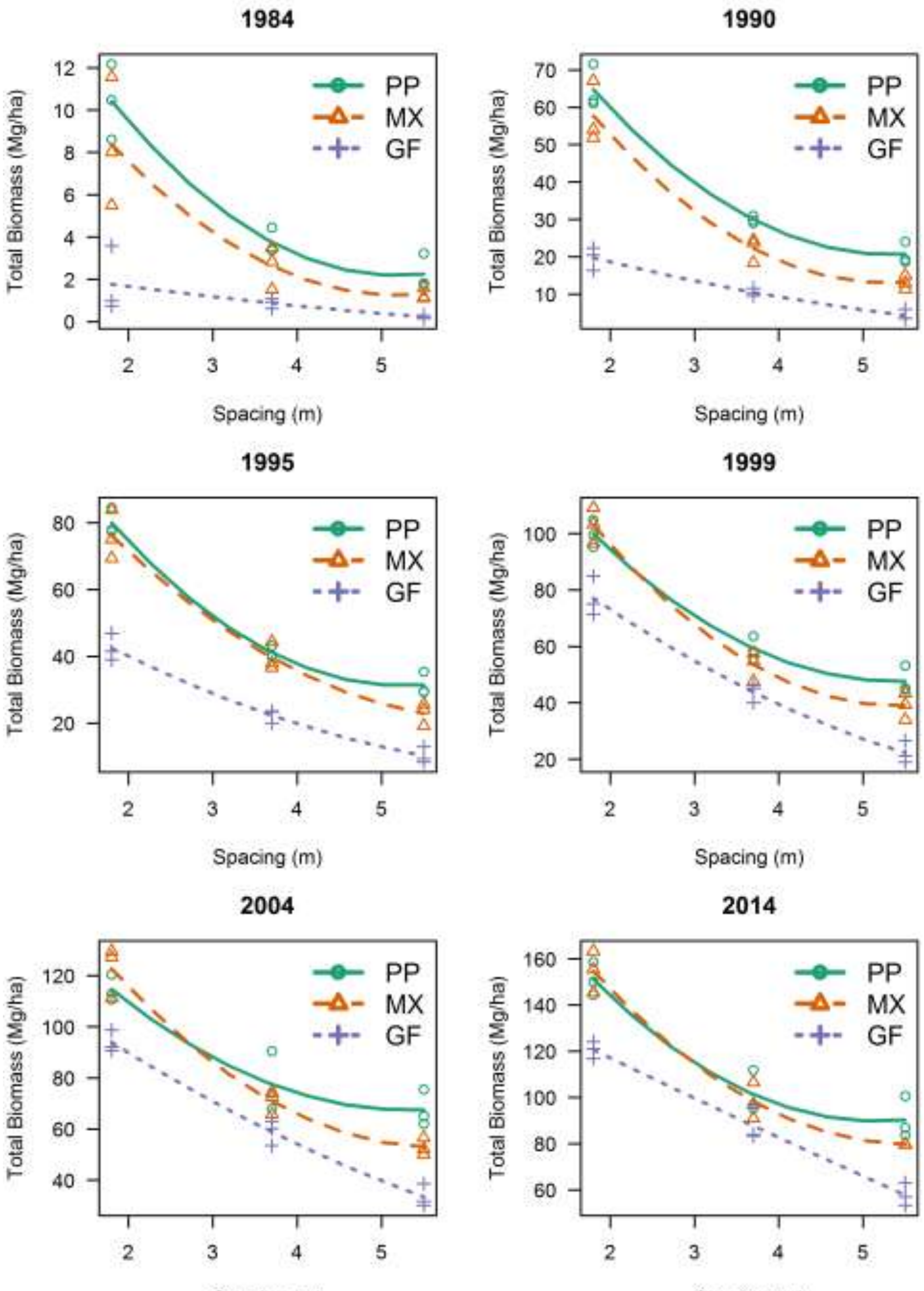


Figure 21 Trend in total biomass per hectare by spacing and species composition at the Lookout Mountain mixed-species spacing trials.

Table 21. Total foliage mass, total branch-wood mass and total biomass (Kg/ha) by plots in 1975.

YEAR 1975									
plot	**Spacing (feet)**	**Spacing (m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (kg/ha)**	**TWM (kg/ha)**	**TOTAL BIOMASS (Kg/ha)**
1A	18	5.5	PP	1975	726	0.0726	0.0291559	0.0035942	0.0327501
1B	18	5.5	MX	1975	726	0.0726	0.1745677	0.0381253	0.2126930
1C	18	5.5	GF	1975	726	0.0726	0.3976648	0.1012536	0.4989185
2A	18	5.5	PP	1975	726	0.0726	0.0345504	0.0041646	0.038715
2B	18	5.5	MX	1975	726	0.0726	0.2761076	0.0673137	0.34342134
2C	18	5.5	GF	1975	726	0.0726	0.3148492	0.0757278	0.39057707
3A	12	3.7	MX	1975	328.56	0.032856	0.4183109	0.0971034	0.51541441
3B	12	3.7	PP	1975	328.56	0.032856	0.0740833	0.0089827	0.08306608
3C	12	3.7	GF	1975	328.56	0.032856	0.8643304	0.2151203	1.07945082
4A	6	1.8	MX	1975	77.76	0.007776	2.1598909	0.5035331	2.66342413
4B	6	1.8	PP	1975	77.76	0.007776	0.4757028	0.0643766	0.54007948
4C	6	1.8	GF	1975	77.76	0.007776	3.0241752	0.7304930	3.75466834
5A	12	3.7	MX	1975	328.56	0.032856	0.5709961	0.1400341	0.71103034
5B	12	3.7	PP	1975	328.56	0.032856	0.0450428	0.0047722	0.0498151
5C	12	3.7	GF	1975	328.56	0.032856	0.7601656	0.1813628	0.94152846
6A	6	1.8	PP	1975	77.76	0.007776	0.3486039	0.0437312	0.39233513
6B	6	1.8	MX	1975	77.76	0.007776	2.1707087	0.5102437	2.68095242
6C	6	1.8	GF	1975	77.76	0.007776	3.6346505	0.8765003	4.51115098
7A	12	3.7	PP	1975	328.56	0.032856	0.0838395	0.0101204	0.09395998
7B	12	3.7	MX	1975	328.56	0.032856	0.9189390	0.2366513	1.15559039
7C	12	3.7	GF	1975	328.56	0.032856	0.8095006	0.1960526	1.00555332
8A	18	5.5	PP	1975	726	0.0726	0.0477583	0.0062092	0.05396752
8B	18	5.5	GF	1975	726	0.0726	0.3037971	0.0712643	0.37506153
8C	18	5.5	MX	1975	726	0.0726	0.2306831	0.0531298	0.28381299
9A	6	1.8	MX	1975	77.76	0.007776	1.2069901	0.2636899	1.47068004
9B	6	1.8	PP	1975	77.76	0.007776	0.3664722	0.0466963	0.4131686
9C	6	1.8	GF	1975	77.76	0.007776	3.1928022	0.7654157	3.95821798

Table 22. Total foliage mass, total branch-wood mass and total biomass (Kg/ha) by plots in 1979.

