EFFECTS OF FERTILIZATION AND DENSITY CONTROL ON GROWTH AND YIELD OF YOUNG DOUGLAS-FIR PLANTATIONS: RESULTS FROM SMC TYPE I INSTALLATIONS

YUZHEN LI
ERIC C. TURNBLOM
DAVID G. BRIGGS

STAND MANAGEMENT COOPERATIVE
SMC WORKING PAPER NUMBER 4
AUGUST 2005

COLLEGE OF FOREST RESOURCES
UNIVERSITY OF WASHINGTON
BOX 352100
SEATTLE WASHINGTON 98115-2100
HTTP://WWW.STANDMGT.ORG

EFFECTS OF FERTILIZATION AND DENSITY CONTROL ON GROWTH AND YIELD OF YOUNG DOUGLAS-FIR PLANTATIONS:

RESULTS FROM SMC TYPE I INSTALLATIONS

YUZHEN LI, MS.

ERIC C. TURNBLOM, ASSOCIATE PROFESSOR, AND SILVICULTURE PROJECT LEADER

DAVID G. BRIGGS, PROFESSOR, AND SMC DIRECTOR

STAND MANAGEMENT COOPERATIVE

SMC WORKING PAPER NUMBER 4

AUGUST 2005

COLLEGE OF FOREST RESOURCES

UNIVERSITY OF WASHINGTON
BOX 352100

SEATTLE WASHINGTON 98115-2100

HTTP://WWW.STANDMGT.ORG

TABLE OF CONTENTS

ACKNOWLEDGMENTS

This project is part of Yuzhen Li's Master of Science thesis recently finished at the University of Washington. It was supported by the USFS Focused Science Delivery Program and the Stand Management Cooperative. The authors wish to thank SMC members for contributing their data and support. Randy Collier, SMC database manager, provided assistance in database searching and analyses.

ABSTRACT

The objective of this study was to assess fertilization and density (early spacing and subsequent thinning) effects on young Douglas-fir (*Pseudotsuga menziesii* (Mirb.) *Franco*) plantations in the Pacific Northwest. Seven different treatment regimes were studied in sixty-three plots from nine locations across western Washington and Oregon. For fertilization treatment, 200lb N/acre urea was applied at stand establishment and every fourth year thereafter. For density control, four different regimes were used: initial density with no further thinning, initial density with repeated thinning later; spacing to half initial density with minimal thinning later and spacing to one-fourth initial density with no further thinning. Plots were established when mean stand age was 9 years. Measurements at establishment and after three, 4-year growth periods, corresponding to mean stand age of 13, 17, and 21 years, formed the basis of growth and yield analyses conducted at the whole stand and crop tree (the 40 largest diameter trees per acre) levels.

Results showed that density control significantly affects diameter, basal area and volume growth and yield, but not height. Initially, the densest stands had the greatest overall yield and growth. However, accumulation in the dense stands was declining with time and the less dense stands caught or exceeded them by the end of twelve years. Density also affected diameter class distribution with less dense stands having a greater proportion of trees in larger diameter classes. Across all densities, fertilization produced additional growth and yield in terms of diameter, basal area and volume, but not in height. Quadratic Mean Diameter (QMD), basal area and volume growth were significantly increased by the first and second urea applications, but not by the third. In contrast, the first fertilization was insufficient to produce a significant yield increase in QMD, basal area per acre or volume per acre. Significant increases in these variables were found following the second and the third urea applications. This study found no statistically significant interaction between fertilization and density control treatments on all variables tested, but fertilization gains in different density stands did show a little difference. Fertilization gains in basal area and volume growth had a decreasing trend in the dense stands, whereas in the less dense stands, they increased first then slightly decreased. Mortality increased quickly in the dense stands whereas it remained stable in the less dense stands. Also, mortality in fertilized plots was less than in unfertilized plots and relatively more stable. Both fertilization and spacing produced larger crop tree growth and yield. Compared to the whole stand, crop tree responses were smaller in magnitude and expressed later in time.

.

CHAPTER 1. INTRODUCTION

For decades, the timber industry in the Pacific Northwest depended on the large volume of natural old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) *Franco*) present when settlement began. However, as the supply of old-growth Douglas-fir was harvested and public demand for wildlife habitat protection and other non-wood resources increased, this harvest of commercial timber from natural old-growth stands was significantly reduced. At the same time, the demand for forest products continues to grow as population growth increases. These changes have caused the timber industry in the Pacific Northwest to change from old-growth Douglas-fir forests to actively managed second-growth forests and intensively managed plantations.

Density control and fertilization are two commonly used silvicultural management practices. They both provide increased levels of nutrients, moisture and sunlight to a residual stand. By mitigating factors that may constrain tree growth, both allow the residual stand to develop larger trees sooner. The effects of fertilization and density on Douglas-fir forests have been studied in the past few decades across the Pacific Northwest. General results from previous research are summarized below (for a complete literature review, see Li, 2005):

Density: Douglas-fir diameter growth is very sensitive to stand density with diameter growth increasing with increased spacing up to the point at which trees grow without competition (Sjolte-Jorgensen 1967, King 1986, Curtis and Marshall 2002). Besides the mean diameter, spacing also affects diameter distribution by increasing the proportion of larger trees (King 1986, Curtis and Marshall 2002). For height growth, density effects reported in the literature are mixed. Both decreased (Crown et al 1977, Miller and Reukema 1977) and increased (Curtis and Reukema 1970, Smith and Reukema 1986) height growth following thinning have been previously reported. Others found that height growth is insensitive to density change (Hagglund 1981, Miller et al 2001). As for density effects on basal area and volume, the most common results are: immediately after a thinning, basal area and volume growth will be reduced, but the differences between the thinned and unthinned stands will decrease and the thinned stands may eventually exceed unthinned stands (Staebler 1956, Harringtion and Reukema 1983, Curtis and Marshall 2002). In general, past studies demonstrated that commercial thinning in previously unthinned natural stands resulted in moderate increases in diameter increment and some reduction in basal area and gross volume increment, accompanied by a reduction in mortality which may result in modest gains in net volume growth (Reukema 1972, Reukema and Bruce 1977).

Fertilization: Forest growth in the Pacific Northwest is limited by the supply of plant available nitrogen (Gessel et al 1965, Chappell et al 1992). Since the 1960s, several comprehensive forest nutrition research projects were carried out at the region level: Regional Forest Nutrition Research Project (RFNRP) in western Washington and Oregon, the British Columbia Ministry of Forests Experimental Project 703 (EP703) and the Shawnigan Lake Ecosystem study. Results from these studies found that 1) coastal Douglas-fir stands responded positively to nitrogen fertilization; 2) the largest and most long-lasting responses occur when nutrient deficiencies were severe and when fertilization was combined with thinning (Chappell et al 1992, Brix 1993); and 3) mortality was accelerated by fertilization in unthinned stands, but not in thinned stands (Miller et al 1986); 4) fertilization response lasted about 6 to 8 years, and refertilization could be applied after 7-10 years (Chappell et al 1992). However, these generally positive responses found in RFNRP and BC trials are not always the case. According to Peterson and others (1986), about 30% of unthinned and 20% thinned coast Douglas-fir stands did not respond to N fertilization. Fertilizer trials in the Oregon coast range indicated small and statistically nonsignificant response to nitrogen fertilizers (Miller et al 1991, Miller et al 1999).

Interaction between fertilization and density: By increasing tree growth, fertilization can also increase competition in high density stands and thus accelerate mortality losses in smaller than average trees. However, results on interaction effects were not consistent in the literature. Both significant (Lee and Barclay 1985, Stegemoeller and Chappell 1991, Brix 1993) and insignificant (Heilman 1975, McWilliams and Therien 1996, Miller et al 2001) interactions have been reported.

Although previous studies generated a large amount of valuable information; they raised many new questions and, as operational forest management changed over time, the relevance of earlier studies was questioned. For example, most past studies were initiated in the 1960s or 1970s, when 365 stems per acre was considered to be low stocking, but now a stocking with one half this number is common in coastal Douglas-fir where no commercial thinning is planned (Brix 1993). Wide spacing as practiced today was not fully represented in the early studies. Also fertilization regimes began shifting from single to repeated applications, so more information is needed to understand the effect of combining fertilization with thinning; the effect of fertilization on long-term site productivity and wood quality. Furthermore, most previous studies were conducted in second-growth stands that originated from natural seeding or planting and which received little subsequent management. Research with more intensively managed young Douglas-fir plantations was fragmentary and limited in scope. Since the 1960's, Douglas-fir plantations have expanded remarkably across the region and will rapidly replace second-growth stands as the main commercial timber resource of the Pacific Northwest. Unlike old- and second-growth stands, intensively managed plantations require large investments for establishment and subsequent culture. Because most of them are still young, little is known about their response, especially long-term response to silvicultural treatment. Since plantations will be intensively managed to maturity, research results from unmanaged second-growth stands may not apply to young plantations.

CHAPTER 2. OBJECTIVES

The general objective of this study is to assess fertilization and density effects on growth and yield of young Douglas-fir plantations in the Pacific Northwest. In detail, this study attempts to answer the following five research questions.

1. Do different density control regimes significantly affect stand growth and yield in terms of diameter, basal area, height and cubic foot volume?

2. Do repeated urea applications produce significant increases in stand growth and yield in terms of diameter, basal area, height and cubic foot volume?

3. Do significant interactions exist between fertilization and density treatments?

4. Do density and fertilization treatments affect stand mortality?

5. Does the crop tree stand component (the 40 largest diameter trees per acre) have the same response pattern as the whole stand?

CHAPTER 3. METHODOLOGY

3.1 Experimental Sites

SMC Type I installations are located west of the Cascade crest in western Oregon, western Washington, and lower mainland and Vancouver Island in British Columbia (Figure 1) and belong to *Tsuga heterophylla* zone (Franklin and Dyrness 1973).Each installation contains seven density control plots and many contain auxiliary treatment plots for supplementary treatments such as pruning, fertilization and systematic vs best tree selection during thinning (Maguire et al. 1991).

Of these Type I installations, nine, shown as triangles in Figure 1, contain auxiliary fertilization treatment plots as part of a density control / fertilization experiment. Table 1 summarizes characteristics of these nine installations, including physical terrain characteristics; site index; planting date; stock type; and planting density; and date and stand age when plots were established. In interpreting the results, it is important to note two features of these nine installations:

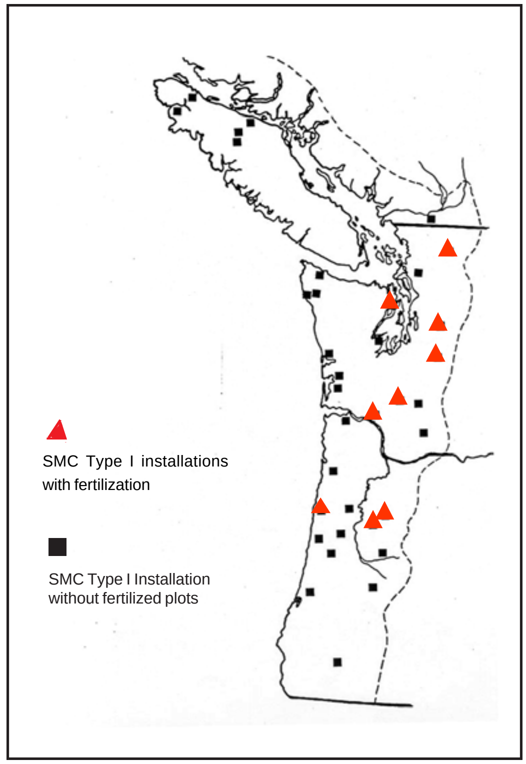


Figure 1: Geographical distribution of SMC Type I installations

- **Site quality of these installations is relatively uniform and above average**. Seven of the nine installations fall into Kings' Site Class II, one is Site Class I and one is Site Class IV.

- **Mean stand age at establishment was 9 years.** Type I Installations were placed in existing young plantations and, for the nine installations in this study, stand age at establishment ranged from 7 to 13 years with a mean of 9 years, Response analyses in this report reflect three 4-year growth periods following establishment, hence 4, 8 and 12 years should be added to the stand age at establishment to get the age of a stand corresponding to each of these growth periods. Using the mean stand age at establishment, the mean stand ages corresponding to these growth periods are 13, 17, and 21 years.

3.2 Treatment Regimes

The seven treatment regimes in the density control / fertilization experiment on these nine installations are defined in Table 2. These treatment regimes represent two main factors: fertilization and density. The fertilization factor had two levels: no fertilization and fertilization. For fertilization, urea was hand delivered to each plot at a rate of 200lbs N/acre at establishment and every four years thereafter. The density factor was the combination of early spacing and subsequent thinning. Early spacing was systematically employed in the establishment year to yield a range of density levels: keep original density (ISPA), half original density (ISPA/2) and one-fourth original density (ISPA/4). Subsequent repeated thinning

Table 1: Description of Study Installations

Installation	County, State	Elevarion, ft	Slope, %	Aspect	Site Index-50, ft	Site Index-30, ft	Planting Date	Stock Type	Trees Acre	Estab Yr	Estab Age from Planting
704, Ostrander Road	Cowlitz, WA	600	20	270	120	82	Jan-74	2-0,2-1,1-1	575	1987	13
705, East Twin Creek	King, WA	2700	30	180	90	74	Jan-76	1-1	700	1987	11
708, Copper Creek	Lewis, WA	900	5	999	125	91	Jan-81	1-1	430	1988	7
713, Sauk Mountain	Skagit, WA	793	5	180	120	89	1978	NA	538	1988	10
718, Roarin River	Linn, OR	1100	10	888	128	92	Jan-82	2-1,2-0	400	1989	7
722, Silver Creek Mainline	Marion, OR	2200	10	270	120	72	Feb,77	2-0	550	1989	12
725, Sandy Shore	Jefferson, WA	550	0	999	120	89	Dec-80	1-0	450	1990	10
726, Toledo	Lincoln, OR	300	10	225	135	93	Jan-84	1-1	362	1990	6
736, Twin Peaks	King, WA	600	40	270	120	93	Mar-84	2-0	450	1992	8
Mean											9

Note 1: Site Index-50, based on breast-height age, is from King (1966)

Note 2: Site Index-30, based on age from seed, is from Flewelling et.al (2001) and is the mean for all plots on the installation.

Note 3: Azimuth in degrees N=360, flat=999, variable=888

Table 2: Treatment regimes common to nine SMC Type I Douglas-fir installations

Number	Name	Description
1	ISPA_NoThinNoFert	Plots remained at their Initial Stems Per Acre (ISPA) with no further thinning and no fertilization
2	ISPA_RepThinNoFert	Plots remained at their initial density (ISPA), but were repeatedly thinned later. No fertilization.
3	ISPA_RepThinFert	Plots remained at their initial density (ISPA), but were repeatedly thinned* later. Urea was applied at establishment and every four years later.
4	ISPA/2_MinThinNoFert	Plots were spaced to half their initial density (ISPA/2) with minimal thinning† later. No Fertilization.
5	ISPA/2_MinThinFert	Plots were spaced to half their initial density (ISPA/2) with minimal thinning later. Urea was applied at establishment and every four years later.
6	ISPA/4_NoThinNoFert	Plots were spaced to one-fourth of their initial density (ISPA/4) with no further thinning. No fertilization.
7	ISPA/4_NoThinFert	Plots were spaced to one-fourth of their initial density (ISPA/4) with no further thinning. Urea was applied at establishment and every four years later.

*Repeated thinning: first thin when RD = 55 and thin to RD = 35, next when RD = 55 again thin to RD = 40, subsequently whenever RD =60, thin to RD = 40.
† Minimal thinning: When RD = 55, thin to RD = 35. No further thinning.

Table 3: Number of sample plots for each treatment regime

	ISPA_NoThin	ISPA_RepThin	ISPA/2_MinThin	ISPA/4_NoThin
No Fertilization	9	9	9	9
Fertilization	-	9	9	9

was conducted in a subset of ISPA plots and minimal thinning was conducted in ISPA/2 plots. So the density factor had four levels: ISPA_NoThin, ISPA_RepThin, ISPA/2_MinThin and ISPA/4_NoThin. With the exception of the ISPA with no further treatments (treatment 1 in Table 2), other density levels had both a fertilized and unfertilized plot, producing the other six treatment regimes as shown in Table 2. Within each installation, treatment regimes were randomly assigned to plots. Since the objective of SMC installations is to provide data for regional responses rather than site-specific assessments, there is no replications within an installation. Instead, treatment regimes are replicated across installations in the region. There were nine installations for each treatment regime, hence totally sixty-three plots are available for analysis (Table 3).