YEAR 1979									
plot	**Spacing (feet)**	**Spacing (m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (kg/ha)**	**TWM (kg/ha)**	**TOTAL BIOMASS (Kg/ha)**
1A	18	5.5	PP	1979	726	0.0726	4.58657468	1.88701661	6.473591295
1B	18	5.5	MX	1979	726	0.0726	6.51965683	2.48825877	9.007915606
1C	18	5.5	GF	1979	726	0.0726	10.0513313	3.65858438	13.70991566
2A	18	5.5	PP	1979	726	0.0726	4.83136697	1.88882141	6.720188375
2B	18	5.5	MX	1979	726	0.0726	8.37700895	3.18526959	11.56227854
2C	18	5.5	GF	1979	726	0.0726	21.5783285	8.51909076	30.09741924
3A	12	3.7	MX	1979	328.56	0.032856	16.628097	6.33818067	22.9662777
3B	12	3.7	PP	1979	328.56	0.032856	12.2339179	5.17765735	17.41157526
3C	12	3.7	GF	1979	328.56	0.032856	30.2383154	11.5790666	41.81738194
4A	6	1.8	MX	1979	77.76	0.007776	99.8518449	39.2335604	139.0854054
4B	6	1.8	PP	1979	77.76	0.007776	56.2138488	24.0369105	80.25075926
4C	6	1.8	GF	1979	77.76	0.007776	100.453186	36.9371719	137.3903579
5A	12	3.7	MX	1979	328.56	0.032856	27.3975035	11.0186575	38.41616098
5B	12	3.7	PP	1979	328.56	0.032856	10.6090955	4.43892893	15.04802444
5C	12	3.7	GF	1979	328.56	0.032856	26.4143501	9.97237844	36.38672851
6A	6	1.8	PP	1979	77.76	0.007776	73.5105751	33.0466286	106.5572037
6B	6	1.8	MX	1979	77.76	0.007776	124.664637	51.6622536	176.3268906
6C	6	1.8	GF	1979	77.76	0.007776	144.174836	55.2809676	199.4558036
7A	12	3.7	PP	1979	328.56	0.032856	13.1169891	5.38599729	18.50298636
7B	12	3.7	MX	1979	328.56	0.032856	41.1033787	17.3838333	58.48721195
7C	12	3.7	GF	1979	328.56	0.032856	40.5410909	15.7395888	56.28067963
8A	18	5.5	PP	1979	726	0.0726	9.13310247	4.308185	13.44128747
8B	18	5.5	GF	1979	726	0.0726	9.46731302	3.43847383	12.90578685
8C	18	5.5	MX	1979	726	0.0726	9.54133631	3.86154207	13.40287838
9A	6	1.8	MX	1979	77.76	0.007776	111.191975	45.1237639	156.3157386
9B	6	1.8	PP	1979	77.76	0.007776	67.9157078	29.599329	97.51503678
9C	6	1.8	GF	1979	77.76	0.007776	140.295504	54.7484754	195.0439789

Table 23. Total foliage mass, total branch-wood mass, stem wood mass and total biomass (Kg/ha) by plots in 1984.

YEAR 1984											
plot	**Spacing (feet)**	**Spacing (m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (kg/ha)**	**TWM (kg/ha)**	**STEM WOOD (Kg/ha)**	**TOTAL(Kg/ha)**	**TOTAL(Mg/ha)**
1A	18	5.5	PP	1984	726	0.0726	368.904931	483.116195	958.9331845	1810.95431	1.81095431
1B	18	5.5	MX	1984	726	0.0726	246.861724	298.525964	571.6380187	1117.02571	1.11702571
1C	18	5.5	GF	1984	726	0.0726	108.539772	37.5476586	33.54389323	179.631323	0.17963132
2A	18	5.5	PP	1984	726	0.0726	347.460314	448.477063	943.9724366	1739.90981	1.73990981
2B	18	5.5	MX	1984	726	0.0726	274.169543	299.997593	586.628718	1160.79585	1.16079585
2C	18	5.5	GF	1984	726	0.0726	168.666407	72.23978	75.13371324	316.0399	0.3160399
3A	12	3.7	MX	1984	328.56	0.032856	410.790501	376.358133	740.9865726	1528.13521	1.52813521
3B	12	3.7	PP	1984	328.56	0.032856	649.601432	836.77442	1937.535227	3423.91108	3.42391108
3C	12	3.7	GF	1984	328.56	0.032856	293.120784	157.903153	173.9749295	624.998867	0.62499887
4A	6	1.8	MX	1984	77.76	0.007776	1770.50959	1860.66445	4383.852848	8015.02689	8.01502689
4B	6	1.8	PP	1984	77.76	0.007776	1583.46194	1873.19868	5165.122214	8621.78284	8.62178284
4C	6	1.8	GF	1984	77.76	0.007776	508.422526	215.80605	23.2113495	747.439925	0.74743993
5A	12	3.7	MX	1984	328.56	0.032856	636.07424	697.530272	1505.40377	2839.00828	2.83900828
5B	12	3.7	PP	1984	328.56	0.032856	649.888162	824.307978	1906.690349	3380.88649	3.38088649
5C	12	3.7	GF	1984	328.56	0.032856	443.41797	248.039237	238.1946865	929.651893	0.92965189
6A	6	1.8	PP	1984	77.76	0.007776	1864.79627	2254.54165	6357.915399	10477.2533	10.4772533
6B	6	1.8	MX	1984	77.76	0.007776	1339.54638	1326.86851	2845.368437	5511.78332	5.51178332
6C	6	1.8	GF	1984	77.76	0.007776	594.980574	270.854477	119.4679808	985.303032	0.98530303
7A	12	3.7	PP	1984	328.56	0.032856	846.617537	1108.43418	2497.244347	4452.29606	4.45229606
7B	12	3.7	MX	1984	328.56	0.032856	818.770376	918.055756	1778.327974	3515.1541	3.5151541
7C	12	3.7	GF	1984	328.56	0.032856	504.261723	282.717881	306.0182835	1092.99789	1.09299789
8A	18	5.5	PP	1984	726	0.0726	622.062944	876.838051	1727.282172	3226.18317	3.22618317
8B	18	5.5	GF	1984	726	0.0726	80.293279	38.5363619	31.34242868	150.17207	0.15017207
8C	18	5.5	MX	1984	726	0.0726	347.741237	436.523506	818.4530571	1602.7178	1.6027178
9A	6	1.8	MX	1984	77.76	0.007776	2321.28286	2759.96701	6485.240244	11566.4901	11.5664901
9B	6	1.8	PP	1984	77.76	0.007776	2270.0747	2802.86968	7089.73839	12162.6828	12.1626828
9C	6	1.8	GF	1984	77.76	0.007776	1649.60204	898.650832	1035.284504	3583.53738	3.58353738