Among these sixty-three plots, fifty-six plots have the first four measurements data available for analysis, i.e. establishment year, 4th, 8th and 12th year, and the other seven plots only have three measurements data available, i.e. establishment year, 4th and 8th year. So there are 63 sample plots during growth periods 1 and 2, and 56 sample plots during growth period 3.

Table 4: Average stand attributes at establishment for seven density vs fertilization treatments on nine SMC Installations

Stand Attributes	1.ISPA_ No Thin No Fert	ISPA_RepThin		ISPA/2_MinThin		ISPA/4_NoThin	
		2. No Fert	3. Fert	4. No Fert	5. Fert	6. No Fert	7. Fert
QMD (in.)	2.96 (1.94-4.04)*	2.90 (1.96-3.64)	2.98 (2.23-4.57)	3.07 (2.12-3.98)	3.04 (2.19-4.58)	3.11 (2.07-4.59)	2.90 (1.88-3.93)
Basal area (sq ft/acre)	26.74 (6.04-62.50)	24.95 (7.74-54.86)	25.78 (8.65-63.82)	12.53 (3.08-22.65)	13.01 (4.44-31.39)	6.86 (3.00-14.24)	5.95 (2.09-12.28)
HT40 (ft.)	23.4 (15.2-31.6)	23.3 (15.5-31.4)	22.8 (15.6-32.9)	23.7 (15.0-34.2)	22.5 (15.3-33.2)	22.4 (16.0-33.2)	20.9 (15.2-30.3)
Volume (cu ft/acre)	280.7 (51.0-784.0)	258.5 (60.0-683.0)	272.6 (67.0-838.0)	129.6 (26.0-285.0)	137.0 (35.0-410.0)	71.8 (23.0-188.0)	60.0 (16-151.0)
Breast height Age (year)	5.6 (3-9)	5.4 (3-9)	5.6 (3-10)	5.7 (3-9)	5.3 (3-9)	5.0 (3-10)	5.0 (3-9)
Trees per acre	509 (248-716)	509 (302-800)	481 (294-752)	228 (126-324)	234 (170-334)	121 (94-154)	119 (76-162)
Relative density	15.24 (4.16-33.52)	14.66 (5.26-32.80)	14.43 (5.79-31.17)	6.96 (2.12-11.35)	7.17 (3.00-14.75)	3.75 (1.93-6.65)	3.36 (1.52-6.20)
Site index (30 year total age)	88.3 (74-100)	85.4 (74-98)	85.2 (71-94)	87.8 (70-97)	87.3 (70-95)	86.0 (72-96)	85.3 (75-94)
Sample Size	9	9	9	9	9	9	9

* Numbers inside parentheses denote the range

3.3 Measurements

Each plot is 1.1 acre and consists of a 0.5 acre square measurement sample plot (MSP) surrounded on all sides by a 30.5 foot buffer strip (Maguire et al. 1991). Diameter at breast height (DBH) was measured every four years to the nearest 0.1 inch for all trees in the MSP. Total height was measured to the nearest 0.1 foot on a 42-tree sample, which includes the smallest tree, the largest tree and 40 trees distributed across the DBH range with roughly two thirds greater than QMD and one third smaller. Total height for other trees was estimated from non-linear height-diameter regression equations fitted across the 42 height-measured trees in every plot at any given measurement. Individual tree cubic foot volume was calculated using Bruce and DeMars's (1974) equations. QMD, basal area per acre, and volume per acre were calculated at plot level for each measurement. Average height of the 40 largest diameter trees per acre (HT40) was also calculated. Stand board foot volume is defined as Scribner volume to 6-inch tops for stands with DBH greater than 7.5 inches and it was calculated from total cubic foot volume by using Williamson and Curtis (1980) equations.

Once established, i.e. after any initial spacing had been conducted, trees per acre (TPA) in these plots ranged from 76 to 800 and initial breast height age ranged from 3 to 10 years old. Plot site index varied from 70 to 100 feet at 30 years total age (Flewelling et al 2001). Average stand attributes at establishment are summarized in Table 4.

3.4 Estimation of Site Index

Two kinds of site index are available in the SMC database: installation site index and plot site index. Installation site index is based on King's (1966) site index curve, (Tabel 1) which is the dominant height at breast height age 50. A concern with installation site index is that it was provided by landowners and could be based on various sources such as soil properties, site index of the adjacent stand, or site index of the preceding stand. There are concerns over the accuracy of these diverse estimates as well as concerns that they may not accurately reflect the productivity of the current stand on the site. In response to these concerns, the SMC developed a new site index, which is the mean height of the largest 40 trees per acre by diameter at total age 30 (Flewelling 2001). This site index has been calculated for each plot based on the current stand; mean values by installation are shown in Table 1 and mean values by treatment are shown in Table 4.

3.5 Data Analysis

For each plot, average net periodic annual increments (PAI) of QMD, basal area, dominant height (HT40) and cubic foot volume were calculated for every four-year growth period after establishment. Growth analysis was then conducted on these variables in terms of three four-year growth periods, i.e. the first growth period (0-4 year), the second growth period (4-8 year) and the third growth period (8-12 year). Average breast height age during these three growth periods is 6-10, 10-14 and 14-18 respectively. Because urea was applied to fertilized plots at the start of each growth period, growth response to fertilizer reflects response to 200lb N/acre in the first growth period, 400lb N/acre in the second growth period and 600lb N/acre in the third growth period. Yield analysis was conducted on net yield of QMD, basal area, dominant height and cubic foot volume at establishment, the 4th, 8th and 12th year, which respectively correspond to mean breast height age 6, 10, 14 and 18. Yield response reflects response to 0lb N/acre at establishment, 200lb N/acre in the 4th year, 400lb N/acre in the 8th year and 600lb N/acre in the 12th year. Besides the whole stand, growth and yield analyses for the forty largest diameter trees per acre (crop tree) were also performed.

Data were analyzed as an augmented two-factor fixed-effect model with initial trees per acre (before spacing), breast height age (BHAge) and plot site index (PlotSI) as covariates. PlotSI here is site index at total age 30. The main effects of fertilization and density, their interaction, along with covariance effects, were tested by using analysis of covariance (ANCOVA) in SAS at 0.05 significance level. ANCOVA was used in an attempt to reduce or account for measurable extraneous factors that contribute to variability in the dependent variables. The initial general linear model has the following form:

Dependent variable = f (fertilization, density, fertilization * density, TPA, BHAge, PlotSI)

Where:

Dependent variables are

- ✓ QMD, basal area per acre, dominant height and cubic foot volume per acre at establishment, the 4th, 8th and 12th year
- ✓ PAI of these stand variables during the 1st, 2nd and 3rd growth periods

Independent variables are

- ✓ Fertilization: represents the effect of fertilizer, two levels;
- ✓ Density: represents the effect of density regime, four levels;
- ✓ Fertilization * Density: represents the interaction effect;
- ✓ TPA: represents the initial (before spacing) trees per acre;
- ✓ BHAge: represents the breast height age (in years) and
- ✓ PlotSI: represents the site index at total age 30.

Based on ANCOVA results, non-significant effects were deleted from the initial models. Then modified models were fitted to data again. Specific comparisons between treatment regimes were conducted by using the modified ANCOVA model with the mean squared error as the pooled variances.

CHAPTER 4. RESULTS

This section briefly presents results of whole stand growth and yield, whole stand mortality and crop tree growth and yield. For the complete results and additional findings, please see Li (2005). Keep in mind that since installations are across the region, these results only represent regional-level trends and are less suited for site specific assessment.

Three points should be noted in interpreting the results presented in this Chapter. First, the site index of the nine installations is relatively high and uniform. Using King's 50 year site index, seven belong to site class II, one is site class I, and one is site class IV. Second, as stated previously, response to fertilizer at the end of any growth period is the response to cumulative application of 200 lb/acre of fertilizer at establishment and every subsequent 4th year. Third, keeping in mind that the mean stand age at study establishment and after 4-year growth period for these installations are 9, 13, 17, and 21 years respectively.

4.1 Initial Conditions

As shown in Table 4, there were no significant differences in quadratic mean diameter (QMD), height, breast height age and site index at establishment among the seven treatment regimes. Basal area (BA), volume, trees per acre and relative density did show differences as would be expected due to the spacing treatments imposed in the establishment year, and their ratios were about 4:2:1 between ISPA, ISPA/2 and ISPA/4. Within each density level, BA, volume, TPA and relative density were statistically the same between fertilized and unfertilized treatments.

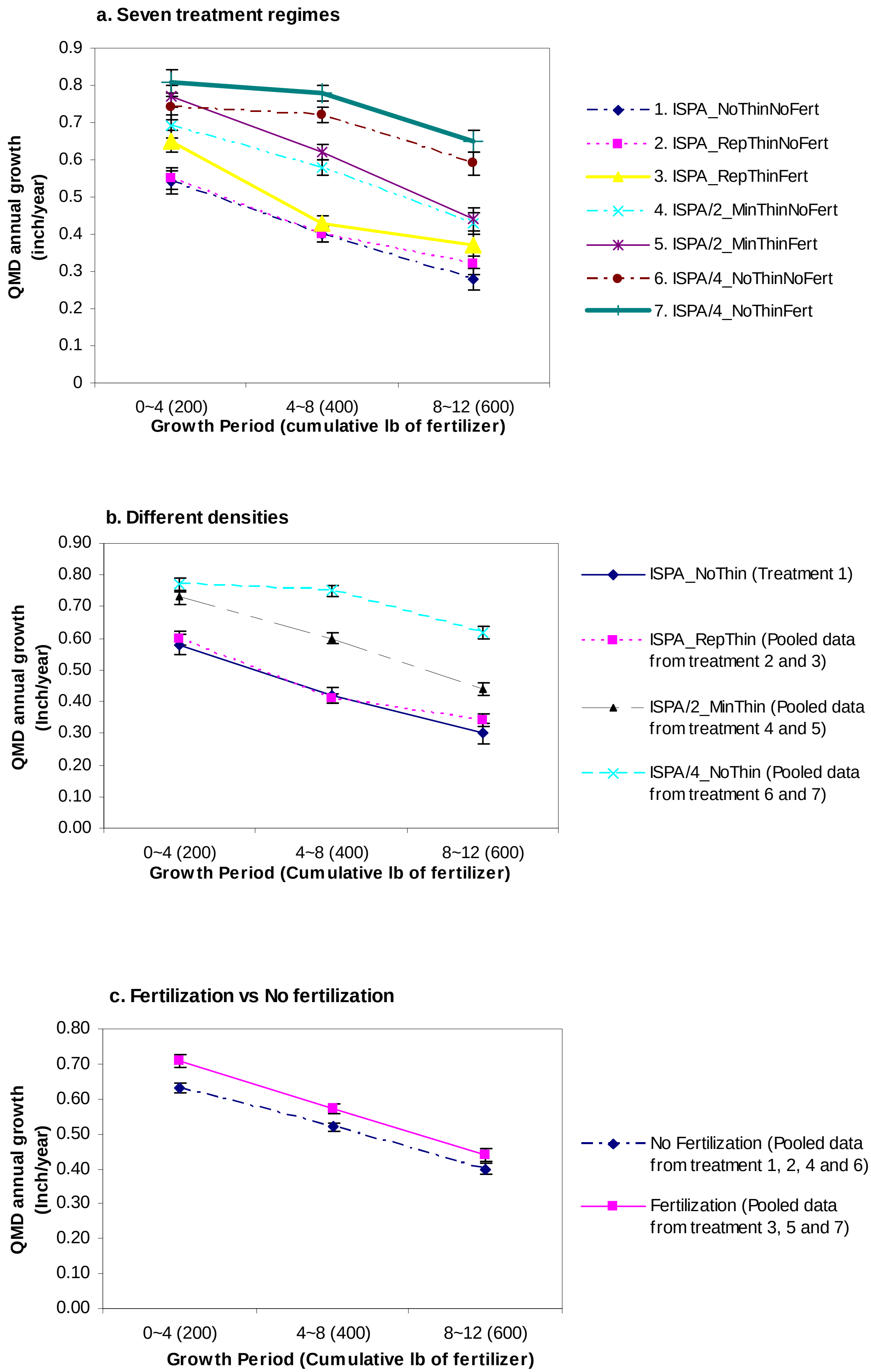
4.2 Whole Stand Growth Analysis Results

4.2.1 Periodic Annual Diameter Increment

Figure 2 shows average periodic annual QMD increment during the first three growth periods for the seven treatment regimes, pooled density treatments and pooled fertilization treatments. From Figure 2, it's clear that ISPA/4 with fertilization had the greatest periodic annual QMD increment for all three growth periods while no treatment (ISPA_NoThinNoFert) had the least. Density showed a greater effect than did fertilization since the distance between different density levels is larger than the distance between fertilization and no fertilization. Within each density level, QMD annual growth in fertilized plots was greater than in unfertilized counterparts. However, these QMD growth gains were not all statistically significant. Specific comparison tests between fertilized and unfertilized plots within each density indicated that during the 1st growth period, QMD PAI fertilization gains were significant in ISPA_RepThin and ISPA/2_MinThin, but not in ISPA/4_NoThin. During the 2nd growth period, these gains were significant only in ISPA/4_NoThin. During the 3rd growth period, none of these gains were statistically significant.

Pooling the plots of the same density treatment together produces Figure 2b. From Figure 2b, density affected periodic annual QMD increment greatly with denser stands exhibiting less QMD growth rate. During the first three growth periods, ISPA/4 had the largest QMD growth rate, ISPA/2 was in the middle, and ISPA exhibited the least QMD growth rate with

Figure 2: Quadratic mean diameter annual increment trends over the course of the study



ISPA_NoThin not different from ISPA_RepThin. During the 1st growth period, the difference between ISPA/2 and ISPA/4 was not significant, but their differences increased over time and ISPA/4 became significantly greater than ISPA/2 in the 2nd and 3rd growth periods.

Pooling the plots with the same fertilization treatment together produces Figure 2c. Across all densities, fertilization increased QMD annual increment by 0.08, 0.05 and 0.04 inch/year respectively in the 1st, 2nd and 3rd growth periods, and these represented 12.7%, 9.6% and 10.0% growth gain in diameter. Statistical testing indicated that these gains were significant during the 1st ($p=0.0010$) and 2nd ($p=0.0183$) growth periods, but not significant during the 3rd growth period ($p=0.0807$).

4.2.2 Periodic Annual Basal Area Increment

Like QMD, basal area growth response was more strongly affected by density treatments than by fertilization treatment, especially in the first two growth periods (Figure 3a). But the basal area response patterns to density treatment are different than found for QMD. For basal area, denser ISPA plots exhibited greater growth rate than less dense ISPA/2 and ISPA/4 plots due to the larger number of trees per acre (Figure 3a, 3b). However, from period 2 to 3, BA growth rate in ISPA dropped sharply and fell below ISPA/2. In contrast, BA growth rate in ISPA/2 and ISPA/4 continued to increase at a more modest rate. Within each density level, fertilized plots generally exhibited greater basal area growth rate than their unfertilized counterparts. Significant fertilization gains were found in the 1st growth period for ISPA/4 and again in the 2nd growth period for all three densities. But these gains became insignificant during the 3rd growth period and even disappeared in ISPA_RepThin regime. Across all seven treatment regimes, the difference in basal area annual growth became smaller over time.

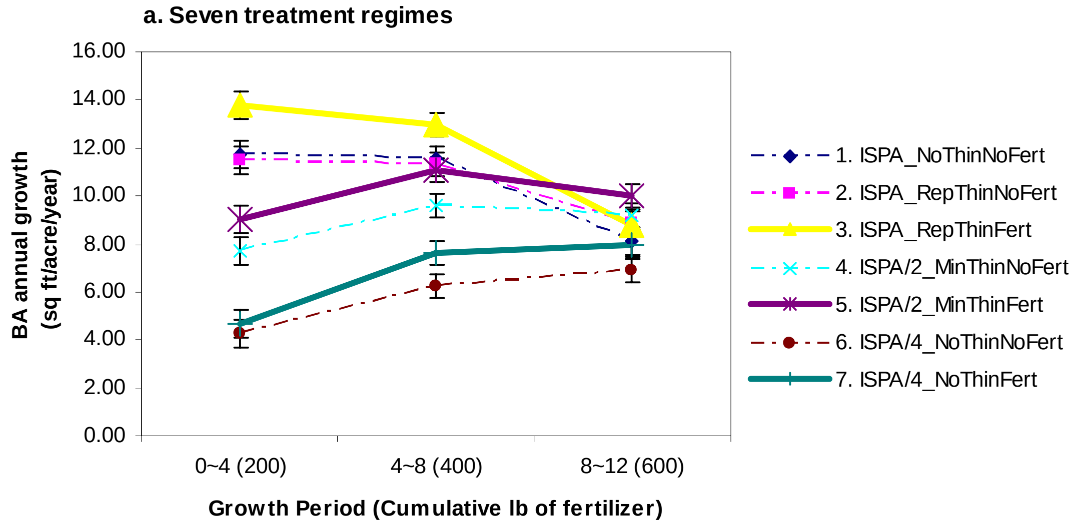
Pooling the same density plots together, BA growth rate during the 3rd growth period was statistically the same among these four density levels, implying that ISPA/2 and ISPA/4 are accumulating basal area at about the same rate as ISPA (Figure 3b).