Table 24. Total foliage mass, total branch-wood mass, stem wood mass and total biomass (Kg/ha) by plots in 1990.

YEAR 1990										
plot	**Spacing(feet)**	**Spacing(m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (Mg/ha)**	**TWM (Mg/ha)**	**STEM WOOD (Mg/ha)**	**TOTAL(Mg/ha)**
1A	18	5.5	PP	1990	726	0.0726	2.0647	3.7429	13.5152	19.3228
1B	18	5.5	MX	1990	726	0.0726	1.4750	2.2342	7.6496	11.3588
1C	18	5.5	GF	1990	726	0.0726	0.7426	0.4809	2.3313	3.5548
2A	18	5.5	PP	1990	726	0.0726	2.0515	3.7040	12.9245	18.6800
2B	18	5.5	MX	1990	726	0.0726	1.8268	2.9471	8.1738	12.9478
2C	18	5.5	GF	1990	726	0.0726	1.4061	0.9852	3.5692	5.9605
3A	12	3.7	MX	1990	328.56	0.032856	2.4328	3.0804	12.8355	18.3487
3B	12	3.7	PP	1990	328.56	0.032856	3.1286	5.3243	22.4967	30.9496
3C	12	3.7	GF	1990	328.56	0.032856	2.2081	1.5242	5.8752	9.6075
4A	6	1.8	MX	1990	77.76	0.007776	6.3822	8.3227	37.1537	51.8587
4B	6	1.8	PP	1990	77.76	0.007776	5.8437	8.9177	47.0315	61.7928
4C	6	1.8	GF	1990	77.76	0.007776	3.0986	1.8811	11.3666	16.3463
5A	12	3.7	MX	1990	328.56	0.032856	3.4153	4.8043	15.5236	23.7432
5B	12	3.7	PP	1990	328.56	0.032856	3.2057	5.4393	21.0548	29.6998
5C	12	3.7	GF	1990	328.56	0.032856	2.3743	1.6114	6.2551	10.2408
6A	6	1.8	PP	1990	77.76	0.007776	6.0781	9.0276	45.9511	61.0568
6B	6	1.8	MX	1990	77.76	0.007776	6.5165	8.4086	39.1265	54.0516
6C	6	1.8	GF	1990	77.76	0.007776	4.3562	2.6299	13.5031	20.4892
7A	12	3.7	PP	1990	328.56	0.032856	3.2746	5.5186	20.2538	29.0470
7B	12	3.7	MX	1990	328.56	0.032856	3.4778	4.9929	15.9790	24.4497
7C	12	3.7	GF	1990	328.56	0.032856	2.6273	1.7994	7.1466	11.5733
8A	18	5.5	PP	1990	726	0.0726	2.9448	5.5209	15.5197	23.9854
8B	18	5.5	GF	1990	726	0.0726	0.7822	0.5414	2.1381	3.4617
8C	18	5.5	MX	1990	726	0.0726	2.0020	3.2081	9.8157	15.0257
9A	6	1.8	MX	1990	77.76	0.007776	8.2550	11.9817	46.8919	67.1286
9B	6	1.8	PP	1990	77.76	0.007776	7.2426	11.0443	53.2295	71.5164
9C	6	1.8	GF	1990	77.76	0.007776	4.8399	2.9927	14.5071	22.3396

Table 25. Total foliage mass, total branch-wood mass, stem wood mass and total biomass (Kg/ha) by plots in 1995.