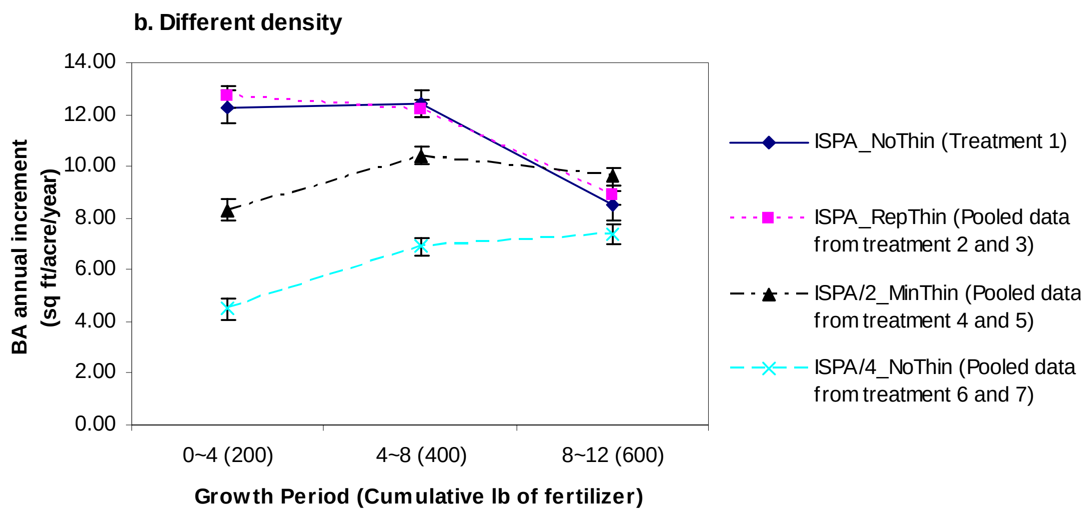
Figure 3c shows basal area growth over the pooled fertilization treatments. Compared to the unfertilized counterpart, fertilization increased basal area growth by 1.3, 1.5 and 0.6 sqft/acre/year respectively in the 1st, 2nd and 3rd growth periods and these increases were significant for the first two growth periods ($p=0.0097$, 0.0003), but not for the third growth period ($p=0.1477$).

4.2.3 Periodic Annual Dominant Height Increment

Figure 4 shows periodic dominant height growth rate during the first three growth periods. A slight reduction in height growth after spacing was observed for the growth periods 1 and 2 as shown in Figure 4a and Figure 4b, in which both ISPA/2 and ISPA/4 had less dominant height growth than ISPAs. However, ISPA/2 caught ISPA during the 3rd growth period and both had the same dominant height annual growth. The reduction was recovered in ISPA/2 plots. But ISPA/4 was still below ISPA and ISPA/2. ANCOVA testing indicated that these reductions were not statistically significant. Within each density level, trees in fertilized plots had a slightly greater dominant height growth rate than in unfertilized plots (Figure 4a), but these fertilization gains were not statistically significant either. This is also true for height growth rate fertilization gains across all density levels (Figure 4c).

Figure 3: Basal area annual increment changes over the course of the study





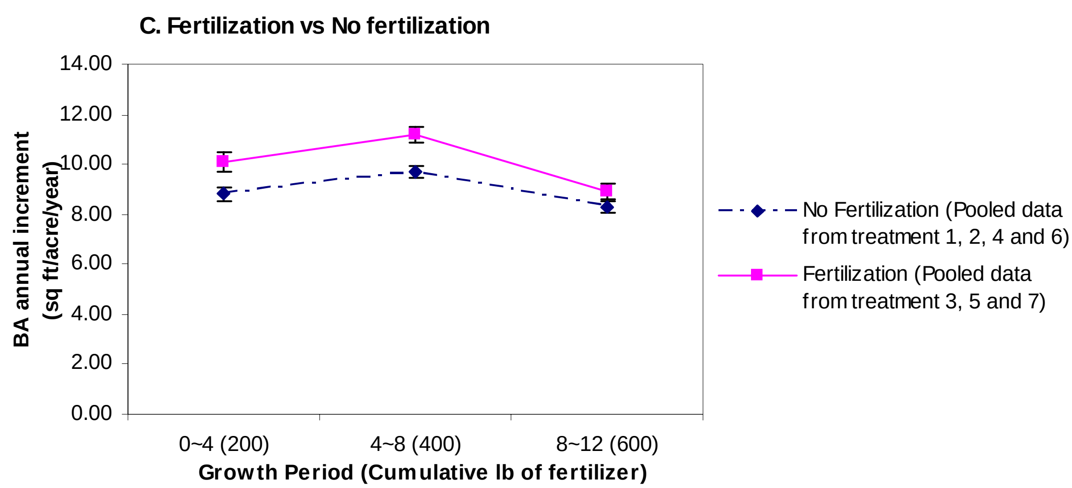


Figure 4: Dominant height annual increment trends over the course of the study

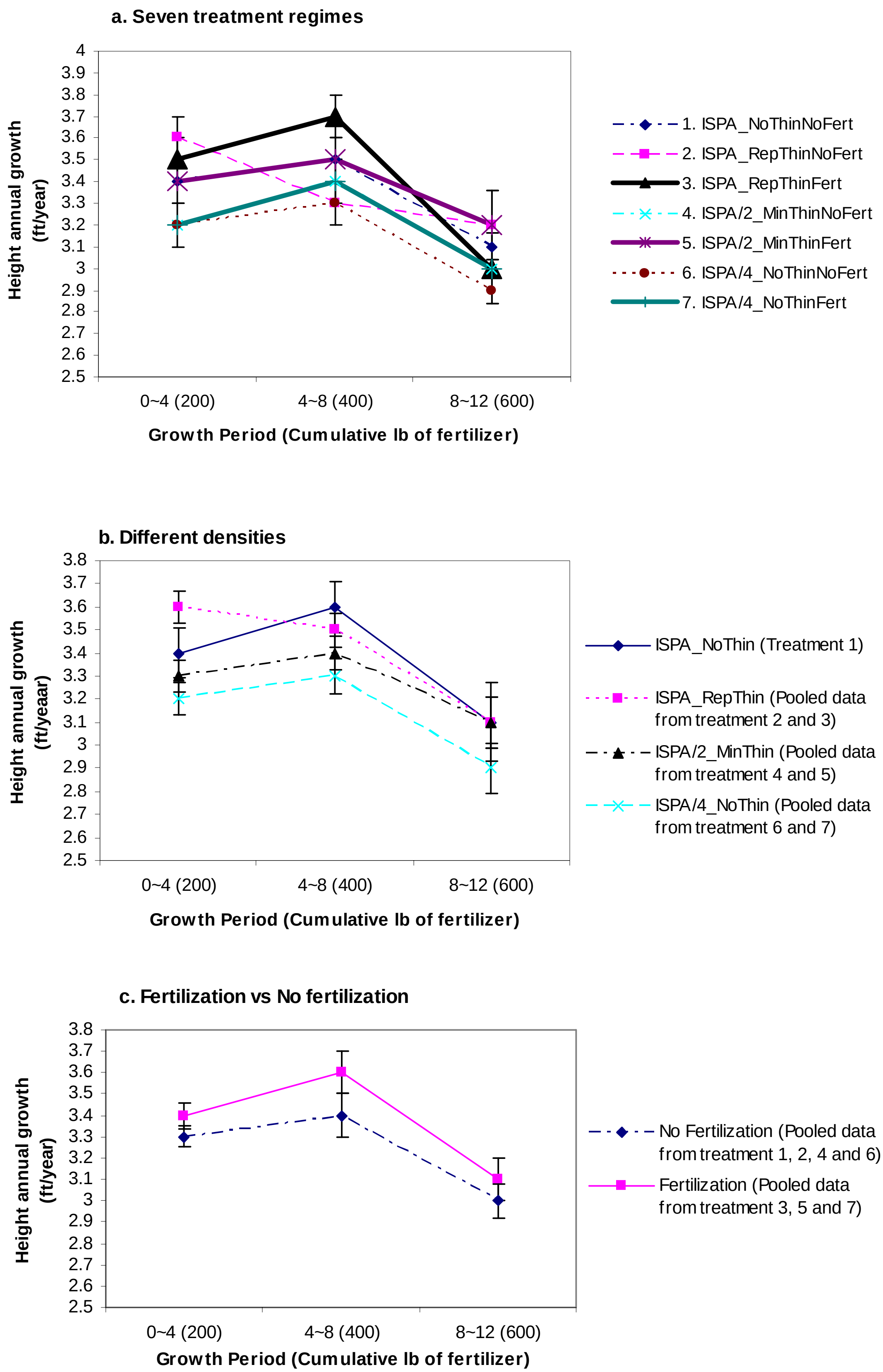
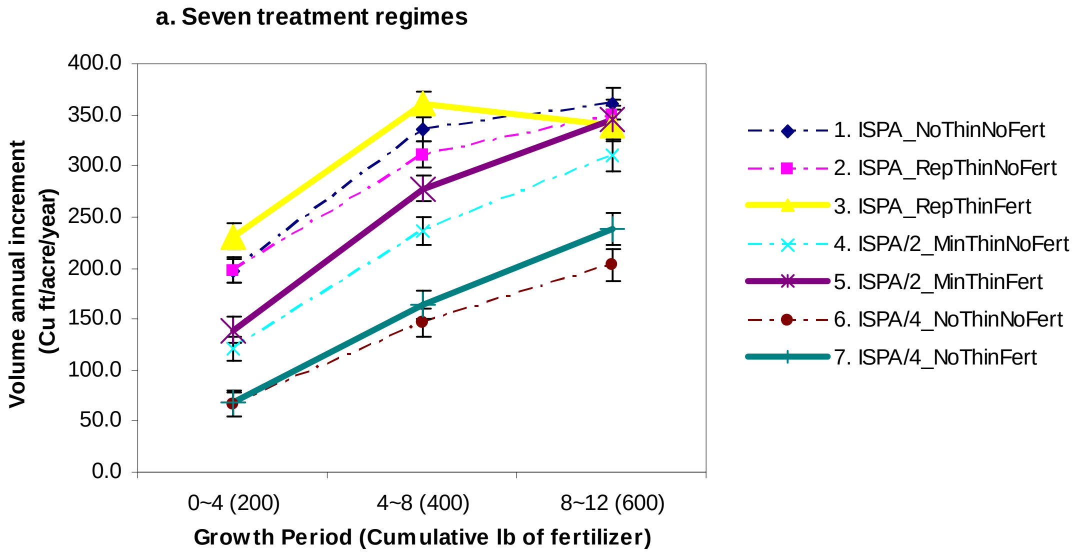
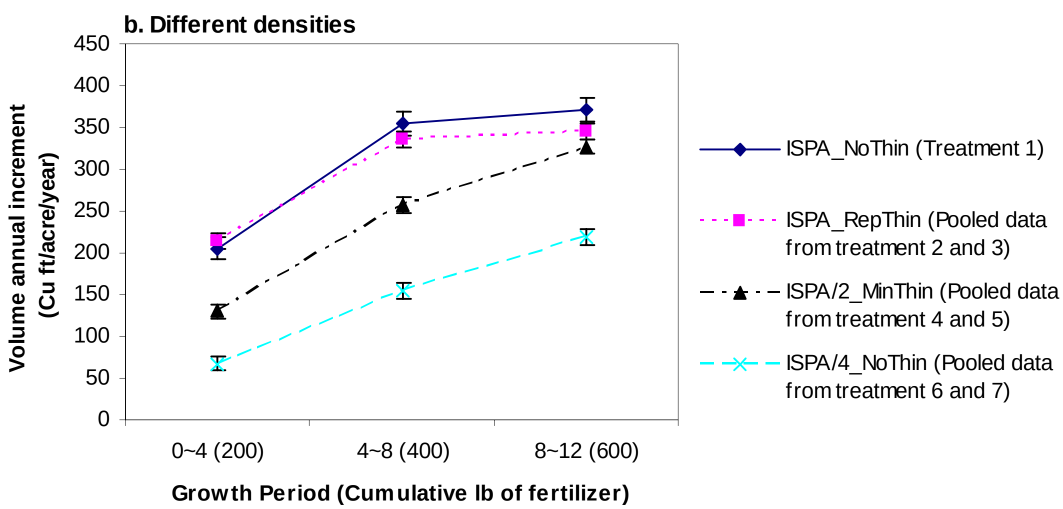
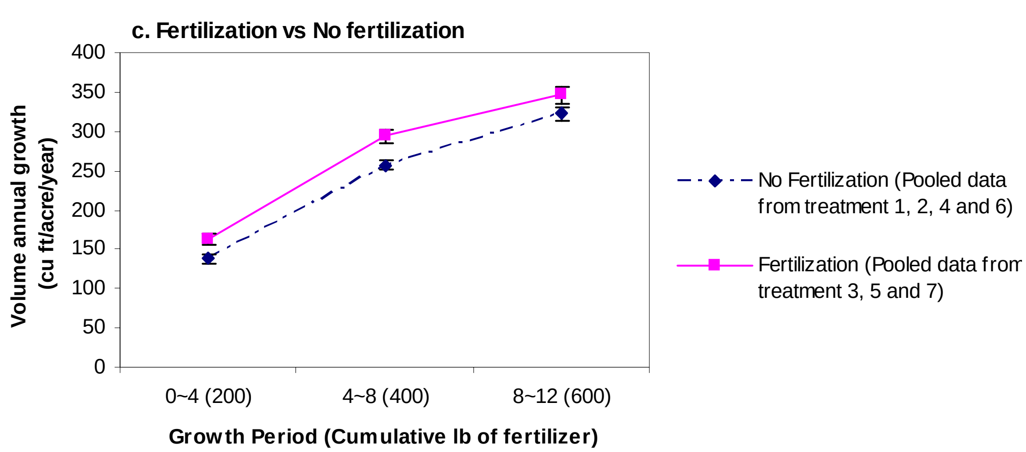


Figure 5: Volume annual increment trends over the course of the study







4.2.4 Periodic Annual Volume Increment

Figure 5 presents periodic volume annual growth trends. All treatment regimes exhibited increasing volume growth rate trends and fertilization generally increased volume annual growth (Figure 5a and 5c). ISPA_RepThin had the greatest volume growth rate, but its fertilization gain disappeared during the 3rd growth period, while in ISPA/2 and ISPA/4, volume growth rate fertilization gains were still observed. Specific comparison tests indicated that during the 1st growth period, fertilization gain was significant only in ISPA_RepThin and, not in ISPA/2 and ISPA/4. During the 2nd growth period, ISPA_RepThin and ISPA/2_MinThin had significant fertilization gains, but ISPA/4 didn't. During the 3rd growth period, there was no fertilization gain in any of the density management regimes.

Within each density level, combining fertilized plots and unfertilized plots produces Figure 5b. ISPA had the greatest volume growth rate and ISPA/4 had the least. Removal of growing stock by spacing had a negative effect on volume growth during the first three growth periods. However, volume growth rate in ISPA began to slow down during the 3rd growth period, while ISPA/2 and ISPA/4 still kept a strong increasing trend.

Pooling sample plots together according to fertilization treatment produces Figure 5c. Across all densities, fertilization increased volume annual growth by about 12%, 14% and 7% respectively for the 1st, 2nd and 3rd growth periods and fertilization increases in the first two growth periods were statistically significant (p=0.0520, 0.0010), but not in the 3rd growth period (p=0.1185).

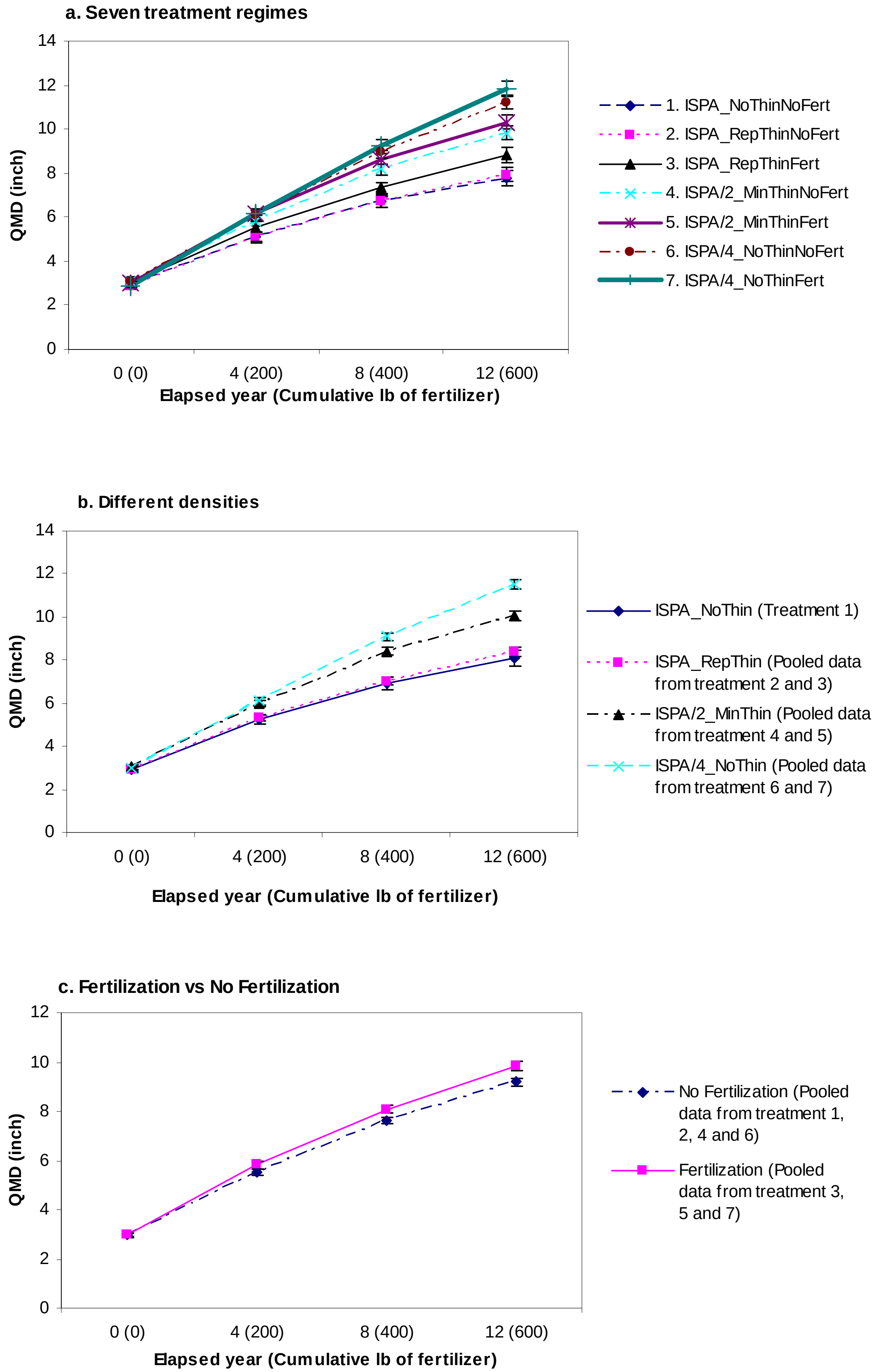
4.3 Whole Stand Yield Analysis Results

4.3.1 Quadratic Mean Diameter

Figure 6 displays QMD development trends for the first twelve years after establishment. As shown in Figure 6a, these seven treatment regimes began with almost the same initial QMD, but ended with 4.06 inches difference twelve years later. ISPA/4 with fertilization had the largest QMD, ISPA with no further treatment had the least QMD, while others were between these two. QMD in ISPA_RepThinNoFert treatment didn't show much difference from that in ISPA_NoThinNoFert. That's probably because during the first twelve years, not many ISPA_RepThinNoFert plots reached their thinning trigger, and thinning was not actually performed extensively in ISPA_RepThinNoFert plots. Within each density level, QMD in fertilized plots was greater than their unfertilized counterparts, but most of these fertilization increases were not statistically significant and the only significant one was in the ISPA_RepThin in the 12th year. Compared to fertilization, density effect on QMD yield was much greater.

Combining all plots within each density regime, we see that initial QMD was the same among ISPAs, ISPA/2 and ISPA/4 (Figure 6b). Four years later, differences began to emerge with denser plots exhibiting smaller QMD. As time elapsed, the difference became increasingly large. It went from 0.85 inch in the 4th year to 2.18 inch in the 8th year and 3.44 inch in the 12th year. The QMD differences in the 8th and 12th year were statistically significant.

Figure 6: Quadratic mean diameter trends over the course of the study



Across all densities, initial QMD in fertilized plots (2.96in.) was a little less than that in unfertilized plots (3.01in.) (Figure 6c). However, four years later, QMD in fertilized plots became 0.28 inch greater than QMD in unfertilized plots. The first urea application increased QMD by 5.1%. As urea was repeatedly applied at every fourth year, QMD in fertilized plots became increasingly larger than that in unfertilized plots. Eight years later, QMD gain by fertilization was 0.45 inch. Twelve years later, this gain increased to 0.65 inch. ANCOVA testing indicated that the QMD gain by fertilization were not significant in the 4th year, but became significant in the 8th ($p=0.0343$) and 12th year ($p=0.0165$) after establishment.

4.3.2 Diameter Distribution

Not only did widely spaced treatment regimes exhibit larger QMD, they also had a higher proportion of trees in larger diameter classes. When established, diameter distribution curves were very similar among the seven treatment regimes, but they gradually differentiate from each other over time (Figure 7). Diameter distribution curve for ISPA/4 plots moved further right than ISPA/2 and ISPAs, implying that ISPA/4 had a greater proportion of trees in larger diameter classes. Within each density level, the diameter distribution curve for fertilized plots was to the right of the unfertilized counterparts, so fertilized plots had more larger diameter trees than their unfertilized counterparts. This can be better visualized by the bar graphs in Figure 8. At the start of the study, all seven treatment regimes had about the same diameter class proportions: 86% 1-4 inch trees and 14% 5-8 inch trees. Four years later, 9-12 inch trees began to show up in ISPA/2 and ISPA/4, but not in ISPAs. Eight years later, 72% of trees in ISPA/4 with fertilization were between diameter class 9 to 12 inches, while for ISPA_NoThinNoFert and ISPA_RepThinNoFert, this percentage was only 18%. Twelve years later, about half of the trees in ISPA/4 were 13-17 inches and another half was 9-12 inches. For ISPAs, the 13-17 inch diameter class accounted for only 1-2% of the trees, while the 5-8 inch diameter classes accounted for about 50%. Within each density level, the fertilized plots had somewhat more larger trees than their unfertilized counterparts. However, this difference was not as big as the difference among different densities.

4.3.3 Basal Area Per Acre

All treatment regimes had an increasing basal area stocking pattern during the first 12 years after establishment with denser stands having more basal area (Figure 9a). However, ISPA_NoThinNoFert treatment began exhibiting a slowing of the basal area increase from year 8 to year 12 while the other treatments displayed no evidence of slowing. In year 12, basal area per acre in ISPA/2_MinThinFert was getting very close to that in ISPA_NoThinNoFert. Within each density level, fertilized plots outperformed their unfertilized counterparts, but specific comparison testing indicated that only fertilization gains in ISPA_RepThin in year 8 were significant. Fertilization gain on basal area was not significant in ISPA/2 and ISPA/4 for the first twelve years. Compared to fertilization, the density effect was greater and statistically significant.

As shown in Figure 9b, basal area stocking fell into three significantly different density groups: ISPA, ISPA/2 and ISPA/4. ISPA_NoThin and ISPA_RepThin are in the same ISPA group. However, ISPA_RepThin began to exceed the ISPA_NoThin in the 12th year. The basal area ratio between ISPA, ISPA/2 and ISPA/4 changed from 4:2:1 at establishment to 4:3:2 in the 12th year.

Figure 7: Diameter distribution changes over the course of the study

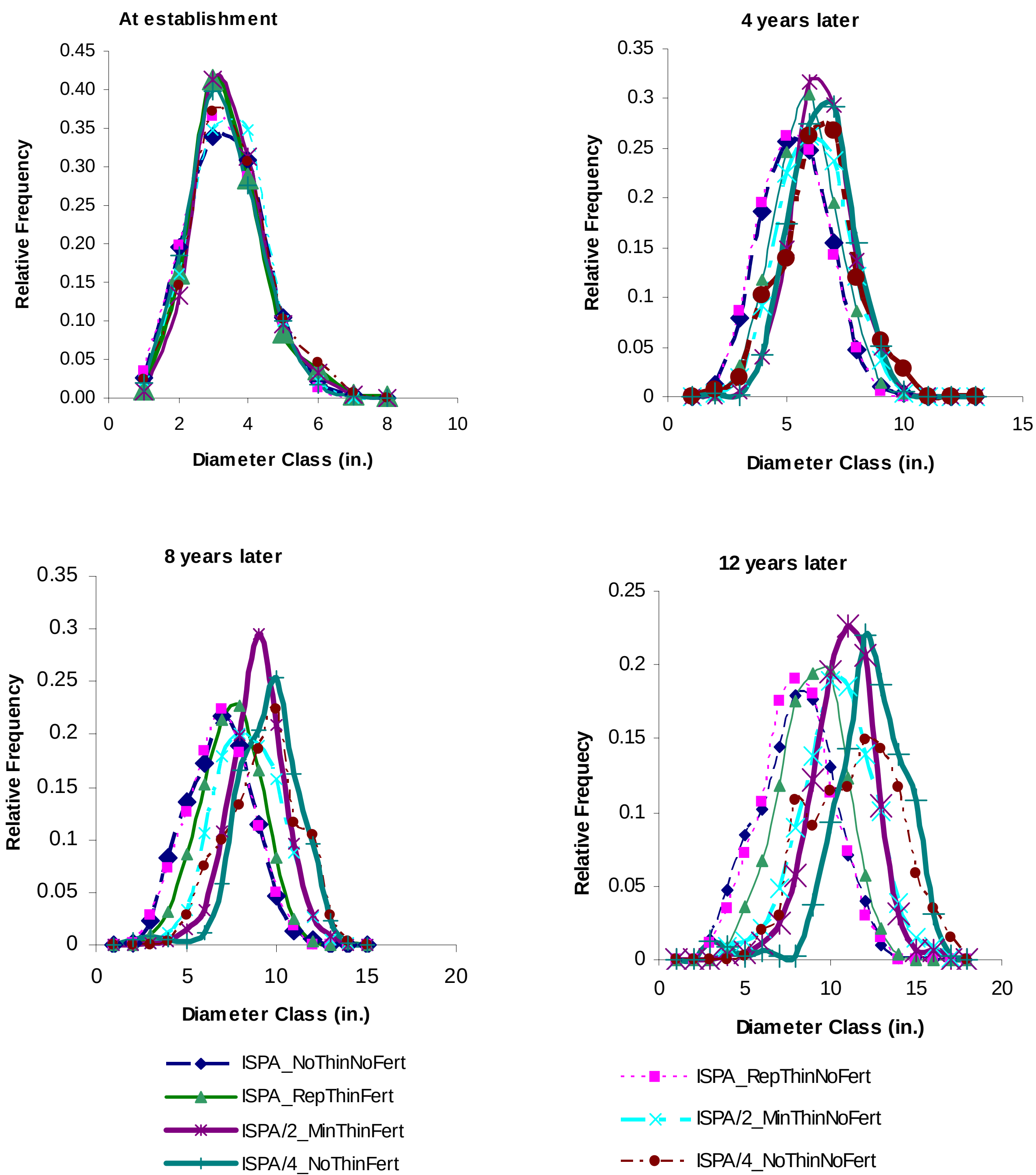
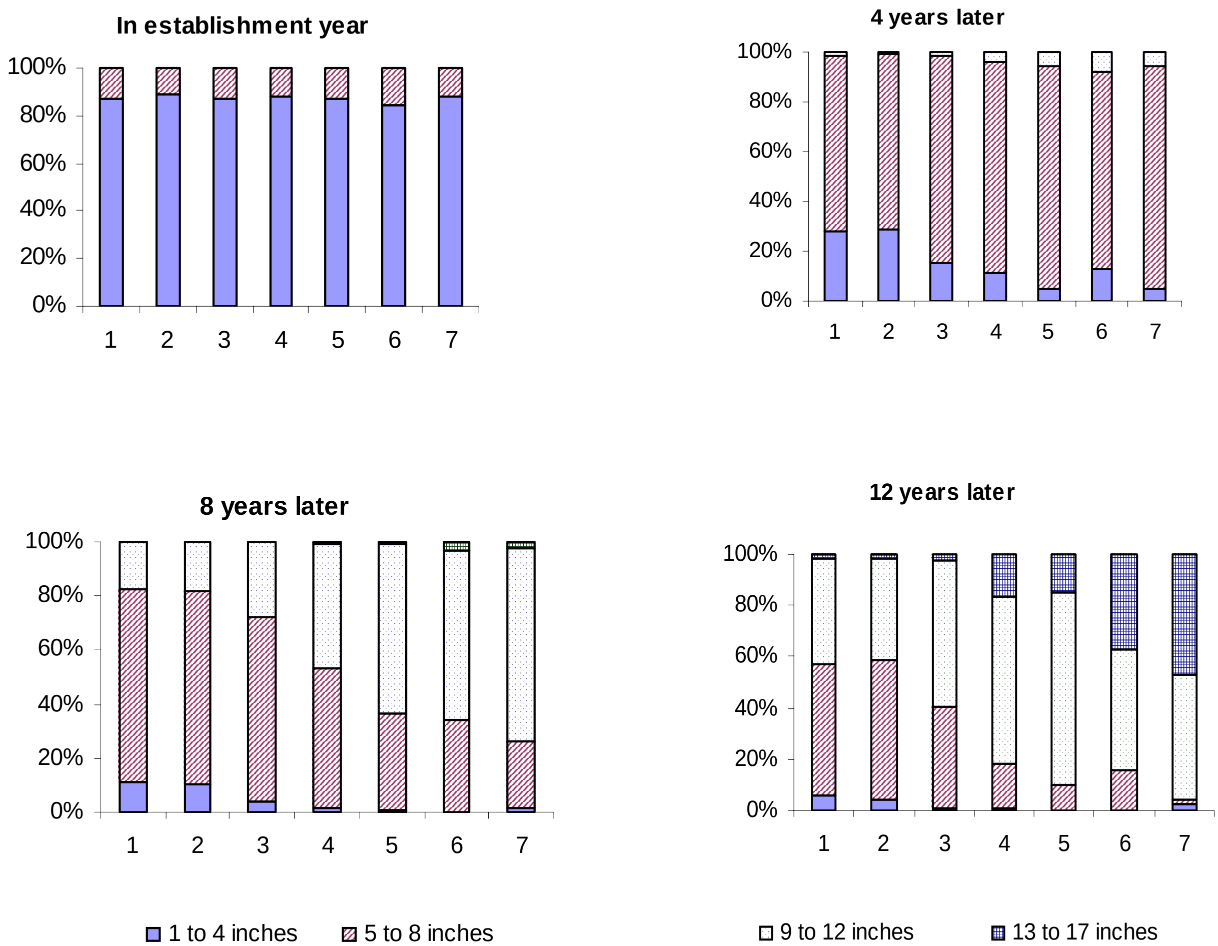