YEAR 1995										
plot	**Spacing(feet)**	**Spacing(m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (Mg/ha)**	**TWM (Mg/ha)**	**STEM WOOD (Mg/ha)**	**TOTAL(Mg/ha)**
1A	18	5.5	PP	1995	726	0.0726	4.18192176	7.72432023	17.62538912	29.5316311
1B	18	5.5	MX	1995	726	0.0726	3.29315718	4.770018	11.20444085	19.267616
1C	18	5.5	GF	1995	726	0.0726	2.41897319	1.69280382	5.186866045	9.29864305
2A	18	5.5	PP	1995	726	0.0726	4.15129537	7.66539657	17.49269171	29.3093837
2B	18	5.5	MX	1995	726	0.0726	4.21076685	6.92499062	14.52160178	25.6573593
2C	18	5.5	GF	1995	726	0.0726	3.46941385	2.51917076	6.935030889	12.9236155
3A	12	3.7	MX	1995	328.56	0.032856	5.11326268	6.50193136	32.77513375	44.3903278
3B	12	3.7	PP	1995	328.56	0.032856	5.79947881	9.92502432	27.41085142	43.1353546
3C	12	3.7	GF	1995	328.56	0.032856	5.28199057	3.63681001	11.09309099	20.0118916
4A	6	1.8	MX	1995	77.76	0.007776	10.1807048	12.4378893	46.75534662	69.3739407
4B	6	1.8	PP	1995	77.76	0.007776	8.93890889	13.4596214	55.46016636	77.8586966
4C	6	1.8	GF	1995	77.76	0.007776	9.2824346	5.82993348	23.87290192	38.98527
5A	12	3.7	MX	1995	328.56	0.032856	6.44584541	8.83421864	22.63641276	37.9164768
5B	12	3.7	PP	1995	328.56	0.032856	5.3310171	8.96194884	26.06857454	40.3615405
5C	12	3.7	GF	1995	328.56	0.032856	6.23669334	4.35880922	12.83926787	23.4347704
6A	6	1.8	PP	1995	77.76	0.007776	8.85672357	12.87574	55.72833371	77.4607973
6B	6	1.8	MX	1995	77.76	0.007776	11.1685551	13.7231392	50.26856627	75.1602606
6C	6	1.8	GF	1995	77.76	0.007776	11.5946368	7.23685561	28.10438898	46.9358814
7A	12	3.7	PP	1995	328.56	0.032856	5.31348002	8.92530685	25.59452741	39.8333143
7B	12	3.7	MX	1995	328.56	0.032856	6.21134254	8.5231038	21.89771303	36.6321594
7C	12	3.7	GF	1995	328.56	0.032856	6.27383416	4.41004778	12.88544065	23.5693226
8A	18	5.5	PP	1995	726	0.0726	5.25675139	9.8734623	20.28952423	35.4197379
8B	18	5.5	GF	1995	726	0.0726	2.18543708	1.54081096	4.657086841	8.38333488
8C	18	5.5	MX	1995	726	0.0726	4.06415353	6.33840362	13.60495521	24.0075124
9A	6	1.8	MX	1995	77.76	0.007776	11.9380119	16.0381876	55.90645246	83.8826519
9B	6	1.8	PP	1995	77.76	0.007776	9.84398858	14.4799122	60.20796208	84.5318629
9C	6	1.8	GF	1995	77.76	0.007776	10.1266267	6.40681879	24.95067784	41.4841234

Table 26. Total foliage mass, total branch-wood mass, stem wood mass and total biomass (Kg/ha) by plots in 1999.

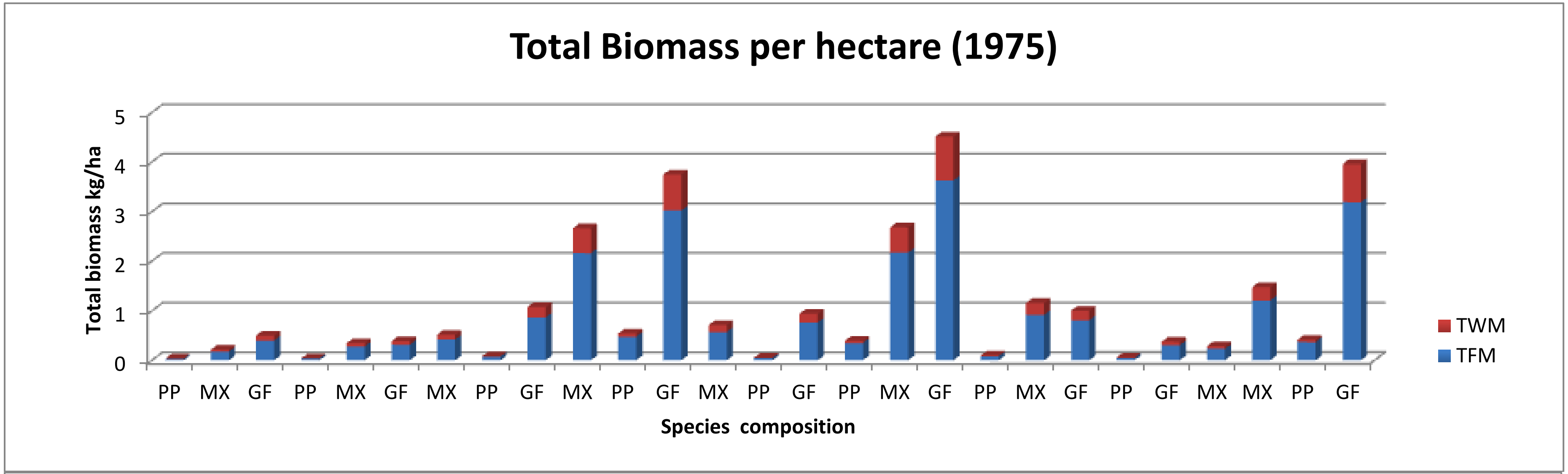
YEAR 1999										
plot	**Spacing(feet)**	**Spacing (m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (Mg/ha)**	**TWM (Mg/ha)**	**STEM WOOD (Mg/ha)**	**TOTAL(Mg/ha)**
1A	18	5.5	PP	1999	726	0.0726	6.49127002	12.7457085	25.84615957	45.0831381
1B	18	5.5	MX	1999	726	0.0726	6.53216194	9.53268931	17.99589492	34.0607462
1C	18	5.5	GF	1999	726	0.0726	5.96796151	4.69754163	10.45534252	21.1208457
2A	18	5.5	PP	1999	726	0.0726	6.73309252	12.8033047	25.01527557	44.5516728
2B	18	5.5	MX	1999	726	0.0726	8.72194869	12.6234378	22.03912868	43.3845151
2C	18	5.5	GF	1999	726	0.0726	7.61884916	6.18345576	12.76073523	26.5630402
3A	12	3.7	MX	1999	328.56	0.032856	8.9764529	11.4740711	27.24519142	47.6957154
3B	12	3.7	PP	1999	328.56	0.032856	9.04371059	16.2247736	38.26869758	63.5371817
3C	12	3.7	GF	1999	328.56	0.032856	11.2870195	8.78704536	19.98141081	40.0554757
4A	6	1.8	MX	1999	77.76	0.007776	14.4810121	17.9240728	64.18571372	96.5907986
4B	6	1.8	PP	1999	77.76	0.007776	11.0237784	17.4136606	66.77842906	95.2158681
4C	6	1.8	GF	1999	77.76	0.007776	19.4069657	13.5187051	42.12304076	75.0487116
5A	12	3.7	MX	1999	328.56	0.032856	10.6985464	15.3436329	31.6750789	57.7172582
5B	12	3.7	PP	1999	328.56	0.032856	7.77354491	13.4771661	34.44750577	55.6982168
5C	12	3.7	GF	1999	328.56	0.032856	13.0391822	10.2702383	22.83107641	46.1404969
6A	6	1.8	PP	1999	77.76	0.007776	12.093421	18.4054492	68.94916569	99.4480358
6B	6	1.8	MX	1999	77.76	0.007776	16.2476012	20.5832696	66.5433055	103.374176
6C	6	1.8	GF	1999	77.76	0.007776	22.3392304	15.5812861	46.93447235	84.8549888
7A	12	3.7	PP	1999	328.56	0.032856	8.15387463	14.5577494	35.69857256	58.4101966
7B	12	3.7	MX	1999	328.56	0.032856	10.1836208	14.0202727	30.59138322	54.7952767
7C	12	3.7	GF	1999	328.56	0.032856	12.7852955	10.0308369	22.31083881	45.1269712
8A	18	5.5	PP	1999	726	0.0726	8.62051149	16.8648058	27.73000868	53.2153259
8B	18	5.5	GF	1999	726	0.0726	5.39117863	4.30502265	9.337791439	19.0339927
8C	18	5.5	MX	1999	726	0.0726	7.511546	11.3525726	20.505724	39.3698426
9A	6	1.8	MX	1999	77.76	0.007776	15.9851336	22.6536892	70.50494808	109.143771
9B	6	1.8	PP	1999	77.76	0.007776	11.9906814	18.7987774	74.09139971	104.880858
9C	6	1.8	GF	1999	77.76	0.007776	18.6252485	12.95962	39.85495485	71.4398233