Figure 8: Diameter class proportion changes over the time of the study



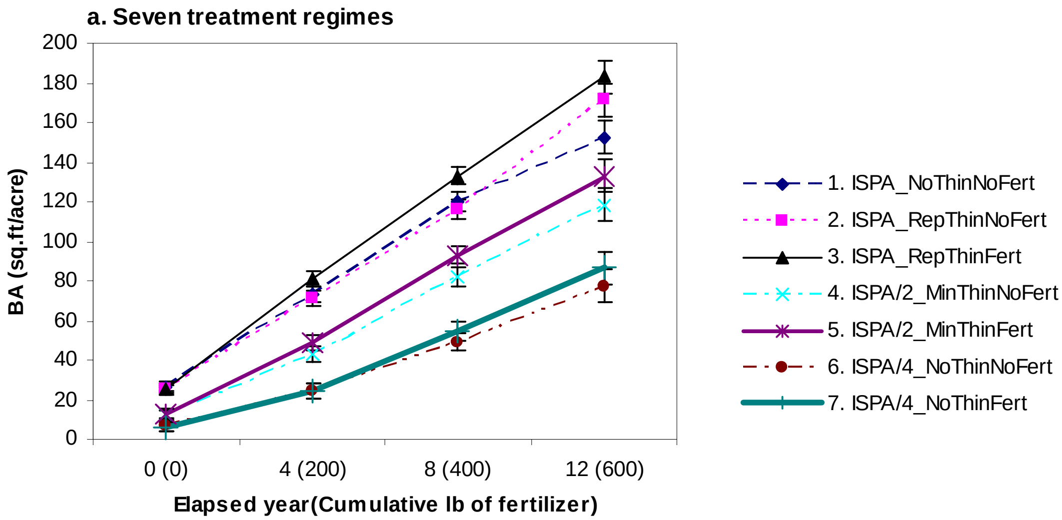
1: ISPA_NoThinNoFert,

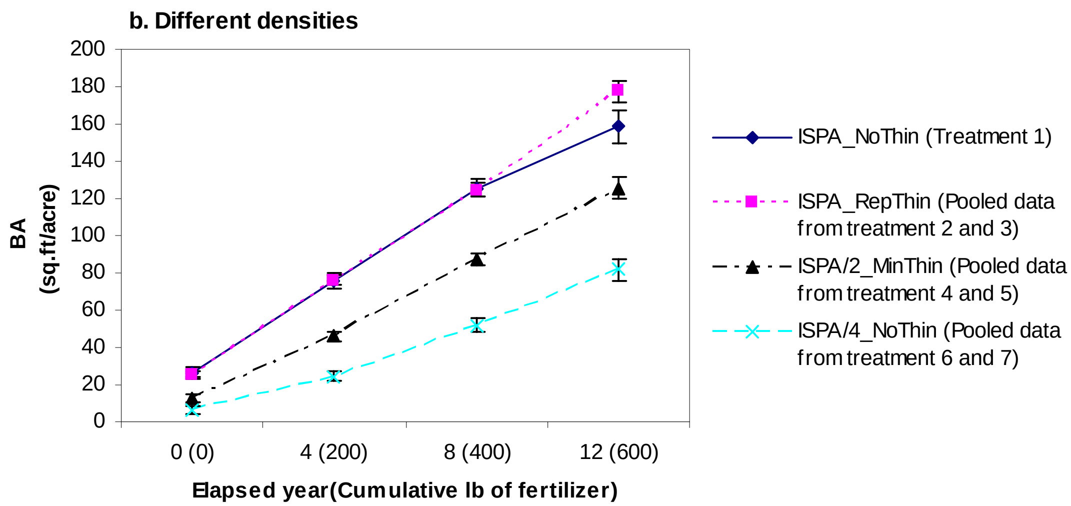
2: ISPA_RepThinNoFert; 3: ISPA_RepThinFert;

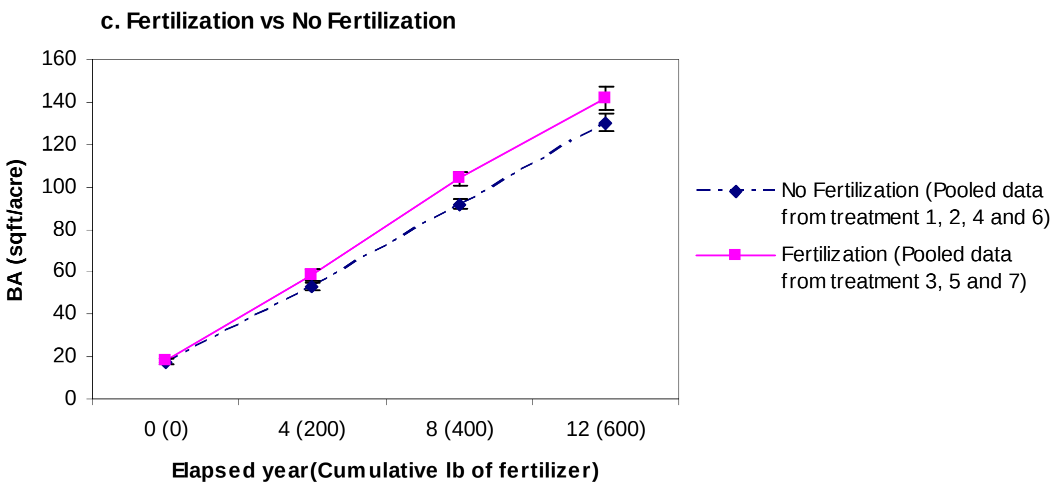
4: ISPA/2_MinThinNoFert 5: ISPA/2_MinThinFert;

6: ISPA/4_NoThinNoFert; 7: ISPA/4_NoThinFert

Figure 9: Basal area per acre trends over the course of the study







Across all densities, initial stand basal area was statistically the same between fertilized and unfertilized plots (Figure 9c). Four years later, basal area in fertilized plots gained about 10% (5.28 sqft/acre) over unfertilized plots, but this gain was not significant at 0.05 level (p=0.1047). After 8 years, basal area in fertilized plots gained 12% (11.35 sqft/acre) and this increase was significant (p=0.0049). In year 12, basal area difference between fertilized and unfertilized plots was 11.82 sqft/acre, which is also statistically significant.

4.3.4 Dominant Height

Both ISPA/2 and ISPA/4 had slightly shorter dominant height than ISPAs (Figure 10). It is likely because dominant height in ISPA/2 and ISPA/4 was slightly less than in ISPAs from the very beginning. Dominant height in fertilized plots had almost the same trend as that in unfertilized plots and fertilization didn't show a significant effect on height at any density. ANCOVA testing supported this finding and most of height differences among different treatment regimes were not statistically significant.

4.3.5 Volume Per Acre

Figure 11 presents cubic foot volume per acre over the study period. As shown in Figure 11a, the greatest cubic foot volume yield was in ISPA_RepThinFert treatment and the least was in ISPA/4_NoThinNoFert treatment. Within each density level, fertilized curves were above unfertilized counterparts implying fertilization increased cubic foot volume at all densities. However, specific comparison testing indicated that only the fertilization increase in ISPA_RepThin in year 8 was significant. Also from Figure 11a, ISPA_RepThinNoFert was not distinguishable from ISPA_NoThinNoFert until in the 12th year, which may suggest that the thinning effect was beginning to show in the year 12.

As shown in Figure 11b, cubic foot volume by density exhibited a general pattern similar to that previously discussed for basal area. The four density treatments fell into three significantly different groups with ISPA_NoThin and ISPA_RepThin in the same group. Twelve years after establishment, ISPAs still exhibited more cubic foot volume per acre than ISPA/2 and ISPA/4. Spaced stands (ISPA/2 and ISPA/4) had not recovered from the initial spacing. ISPA_RepThin was slightly less than ISPA_NoThin in the 4th and 8th years, but had passed the ISPA_NoThin in the 12th year.

Across all densities, initial cubic foot volume in fertilized plots was statistically the same as that in unfertilized plots (Figure 11c). However, in the 4th, 8th, and 12th year, cubic foot volume per acre was increased by fertilization by 113.2, 218.2 and 313.6cuft/acre respectively, which represented about 9.5%, 12.1% and 10.2% volume gain. These gains were not significant in the 4th year; the significant increase in periodic annual volume growth caused by the first fertilization didn't translate into significant volume stocking increase in the 4th year. After the second fertilization and 4 more years of growth, fertilization effect on stand volume stocking became significant. This significant effect remained in the 12th year.

Figure 12 presents Scribner board foot volume per acre counterparts to the cubic foot volumes in Figure 11. Scribner volume was calculated according to procedures of Williamson and Curtis (1980) and represents volume to a 6-inch top for stands with mean QMD greater than

Figure 10: Dominant height trends over the course of the study

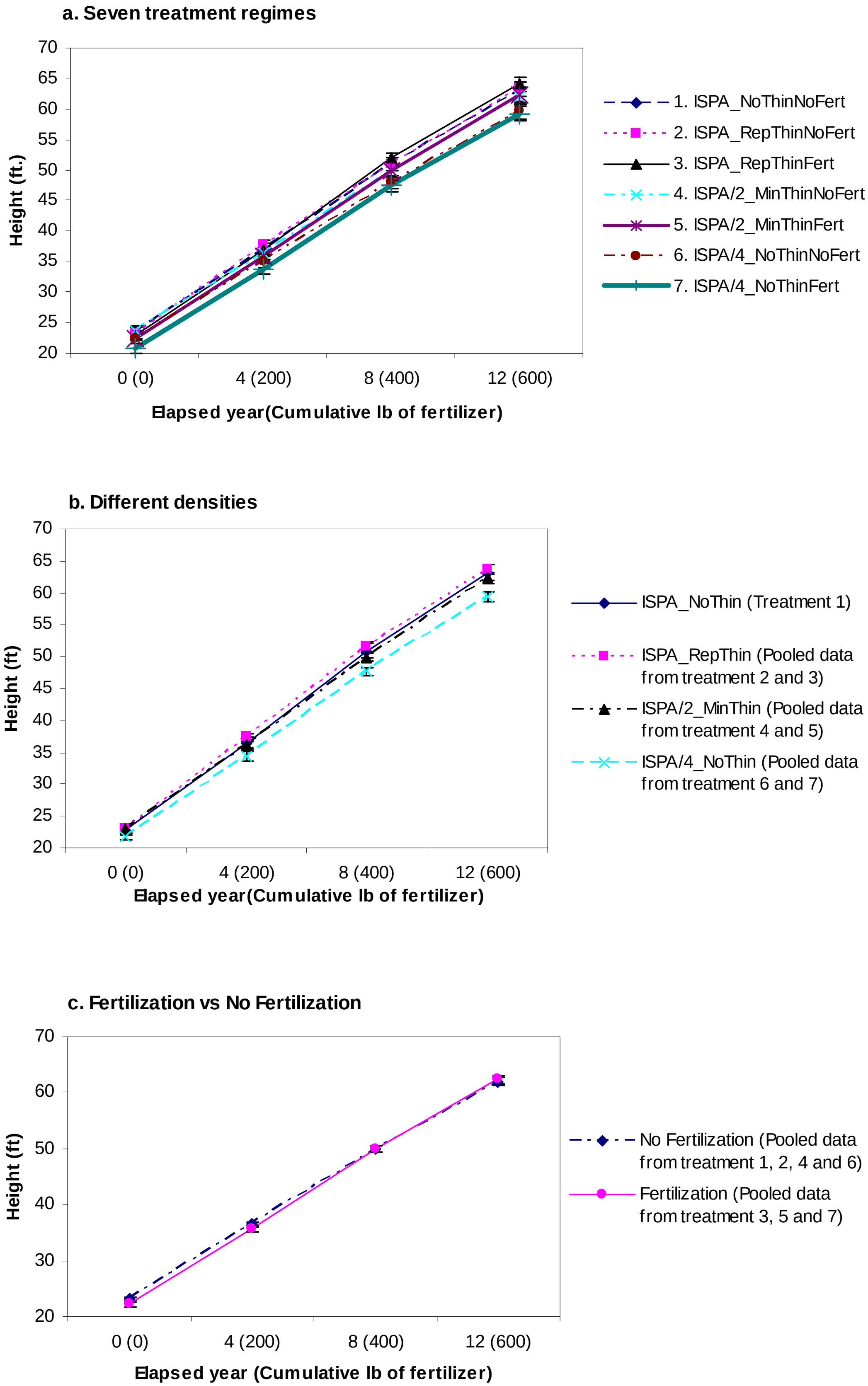
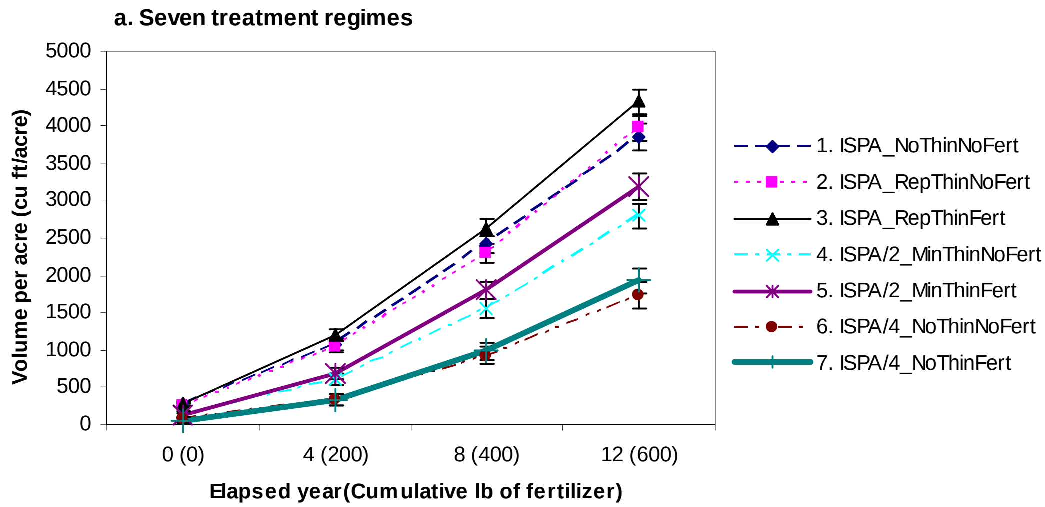
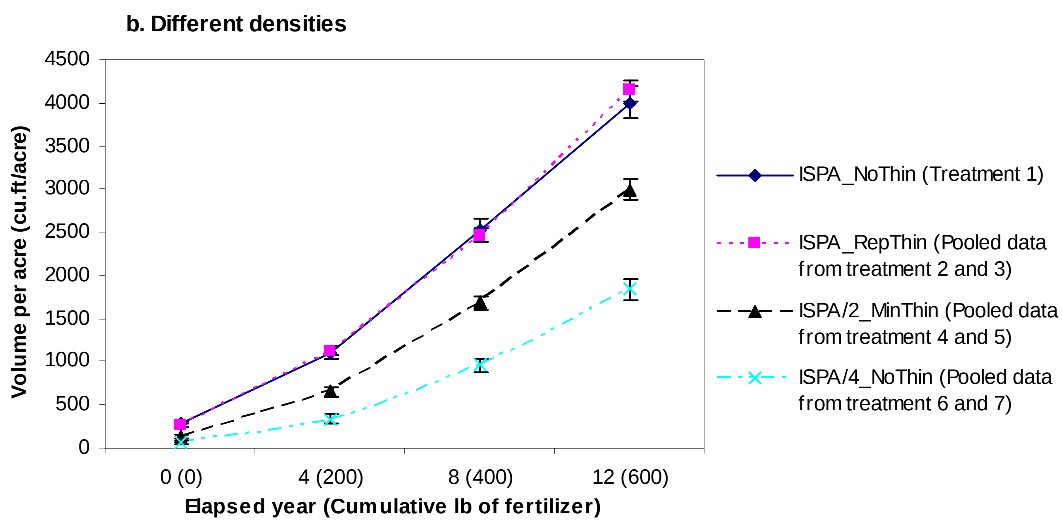


Figure 11: Cubic foot volume per acre trends over the course of the study





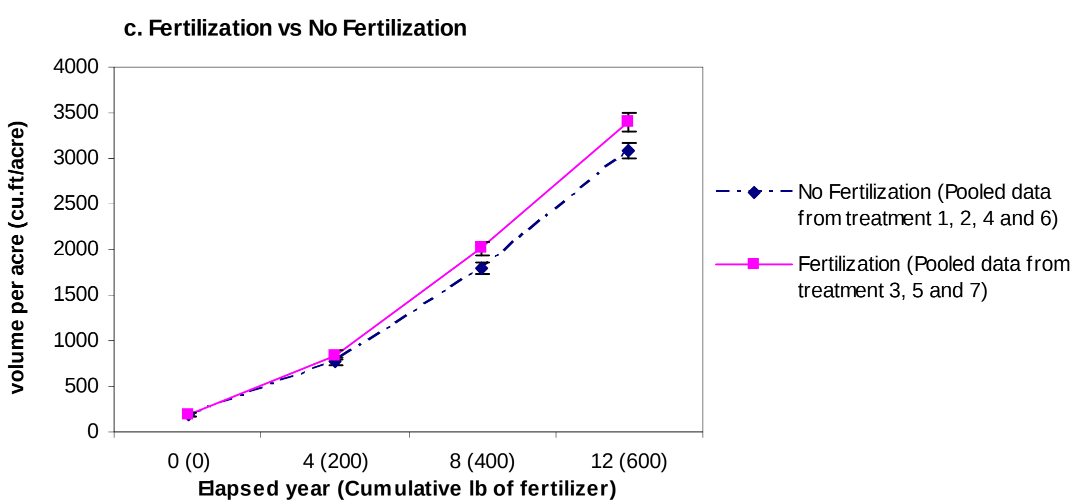
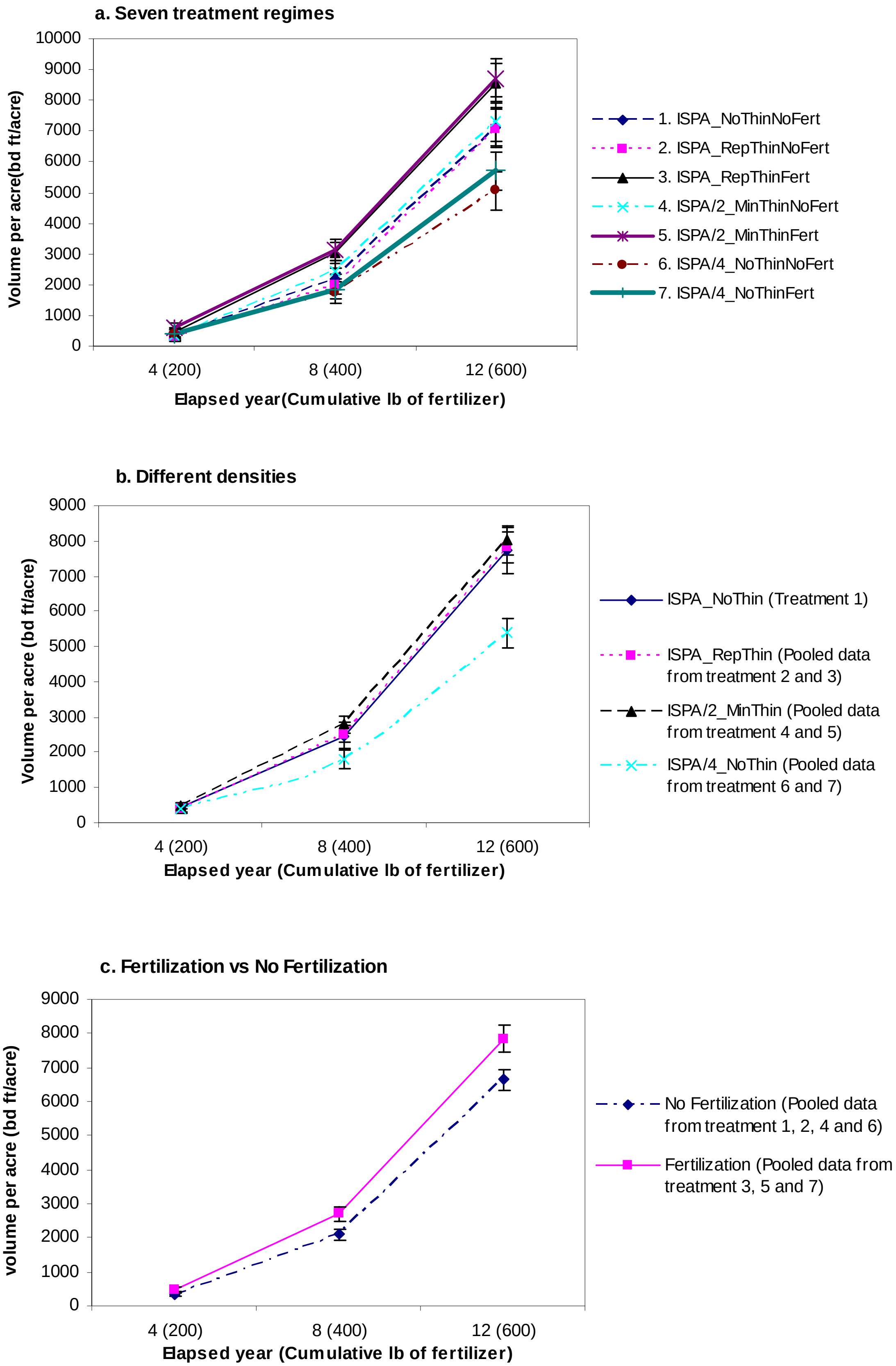


Figure 12: Scribner Board foot volume per acre trends over the course of the study



7.5 inches. At establishment when means stand age was 9 years, average QMD was about 3 inches (Table 4, Figure 6) too small for the Scribner calculation. After the frist growth period when mean stand age was 13, some plots reached the QMD threshold where Scribner volume could be calculated thus Figure 12 only shows the Scribner board foot volume at 4th, 8th and 12th year, mean stand age 13, 17, and 21 respectively, after establishment. Compared with the cubic foot volume trends in Figure 11, Scribner trends are generally similar but there are some shifts that undoubtedly reflect the minimum thresholds and other characteristics of the Scribner rule. For example, ISPA/2_MinThinFert has the greatest Scribner board foot volume from the 8th year after the establishment (Figure 12a), whereas for the cubic foot volume, ISPA/2_MinThinFert has less volume than all ISPAs (Figure 11a).

4.4 Whole Stand Mortality Analysis Results

Tree losses during the first three growth periods are shown in Figure 13. During the 1st growth period these seven treatment regimes had a similar number of dead trees, but their differences began to show during the 2nd growth period and continued to increase during the 3rd growth period. The ISPA_NoThinNoFert regime exhibited much more mortality than other treatment regimes. That's probably because its large initial density without subsequent thinning caused earlier crown closure and inter-tree competition. During the 1st growth period, ISPA_RepThinFert had slightly more dead trees than its unfertilized counterpart, but it fell below its unfertilized counterpart during the 2nd and 3rd growth periods and their difference seems to be increasing with time. Fertilization seemed to reduce mortality in ISPA_RepThin treatment. That's probably because ISPA_RepThin fertilized plots reached their thinning trigger earlier than unfertilized counterparts. The subsequent thinning in ISPA_RepThinFert plots decreased inter-tree competition and thus decreased mortality. In fact, during the first twelve years, more thinning took place in ISPA_RepThin fertilized plots than in unfertilized counterparts. In ISPA/2 and ISPA/4, mortality remained stable during the first three growth periods and there was no significant mortality difference between fertilized and unfertilized plots in ISPA/2 and ISPA/4.

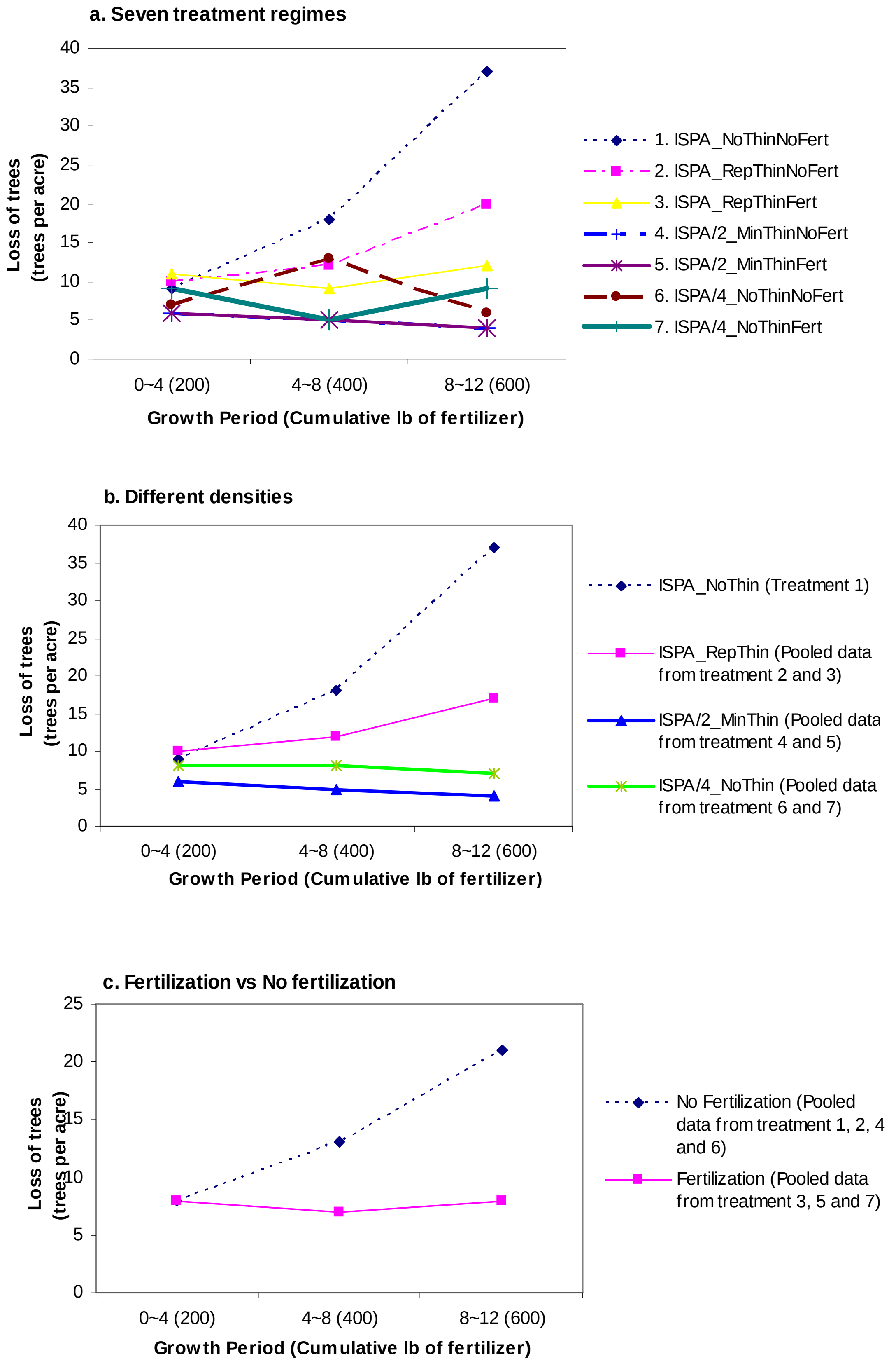
Examining pooled data for density treatments showed that ISPA/2 didn't differentiate from ISPA/4 on mortality, but they both had significantly less mortality than ISPA_NoThin and ISPA_RepThin during the 2nd and 3rd growth periods (Figure 13b). Mortality in ISPA_NoThin increased very quickly during the 2nd and 3rd growth periods and became significantly greater than that in ISPA_RepThin.

Figure 13c shows stand mortality from pooled fertilized and unfertilized plots. Fertilized plots experienced relatively constant but small mortality (about 8 trees per acre per growth period), while mortality in unfertilized plots increased quickly from 8 trees per acre during the 1st growth period, to 13 trees per acre during the 2nd growth period, and to 21 trees per acre during the 3rd growth period.

4.5 Crop Tree Growth and Yield Analysis Results

In this study, crop tree is defined as the 40 largest diameter trees per acre. The idea of crop tree analysis is to see how the large trees respond to density and fertilization treatments, since a given amount of response in larger trees may represent potentially greater final harvest value than the same amount spread over all trees in the stand.

Figure 13: Whole stand mortality over the course of the study

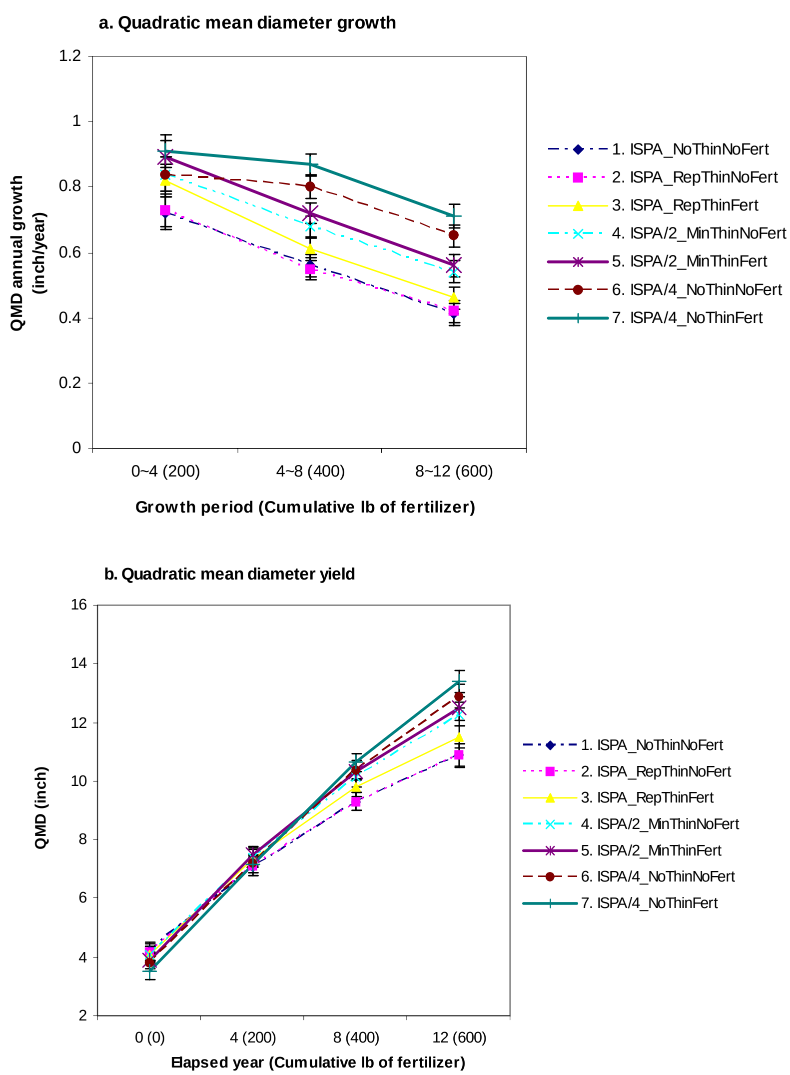


For crop tree analysis, only results from diameter, basal area and volume are presented since height results from the 40 largest trees per acre (dominant height) have already been discussed in the previous whole stand section. Crop tree growth and yield results are presented together and only those differing from the whole stand are highlighted.

4.5.1 Quadratic Mean Diameter

As shown in Figure 14, crop trees had a similar diameter response pattern as did the whole stand, which is the denser stands exhibited less QMD growth and yield and fertilization increased QMD growth and yield within each density. Initial crop tree QMD in ISPA/4 plots was a little less than that in ISPA/2 plots, which was a little less than that in ISPA plots (Figure 14b), but in the 4th year, ISPA/2 plots exceeded ISPA because of its greater crop tree QMD growth rate during the 1st growth period (Figure 14a). However, ISPA/4 was indistinguishable from ISPA in the 4th year despite its greatest QMD growth rate during the 1st growth period. After eight years, crop tree QMD yield in ISPA/4 exceeded ISPA/2 and ISPA and became the largest one, followed by ISPA/2, then by ISPA. At year twelve, the year 8 pattern continued to be true but with bigger differences. Within each density level, fertilization gen-

Figure 14: Crop tree diameter growth and yield trends over the course of the study



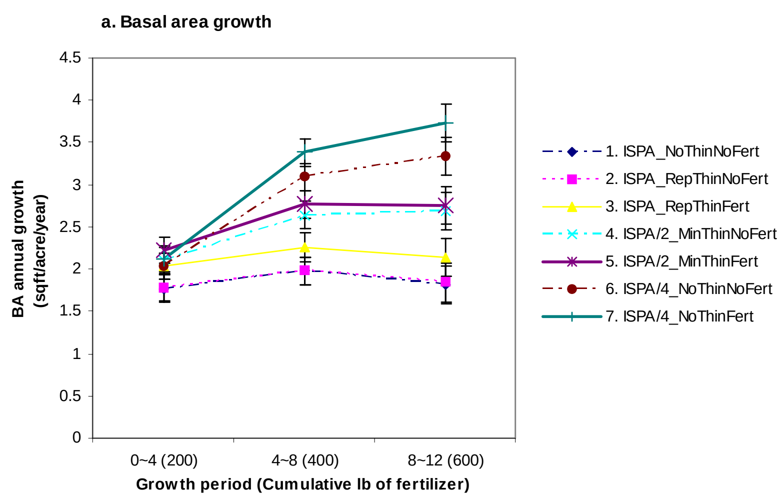
erally increased crop tree QMD growth and yield, but these increases were not statistically significant.

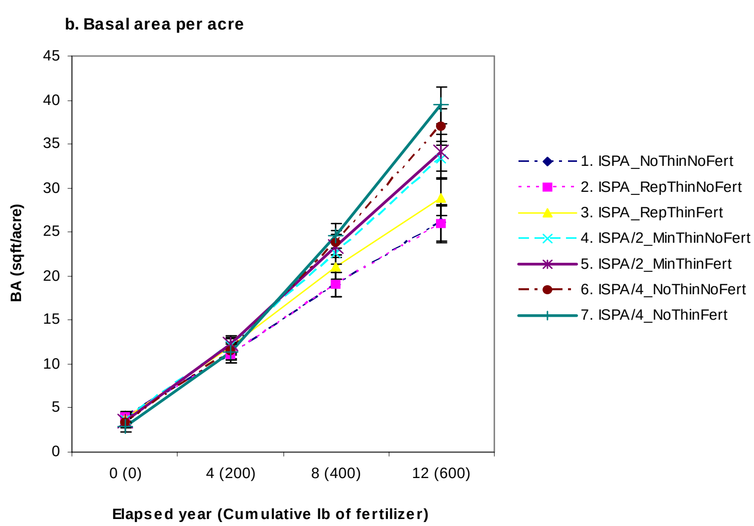
For crop tree QMD growth and yield, there was no significant interaction between density and fertilization treatments. The effects of density control were insignificant for QMD growth during the 1st growth period, but became significant during the 2nd and 3rd periods. Fertilization effects were significant only in the 2nd growth period. As for QMD yield, density was significant in year 8 and 12, but fertilization was not significant at any measurement.