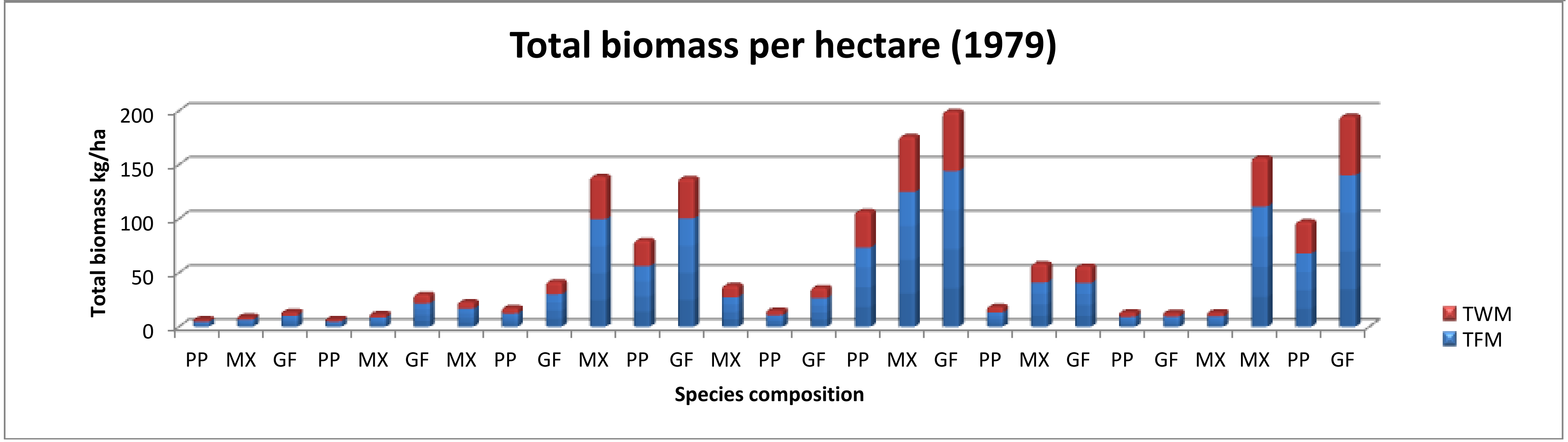
Table 27. Total foliage mass, total branch-wood mass, stem wood mass and total biomass (Kg/ha) by plots in 2004.

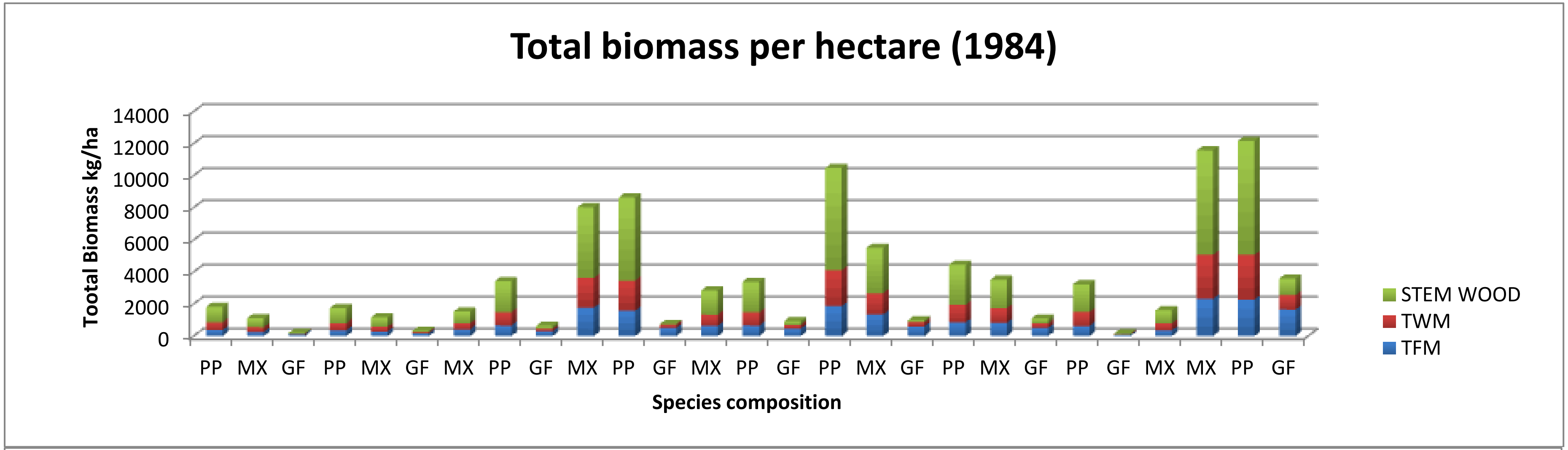
YEAR 2004										
plot	**Spacing(feet)**	**Spacing (m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (Mg/ha)**	**TWM (Mg/ha)**	**STEM WOOD (Mg/ha)**	**TOTAL(Mg/ha)**
1A	18	5.5	PP	2004	726	0.0726	12.2868989	22.6066258	30.09251168	64.9860363
1B	18	5.5	MX	2004	726	0.0726	10.9766245	16.2377609	23.02966891	50.2440543
1C	18	5.5	GF	2004	726	0.0726	9.08593526	7.43023833	15.20581915	31.72199274
2A	18	5.5	PP	2004	726	0.0726	11.7221734	21.3579116	28.89520241	61.97528745
2B	18	5.5	MX	2004	726	0.0726	11.7991999	19.2489627	25.64320041	56.69136306
2C	18	5.5	GF	2004	726	0.0726	11.069906	9.28579559	18.26598225	38.62168386
3A	12	3.7	MX	2004	328.56	0.032856	14.1696892	18.5214118	33.08927588	65.78037682
3B	12	3.7	PP	2004	328.56	0.032856	17.0386455	28.5048487	44.80287889	90.3463731
3C	12	3.7	GF	2004	328.56	0.032856	14.964893	11.8517388	26.70135335	53.51798511
4A	6	1.8	MX	2004	77.76	0.007776	17.7568164	22.828014	70.69340665	111.278237
4B	6	1.8	PP	2004	77.76	0.007776	13.8167775	23.0942222	73.75380178	110.6648015
4C	6	1.8	GF	2004	77.76	0.007776	24.4761028	17.3299087	48.8378273	90.6438388
5A	12	3.7	MX	2004	328.56	0.032856	14.3814447	21.688426	38.20529724	74.27516791
5B	12	3.7	PP	2004	328.56	0.032856	9.96691676	18.2759216	39.65470323	67.89754163
5C	12	3.7	GF	2004	328.56	0.032856	17.3244509	13.8383387	31.6310117	62.79380135
6A	6	1.8	PP	2004	77.76	0.007776	14.1799199	23.0146103	75.7485577	112.9430879
6B	6	1.8	MX	2004	77.76	0.007776	20.9613284	27.6144061	78.60617234	127.1819068
6C	6	1.8	GF	2004	77.76	0.007776	25.2319745	17.4625545	55.99772893	98.69225799
7A	12	3.7	PP	2004	328.56	0.032856	13.9677162	22.2455882	37.86053555	74.07383992
7B	12	3.7	MX	2004	328.56	0.032856	15.5195179	21.0909808	35.94387025	72.5543689
7C	12	3.7	GF	2004	328.56	0.032856	16.9670417	13.5780903	29.65558637	60.20071831
8A	18	5.5	PP	2004	726	0.0726	14.6082328	27.5744975	33.32287559	75.50560588
8B	18	5.5	GF	2004	726	0.0726	8.64208821	7.19997927	14.33389814	30.17596562
8C	18	5.5	MX	2004	726	0.0726	11.7807435	17.2367911	23.22896577	52.24650037
9A	6	1.8	MX	2004	77.76	0.007776	19.9116648	29.5111825	80.14197363	129.5648209
9B	6	1.8	PP	2004	77.76	0.007776	14.1708156	23.6554658	82.51059848	120.3368799
9C	6	1.8	GF	2004	77.76	0.007776	23.9606409	16.9019786	51.31811359	92.1807331

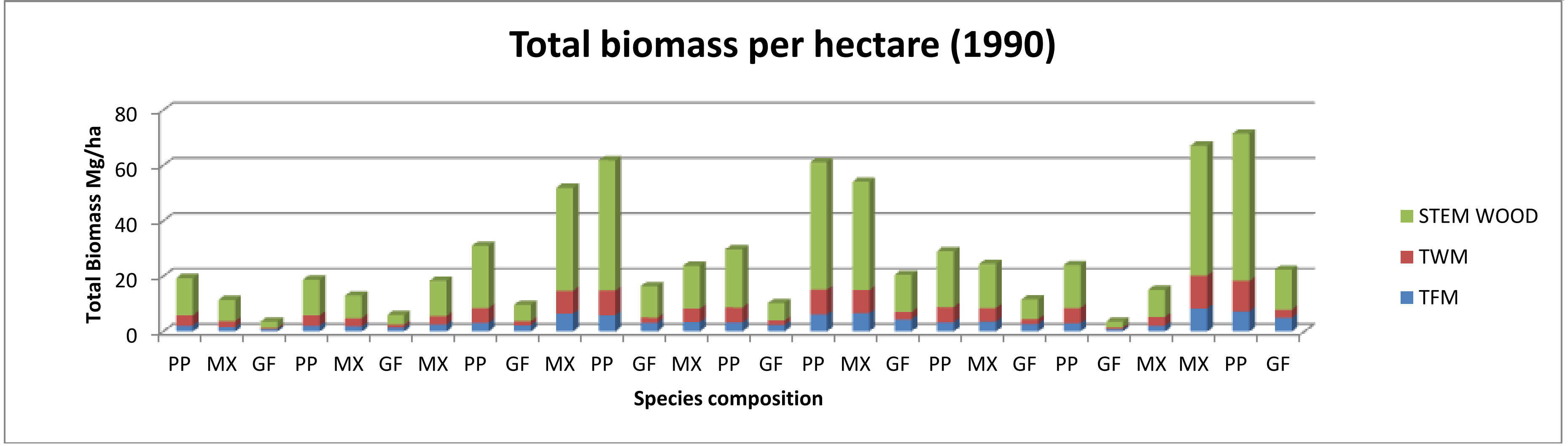
Table 28. Total foliage mass, total branch-wood mass, stem wood mass and total biomass (Kg/ha) by plots in 2014.