4.5.2 Basal Area Per Acre

Crop tree basal area response to density treatment had a very different pattern from the whole stand. For crop trees, initial basal area stocking was the same among all density stands due to the same number of the crop trees. As time went on, crop trees in spaced stands began to outperform unspaced stands and their differences increased over time (Figure 15). During the 3rd growth period, crop trees basal area growth rate in ISPA/4_NoThinFert was about

Figure 15: Crop tree basal acre growth and yield trends over the course of the study





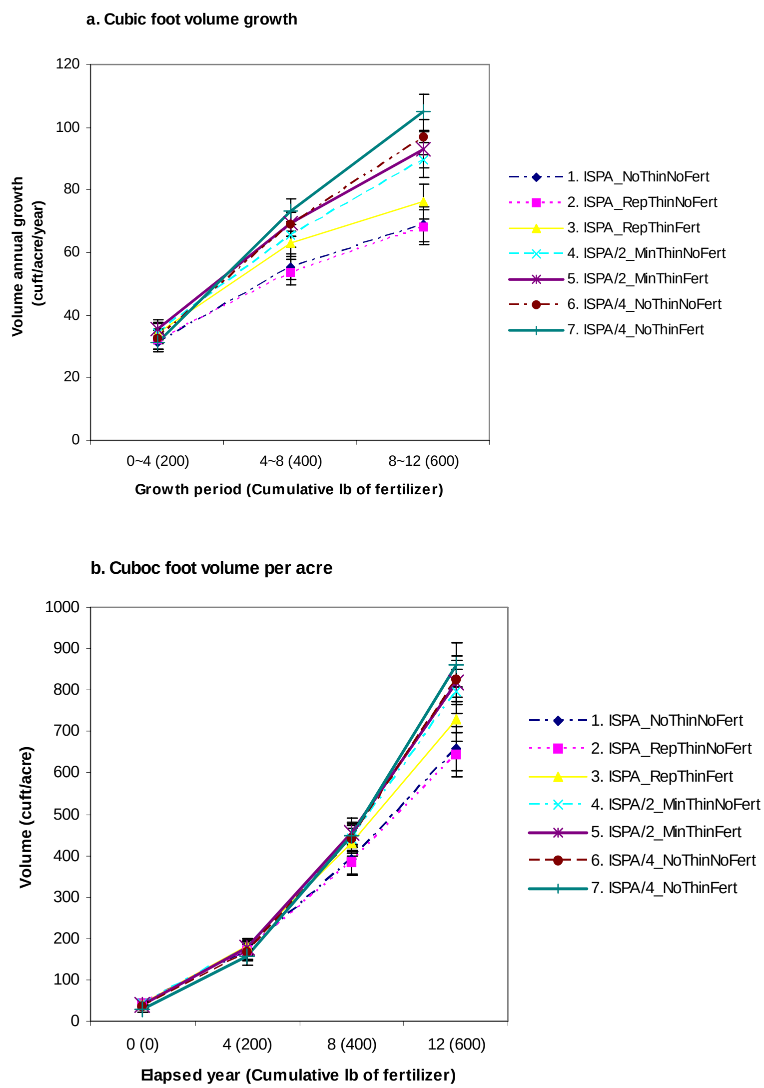
twice that in ISPA_NoThin and ISPA_RepThin. For the whole stand, the results were the opposite with spaced stands having less basal area growth and yield due to the fewer number of trees. Within each density level, fertilization generally increased basal area growth and yield, but these increases were not statistically significant.

For crop tree basal area growth and yield, there was no significant interaction between density and fertilization treatments. The effects of density control were insignificant for basal area growth rate during the 1st growth period, but became significant during the 2nd and 3rd periods. As for basal area yield, density treatment was significant in year 8 and 12, but not in year 4. Fertilization was not significant for basal area growth and yield at any measurement.

4.5.3 Cubic Foot Volume

Crop tree volume responded to density treatment in a pattern similar to that described for basal area. As shown in Figure 16, initial crop tree volume growth and yield were statistically the same among the different densities. As time went on, less dense plots experienced

Figure 16: Crop tree cubic foot volume growth and yield trends over the course of the study



greater crop tree volume growth. Within each density level, fertilization generally increased crop tree growth and yield, but these increases were not statistically significant.

For crop tree cubic foot volume growth and yield, there was no significant interaction between density and fertilization treatments. The effects of density control on volume growth were significant during the 2nd and 3rd periods. But this significant volume growth difference during the 2nd growth period didn't translate into significant volume yield difference in year 8, and significant volume yield difference didn't appear until year 12. Fertilization effects were not significant for volume growth and yield at any measurement.

CHAPTER 5. DISCUSSION

5.1 Whole Stand

Table 5 summarizes the whole stand attributes after three four-year growth periods, a total of 12 years. Compared to Table 4, one can see that, after 12 years, QMD had significantly increased and was progressively greater from ISPA to ISPA/2 to ISPA/4. Basal area and volume also increased significantly and the ratio between ISPA, ISPA/2 and ISPA/4 changed from 4:2:1 at establishment to 4:3:2 in the 12th year. Although height changed over the 12-year period, it remained indistinguishable among the seven treatment regimes. Within each density level, fertilization plots exhibited greater QMD, basal area per acre and volume per acre than their unfertilized counterparts.

5.1.1 Density Effect

Density had great effects on stand growth and yield, and most of the density effects came from the initial spacing since only eight plots were actually thinned during the 12 years study period. That's why in most cases ISPA_NoThinNoFert and ISPA_RepThinNoFert were not significantly different from each other.

Diameter: Many sources indicate that radial growth increases with increased spacing (Sjolte-Jorgensen 1967, King 1986, Curtis and Marshall 2002). This was supported by this study. At establishment, there were no significant differences among the treatments on stand quadratic mean diameter (Table 4). After 12 years growth, QMD progressively increased from ISPA to ISPA/2 to ISPA/4 since the wider spacing experienced by ISPA/4 and ISPA/2 gave remaining trees more room to grow. In fact, ISPA/4 exhibited the greatest QMD growth rate for all three growth periods (Figure 2). Not only did widely spaced treatment regimes exhibit larger QMD, they also had a higher proportion of trees in larger diameter classes (Figures 7 and 8), implying higher value at final harvest. This finding is consistent with results from the LOGS study (Curtis and Marshall 2002).

Basal Area: Basal area is positively correlated with density level, with denser stands having greater basal area growing stock. Removal of growing stock by spacing at establishment had a negative effect on basal area growth immediately after establishment. ISPAs with more trees had greater periodic annual basal area growth than both ISPA/2 and ISPA/4. Twelve years after establishment, ISPAs continued to exhibit more basal area per acre than did ISPA/2 and ISPA/4. However, ISPA/2 and ISPA/4 had an increasing basal area annual growth pattern while ISPA had a decreasing pattern. By the end of the 3rd growth period, basal area growth rate in ISPA/4 became close to ISPAs, and basal area growth rate in ISPA/2 actually exceeded the ISPAs (Figure 3). This implies that ISPA/2 and ISPA/4 have started to accumulate basal area at the same or even greater rate than the ISPAs. We could expect that lightly spaced ISPA/2 stands would recover from initial stocking removal and quickly catch ISPAs in terms of basal area per acre. Heavier spaced ISPA/4 stands might also catch the ISPA in the future.

Table 5: Average stand attributes in the 12th year after establishment for 56 SMC Type I Douglas-fir plots

Stand Attributes	1.ISPA_ No Thin No Fert	ISPA_RepThin		ISPA/2_MinThin		ISPA/4_NoThin	
		2. No Fert	3. Fert	4. No Fert	5. Fert	6. No Fert	7. Fert
QMD (in.)	2.96 (1.94-4.04)*	2.90 (1.96-3.64)	2.98 (2.23-4.57)	3.07 (2.12-3.98)	3.04 (2.19-4.58)	3.11 (2.07-4.59)	2.90 (1.88-3.93)
Basal area (sq ft/acre)	26.74 (6.04-62.50)	24.95 (7.74-54.86)	25.78 (8.65-63.82)	12.53 (3.08-22.65)	13.01 (4.44-31.39)	6.86 (3.00-14.24)	5.95 (2.09-12.28)
HT40 (ft.)	23.4 (15.2-31.6)	23.3 (15.5-31.4)	22.8 (15.6-32.9)	23.7 (15.0-34.2)	22.5 (15.3-33.2)	22.4 (16.0-33.2)	20.9 (15.2-30.3)
Volume (cu ft/acre)	280.7 (51.0-784.0)	258.5 (60.0-683.0)	272.6 (67.0-838.0)	129.6 (26.0-285.0)	137.0 (35.0-410.0)	71.8 (23.0-188.0)	60.0 (16-151.0)
Breast height Age (year)	5.6 (3-9)	5.4 (3-9)	5.6 (3-10)	5.7 (3-9)	5.3 (3-9)	5.0 (3-10)	5.0 (3-9)
Trees per acre	509 (248-716)	509 (302-800)	481 (294-752)	228 (126-324)	234 (170-334)	121 (94-154)	119 (76-162)
Relative density	15.24 (4.16-33.52)	14.66 (5.26-32.80)	14.43 (5.79-31.17)	6.96 (2.12-11.35)	7.17 (3.00-14.75)	3.75 (1.93-6.65)	3.36 (1.52-6.20)
Site index (30 year total age)	88.3 (74-100)	85.4 (74-98)	85.2 (71-94)	87.8 (70-97)	87.3 (70-95)	86.0 (72-96)	85.3 (75-94)
Sample Size	9	9	9	9	9	9	9

* Numbers inside parentheses denote the range

Height: Height response to density control is mixed in the literature. In this study, a slight height growth reduction after early spacing was observed for the first eight years since both ISPA/2 and ISPA/4 exhibited less dominant height growth than ISPAs during the first two four-year growth periods (Figure 4). However, ANCOVA testing indicated that these reductions were not statistically significant. During the 3rd growing period, both ISPA and ISPA/2 had the same dominant height growth rate and the reduction was recovered in ISPA/2. Thinning shock was not really observed in this study. The reason is perhaps because of the relatively high site quality of these installations.

Volume: Volume growth and yield exhibited a general pattern similar to that previously discussed for basal area. ISPAs had the greatest cubic foot volume, ISPA/2 was in the middle and ISPA/4 had the least volume (Figure 11). However, during the 3rd growth period, the ISPA_NoThin began to slow down in terms of volume annual growth while others still kept an increasing volume growth trend (Figure 5).

Mortality: As would be expected, density also affected stand mortality with the denser stand having greater mortality (Figure 13), especially during the last growth period in which the canopy began to close in the unspaced stands and inter-tree competition was intensified. This result is consistent with both RFNRP and BC Shawnigan Lake studies.

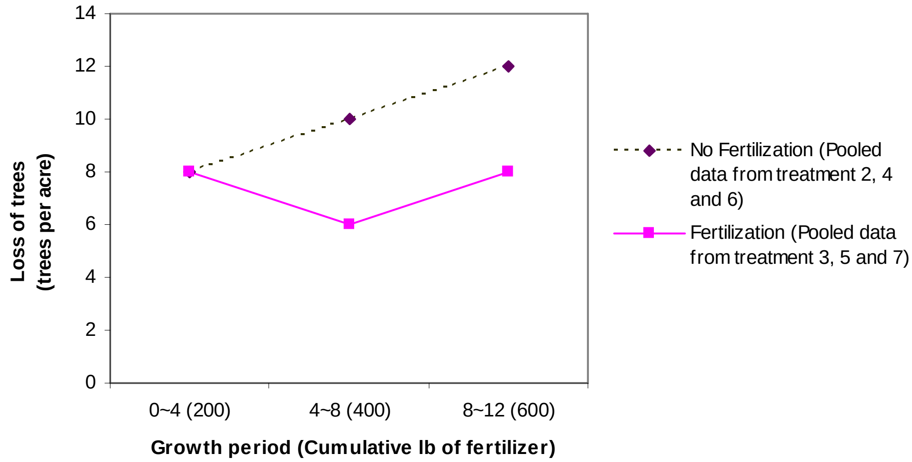
5.1.2 Fertilization Effect

In this study, results across all densities indicated that the first urea application at establishment significantly increased average periodic annual increment of QMD, basal area and volume respectively by 12.7%, 14.8% and 12.0% over the unfertilized plots during the 1st four-year growth period. After the 2nd urea application in year 4, these increases became 9.6% for QMD, 15.5% for basal area and 14.1% for volume during the 2nd growth period (year 4 – year 8). After the 3rd fertilization at year 8, four-year annual growth increases induced by fertilization were 10.0%, 7.2% and 6.7% respectively for QMD, basal area and volume. Though growth in fertilized plots increased after all urea applications, these increases were statistically significant only after the 1st ($p=0.0010$) and 2nd ($p=0.0183$) urea applications. The 3rd urea application combining the residual effects (if any) from the 1st and 2nd applications didn't produce significant growth increase over unfertilized stands ($p=0.0807$). In this study, significant growth response to multiple 200lb N/acre urea applications seemed to last no longer than eight years. This duration is short compared to RFNRP and BC studies. This may be due to the relatively high site quality in the study locations. Among the nine installations analyzed, seven belong to site class II according to the original site index number in the database, one is site class I, and only one installation is site class IV. So after three applications of urea, nitrogen in the soil may no longer be the limiting factor for tree growth. Past studies also showed that stands growing on medium and good sites generally had lower and shorter duration growth gains than stands on poorer sites (Miller et al 1977, Miller et al 1986, Stegemoeller and Chappell 1991).

Compared to growth response, there is a delay in stand yield response to fertilization. Four years after the first urea application, QMD, basal area and volume in fertilized plots were increased by 5.1%, 10.0% and 9.5% respectively, but these increases were not statistically significant. The significant growth response over the first four years following the initial urea application did not translate into an immediately significant change in stand yield. After the 2nd application at the end of year 4 and 4 more years growth (8 years total), the gains due to fertilization became 5.9%, 13.1% and 12.1% respectively for QMD, basal area and volume and these gains were statistically significant. After the third application at the end of year 8, and 4 more years growth (12 years total), the gains were 7.1% for QMD, 9.1% for basal area and 10.2% for volume and these were also significant. Significant fertilization effects on stand yield showing later than on growth implied that there may be a possible lag or cumulative effect before the gains in growth rate translated into significant gains in yield. Another point is that the greater stand yields in the fertilized plots is concentrated on larger size trees (Figures 7 and 8), which represent greater potential future value.

Fertilization accelerating mortality in unthinned dense stands has been reported by many studies (Gessel et al 1965, Heilman 1971, Miller and Tarrant 1983). There are also reports indicating that fertilization does not increase mortality in thinned stands (Miller et al 1986). In this study, pooled data from all density levels indicated that mortality in the fertilized plots was less and relatively more stable compared to unfertilized plots (Figure 13). The reason is probably because the experimental design is not balanced and there is no ISPA_NoThin with fertilization treatment regime, in which much mortality would be expected due to tight spacing and intense inter-tree competition. In fact, during the first 12 years, mortality in the ISPA_NoThinNofert treatment regime increased very quickly and most

Figure 17: Whole stand mortality trends for fertilization regimes (without ISPA_NoThinNoFert plots) over the course of the study



mortality came from this treatment. Figure 17 shows the mortality in pooled fertilized and unfertilized plots but without the ISPA_NoThinNoFert plots. Compared to Figure 12c, after leaving ISPA_NoThinNoFert plots out, mortality in unfertilized plots dropped quickly, thus the mortality difference between fertilized and unfertilized plots decreased. However, mortality in fertilized plots is still below that in unfertilized plots. This may be due to the relatively modest stand densities tested, in which tree vigor was increased by fertilizer, thus the probability of tree death decreased.