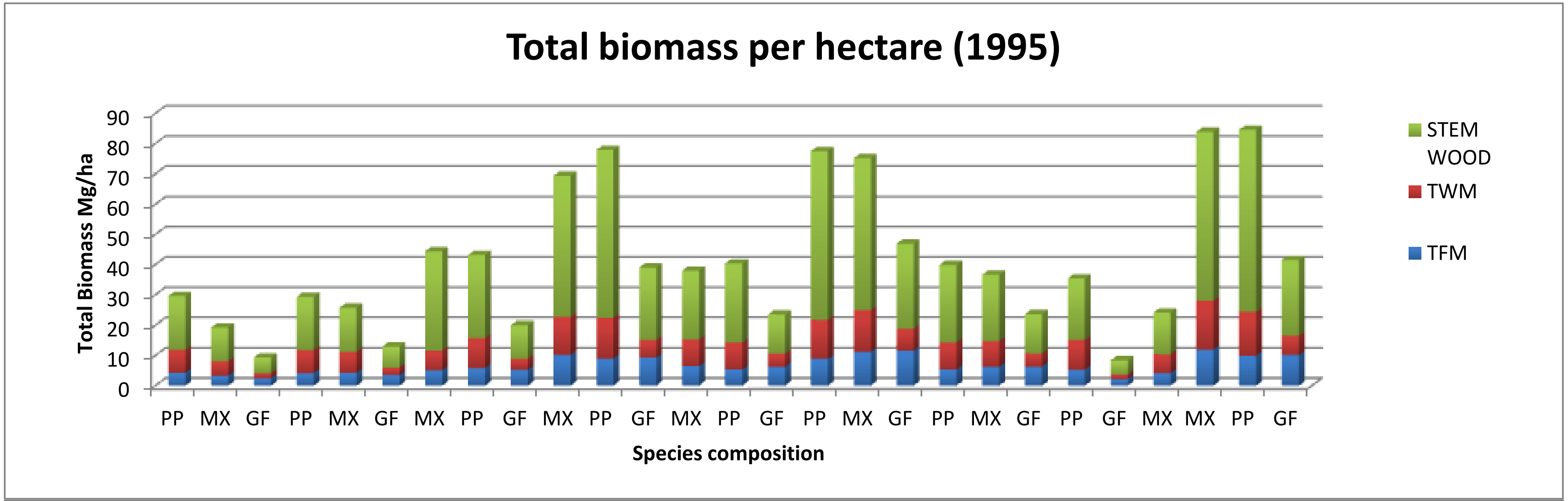
YEAR 2014										
plot	**Spacing(feet)**	**Spacing (m)**	**sp**	**year**	**Plot area (m2)**	**Plot area (ha)**	**TFM (Mg/ha)**	**TWM (Mg/ha)**	**STEM WOOD (Mg/ha)**	**TOTAL(Mg/ha)**
1A	18	5.5	PP	2014	726	0.0726	15.8195203	32.8704826	38.13954212	86.829545
1B	18	5.5	MX	2014	726	0.0726	17.5010313	27.5551938	34.72264607	79.7788711
1C	18	5.5	GF	2014	726	0.0726	15.8030463	13.649161	27.45289767	56.905105
2A	18	5.5	PP	2014	726	0.0726	15.2128021	31.7000703	36.76509195	83.6779644
2B	18	5.5	MX	2014	726	0.0726	16.5061488	28.57637	34.54113254	79.6236513
2C	18	5.5	GF	2014	726	0.0726	17.6093021	15.5765385	29.81663771	63.0024782
3A	12	3.7	MX	2014	328.56	0.032856	18.4761802	26.0973331	46.39857459	90.9720879
3B	12	3.7	PP	2014	328.56	0.032856	19.1252782	37.2250088	55.31670961	111.666997
3C	12	3.7	GF	2014	328.56	0.032856	22.1802481	18.1404658	42.94828966	83.2690035
4A	6	1.8	MX	2014	77.76	0.007776	26.8847927	36.378783	92.16977211	155.433348
4B	6	1.8	PP	2014	77.76	0.007776	19.6108881	32.3334021	92.54411377	144.488404
4C	6	1.8	GF	2014	77.76	0.007776	29.9632148	21.1528823	69.90998634	121.026083
5A	12	3.7	MX	2014	328.56	0.032856	21.0919652	33.9260158	51.53257744	106.550558
5B	12	3.7	PP	2014	328.56	0.032856	16.248531	30.5099542	50.16714618	96.9256313
5C	12	3.7	GF	2014	328.56	0.032856	25.0500328	20.5111445	50.16310943	95.7242867
6A	6	1.8	PP	2014	77.76	0.007776	22.0523366	36.1928335	91.89290462	150.138075
6B	6	1.8	MX	2014	77.76	0.007776	24.8712955	34.5295034	86.16875393	145.569553
6C	6	1.8	GF	2014	77.76	0.007776	29.1372909	20.1092237	74.87407196	124.120587
7A	12	3.7	PP	2014	328.56	0.032856	16.4783484	30.6532053	48.16094056	95.2924943
7B	12	3.7	MX	2014	328.56	0.032856	19.7511756	29.0030886	48.29015541	97.0444196
7C	12	3.7	GF	2014	328.56	0.032856	22.2842854	18.0029083	43.69665522	83.983849
8A	18	5.5	PP	2014	726	0.0726	18.6637018	40.0117791	41.91230145	100.587782
8B	18	5.5	GF	2014	726	0.0726	14.8688679	12.9997605	25.43807844	53.3067068
8C	18	5.5	MX	2014	726	0.0726	17.9458786	28.0842606	33.83606555	79.8662047
9A	6	1.8	MX	2014	77.76	0.007776	28.0659834	41.4206301	93.8450548	163.331668
9B	6	1.8	PP	2014	77.76	0.007776	22.748965	37.7099295	98.10849181	158.567386
9C	6	1.8	GF	2014	77.76	0.007776	28.7895465	20.3256848	67.73091857	116.84615

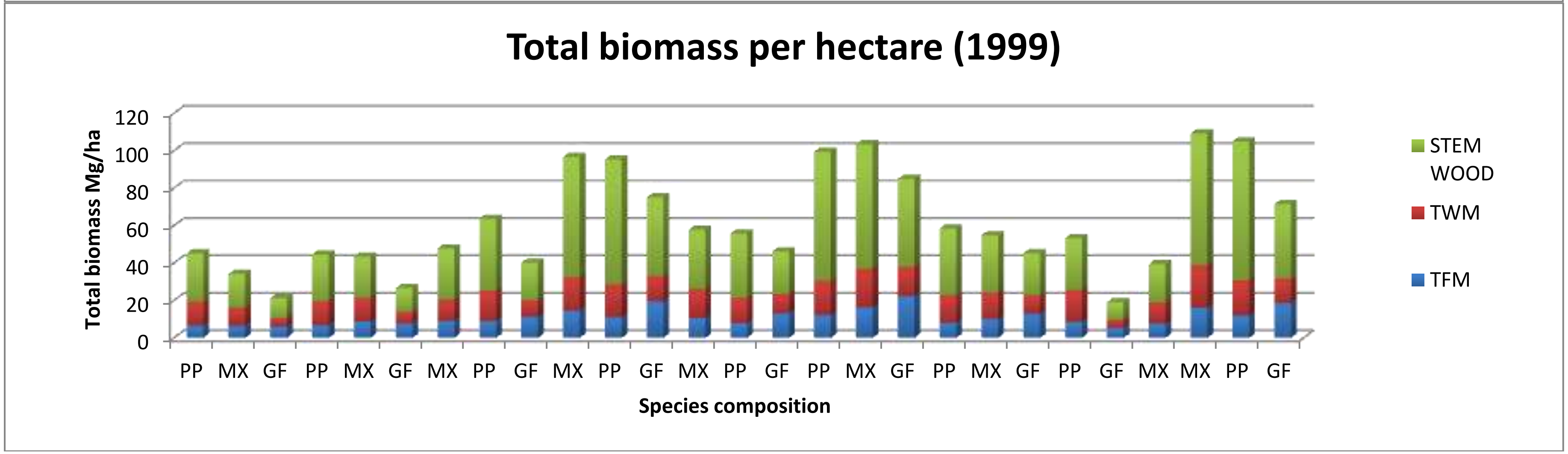

Total Biomass per hectare (1975)
Total biomass kg/ha
0
1
2
3
4
5
PP MX GF PP MX GF MX PP GF MX PP GF MX PP GF PP MX GF PP MX GF PP GF MX MX PP GF
Species composition
TWM
TFM


Total biomass per hectare (1979)
Total biomass kg/ha
0
50
100
150
200
PP MX GF PP MX GF MX PP GF MX PP GF MX PP GF PP MX GF PP MX GF PP GF MX MX PP GF
Species composition
TWM
TFM


Total biomass per hectare (1984)
Tootal Biomass kg/ha
14000
12000
10000
8000
6000
4000
2000
0
PP MX GF PP MX GF MX PP GF MX PP GF MX PP GF PP MX GF PP MX GF PP GF MX MX PP GF
Species composition
STEM WOOD
TWM
TFM


Total biomass per hectare (1990)
Total Biomass Mg/ha
80
60
40
20
0
PP MX GF PP MX GF MX PP GF MX PP GF MX PP GF PP MX GF PP MX GF PP GF MX MX PP GF
Species composition
STEM WOOD
TWM
TFM


Total biomass per hectare (1995)


Total biomass per hectare (1999)

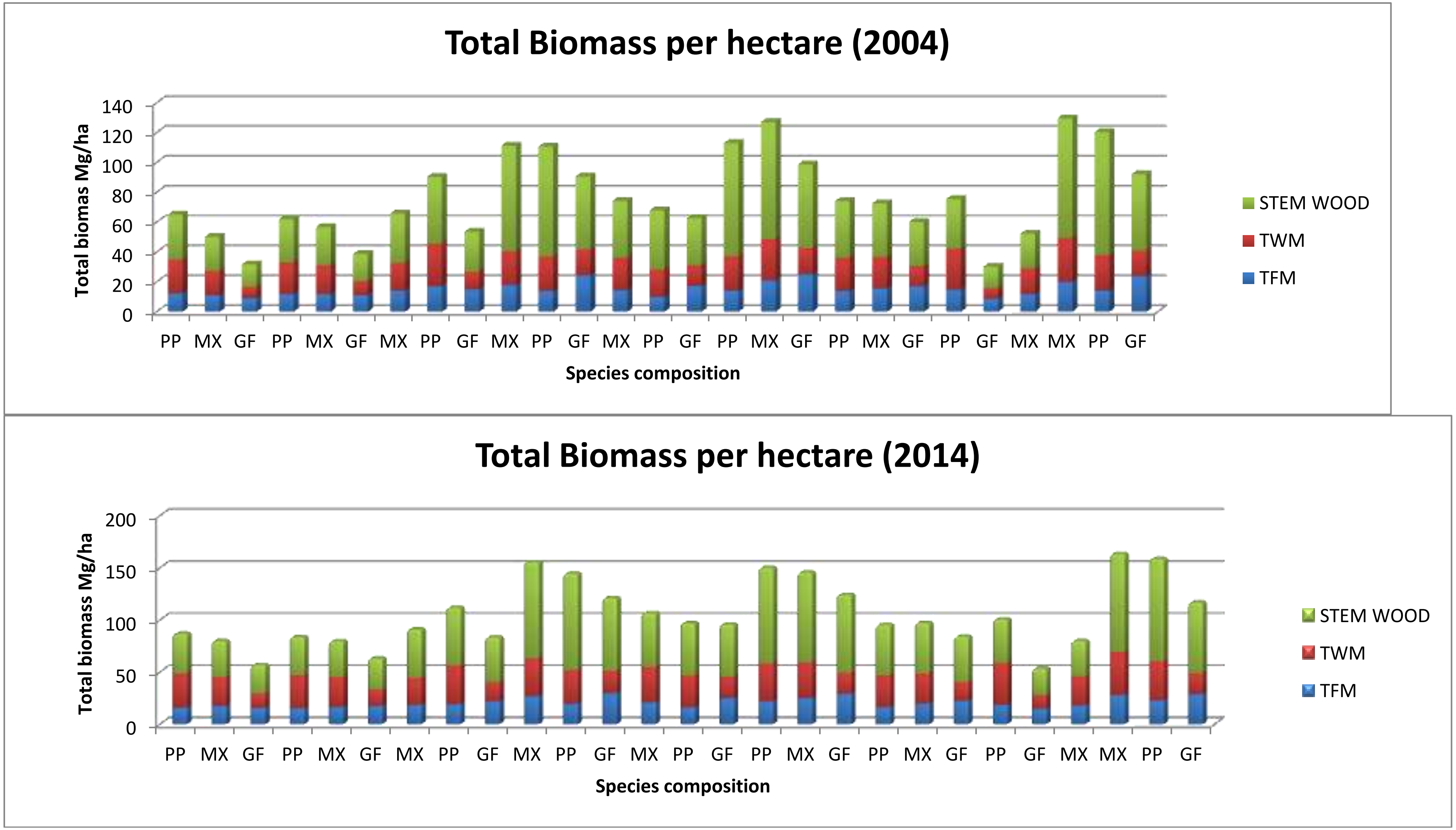


Figure 22 Total biomass components (foliage, branch-wood mass and stem wood mass) by years and plots.