5.1.3 Fertilization Effect Within Different Density Treatments

Across all densities, fertilization significantly increased diameter, basal area and volume growth in the first two growth periods. However, close inspection revealed that growth response patterns to fertilization were not the same among different density stands, even though no statistically significant interaction was found. Figure 18 shows the growth rate gains by fertilization for each growth period and each density treatment. These gains were calculated by subtracting the growth rate of unfertilized plots from their fertilized counterparts. As shown in Figure 18, after the first 200lb N/acre urea application, the greatest growth boost was in ISPA_RepThin. As time went on and more urea applied, QMD growth rate fertilization gains didn't change much, but basal area and volume growth rate gains in ISPA_RepThin decreased. After three urea applications, basal area and volume growth rate in ISPA_RepThin fertilized plots fell below those in the unfertilized plots. In contrast, after the first urea application, stand annual growth in QMD, basal area and volume for the ISPA/4_NoThin regime didn't gain much, but as more urea was applied, growth rate increased. So denser stands responded to the first fertilization faster and greater than did the less dense stands. However, these responses in denser stands decreased over time, while responses in less dense stands increased. That's probably because in denser stands, like ISPA_RepThin, nitrogen was the limiting factor during the first growth period and it responded quickly to the first urea application. As a result, fertilized stands in ISPA_RepThin reached thinning triggers earlier than their unfertilized counterparts, and the subsequent thinning in fertilized stands decreased stand growth in the following growth periods. As for low density stands, wide spacing delayed the use of nitrogen by trees, perhaps due to competition by other vegetation for nitrogen use.

As regards stand yield, fertilization gains in diameter and volume per acre had increasing patterns for all density stands (Figure 19). However, from year 8 to year 12, fertilization gains in volume per acre increased little in ISPA_RepThin, whereas they increased a lot in less dense ISPA/2 and ISPA/4 stands. Due to the decreasing fertilization gains in volume growth rate in ISPA_RepThin (Figure 18), we could expect fertilization gains in volume yield in ISPA_RepThin will decrease soon. Fertilization gains in basal area decreased in ISPA_RepThin while they increased in ISPA/2 and ISPA/4 stands. So after the 1st and 2nd urea applications, fertilization gains in basal area and volume in dense stands were greater than those in less dense stands, but as more urea was applied, these gains either decreased or stayed the same in dense stands while gains increased in less dense stands.

The growth and yield gains shown in Figure 18 and 19 are the marginal gain due to fertilization for each density. They should not be interpreted as evidence of interaction between density and fertilization treatments. As presented earlier, statistical testing using actual measurement data found no significant interaction. The effects from fertilization and density were additive. This is consistent with Shawnigan Lake results (McWilliams and Therien 1996), but contradicts the RFNRP results (Segemoeller and Chappell 1991). The reason is probably because spacing to half and one-quarter of initial density is relatively heavy, and spaced stands haven't fully recovered from this during the first 12 years. As time goes on, after spaced stands catch up with the unspaced ones in terms of stand yield, the advantage of combining density control and fertilization treatments is very likely to be observed.

5.2 Crop Tree

Crop tree density responses were very different from the whole stand. When only crop trees were considered, more intensively spaced stands had greater basal area and volume growth and yield, while in the whole stand, spaced stands had less basal area and volume growth and yield. Crop trees in the ISPA/4 exhibited the greatest growth and yield of diameter, basal area per acre and volume per acre, followed by ISPA/2, then ISPAs. Significant crop tree growth responses to the density treatments occurred during the 2nd and 3rd growth periods, but not in the 1st growth period. So compared to the whole stand, density effects on crop tree growth appeared later. As for the fertilization treatments, crop tree responses were much less than the whole stand. ANCOVA tests indicated that the fertilization effect was only significant on crop tree QMD annual growth during the 2nd growth period and it was not significant on crop tree yield at any measurement. Compared to the whole stand, crop tree responses to density and fertilization treatments were less in magnitude during the first 12-years of the study. That's probably because crop trees are dominant trees and they are superior in competing for resources. So the relatively good site quality provides sufficient resources for them and they may not need the additional advantage from urea application and density treatments.

Figure 18: Whole stand growth gains due to fertilization for each growth period and each density treatment

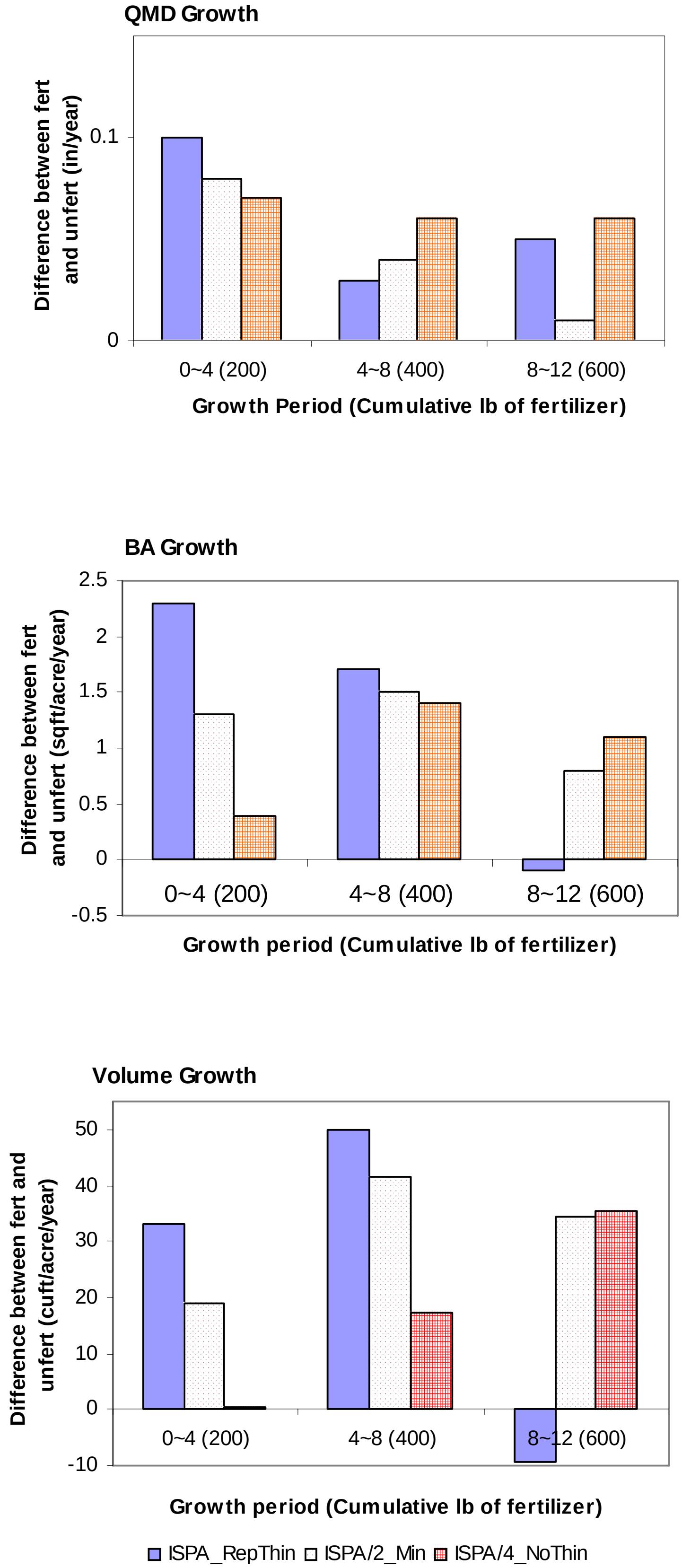
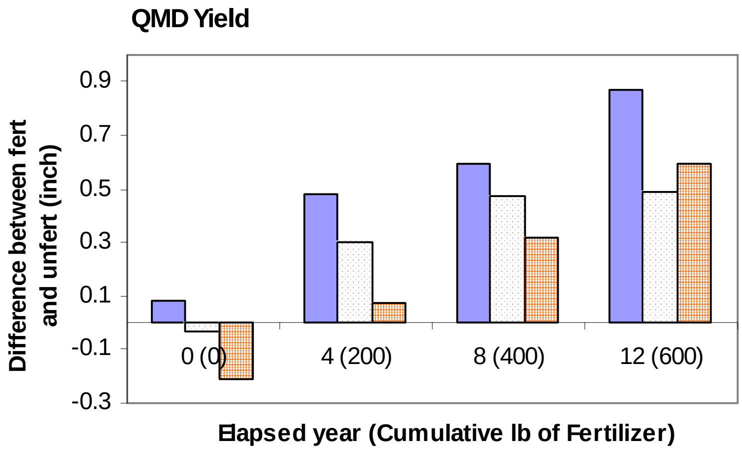
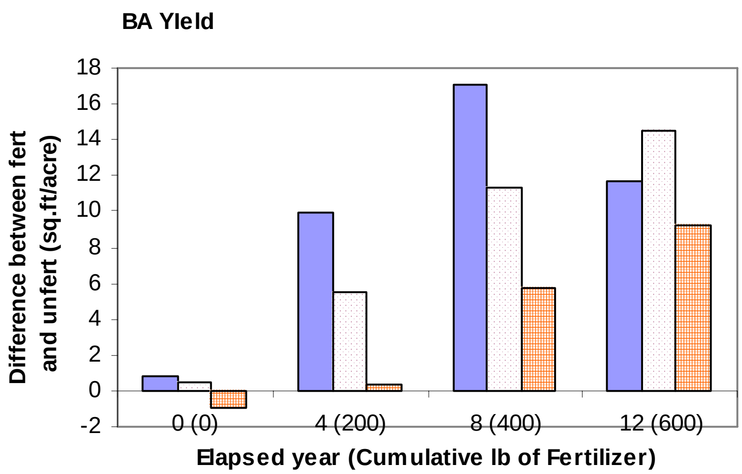
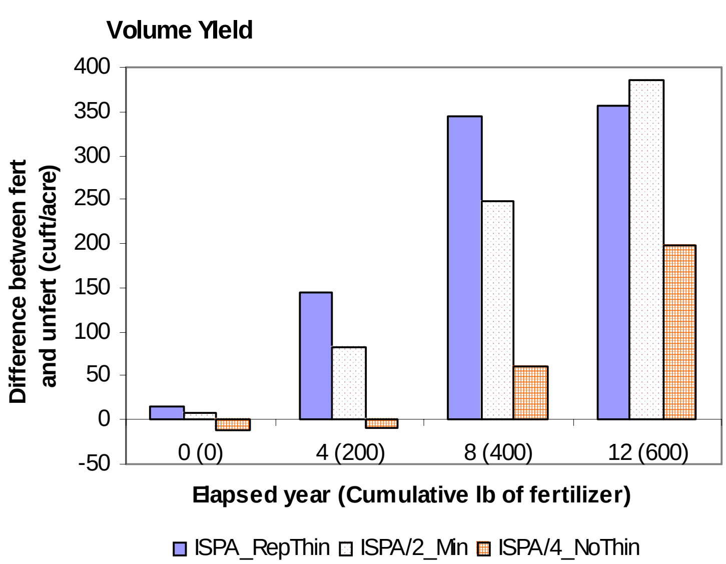


Figure 19: Whole stand yield gains due to fertilization at establishment, year 4, 8 and 12







CHAPTER 6. CONCLUSIONS

The objective of this study was to analyze growth and yield response to fertilization and density treatments in young Douglas-fir stands. Based on previous discussion, now the research questions listed in Chapter 2 will be answered as below.

1. Do different density control regimes significantly affect stand growth and yield in terms of diameter, basal area, height and cubic foot volume?

   Different density control regimes do significantly affect whole stand diameter, basal area and volume growth and yield, but don't affect height very much. Initially, the densest stand had the greatest overall stocking and growth rate. However, accumulation in the dense stands is declining with time and the less dense stands are catching or exceeding them.

   Density control regime also affected diameter class distribution with less dense stands having greater proportions of trees in larger diameter classes.

2. Do repeated urea applications produce significant increases in stand growth and yield in terms of diameter, basal area, height and cubic foot volume?

   Across all densities, fertilization produced additional growth and yield in diameter, basal area and cubic foot volume, but not in dominant height. QMD, basal area and volume growth rates were significantly increased by the first and second urea applications but not by the third. In contrast, the first fertilization was insufficient to produce a significant increase in QMD, basal area per acre or volume per acre; significant increases in these variables were found following the second and the third applications.

   Compared to density treatment, fertilization treatment had less effect on stand growth and yield.

3. Do significant interactions exist between fertilization and density treatments?

   No, no significant interactions were found for all variables tested. However, fertilization responses did show different trends among the different density treatments over time. Fertilization gains in stand basal area and volume growth and yield were decreasing with time in denser stands whereas they were increasing in less dense stands, but these differences are not statistically significant.

4. Do density and fertilization treatments affect stand mortality?

Yes. During the twelve-year study period, mortality increased quickly in denser stands whereas it remained stable in less dense stands. Mortality in fertilized stands was less than unfertilized counterparts

5. Does the crop tree stand component (the 40 largest diameter trees per acre) have the same response pattern as the whole stand?

Compared to the whole stand, crop trees responded differently to the density treatment with crop trees in less dense stands exhibiting greater basal area and volume growth and yield. Also crop trees responses to density treatment appeared later. Like in the whole stand, fertilization produced additional crop trees growth and yield, but these gains in crop trees were not statistically significant.

REFERENCES

Brix, H. 1993. Fertilization and thinning effect on a Douglas-fir ecosystem at Shawnigan Lake: a synthesis of project results. FRDA Rep. 196. Victoria, BC: Forest Canada, Pacific Forestry Center; BC ministry of forests, research branch. 64p.

Bruce, D. and Demars, D.J. 1974. Volume equations for second-growth Douglas-fir. Res. Note. PNW-239. Portland, Oregon: USDA Forest Service. PNW station. 5p.

Chappell, H.N.; Omule, S.A.Y. and Gessel, S.D. 1992. Fertilization in coastal northwest forests: using response information in developing stand-level tactics. *In* Forest fertilization: sustaining and improving nutrition and growth of western forests. *Edit by* Chappell, H.N.; Weetman, G.F; Miller, R.E. University of Washington, College of Forest Resources, Institute of Forest Resources. Seattle. Contrib. 73. : 98-113.

Crown, M., Quenet, R.V., and Layton, C.R. 1977. Fertilizaiton and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake. Can. For. Serv Pac. Forest Research Center Inf. Rep. BC-X-152.

Curtis, R.O. and Reukema, D.L. 1970. Crown development and site estimates in a Douglas-fir plantation spacing test. Forest Science: 16(3): 287-301.

Curtis, R.O. and Marshall, D.D. 2002. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 14 – Stampede Creek: 30-year results. Res. Pap. PNW-RP-543. Portland, OR: USDA Forest Service, PNW station. 77p.

Franklin, J.F. and Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen Tech. Rep. PNW-8. Porland, OR: USDA Forest Service, PNW station. 417p.

Flewelling, J., Collier, R., Gonyea, B., Marshall, D. and Turnblom, E. 2001. Height-age vurves for planted stand of Douglas-fir, with adjustments for density. Stand Management Cooperative working paper. No.1. 25p.

Gessel, S.P., Stoate, T.N. and Turnbull, K.J. 1965. The growth behavior of Douglas-fir eith nitrogenous fertilizer in western Washington. Institute of Forest Resources, Contrib. No. 1. University of Washington, Seattle. 204p.

Hagglund, B. 1981. Evaluation of forest site productivity. For. Abstr. 42 (11): 515-527

Harrington, C.A. and Reukema, D.L. 1983. Initial shock and long term stand development following thinning in a Douglas-fir plantation. Forest Science 29 (1): 33-46.

Heilman, P. 1975. Thinning method and response to urea in Douglas-fir. Forest Science. 21 (4): 418-420.

King, J.E. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forest Paper. 8. Weyerhaeuser Company Research Center, Centralia, Washington. 49p.

King, J.E. 1986. Review of Douglas-fir thinning trials. *In* Douglas-fir: Stand management for the future. *Edited by* C.D.Oliver, D.P. Hanley and J.A. Johnson. College of forest resources, University of Washington, Seattle. Contrib. No.55. 258-280.

Lee, Y. J. and Barclay, H. J. 1985. Ten-year growth response of a 25-year-old and a 55-year-old Douglas-fir. Information report. Pacific Forest Research Center, Canada. BC-X-260, 14p.

Li, Y. Zh. 2005. Effects of Fertilization and Density on Growth and Yield of Young Douglas-fir Plantations in the Pacific Northwest. MS thesis. College of Forest Resources, University of Washington, Seattle, WA.

Maguire, D.A, Bennett, W.S., Kershaw, Jr. J. A., Gonyea, R. and Chappell, H. N. 1991. Stand Management Cooperative silviculture project field installations: Establishment report 27p.

McWilliams, E.R.G. and Therien G. 1996. Fertilization and thinning effects on a Douglas-fir ecosystem at Shawnigan Lake: 24-year growth response. Canada-British Columbia Partership Agreement on Forest Resource Development: FRDA II. FRDA Report 269. 44p

Miller, R.E. and Reukema, D.L. 1977. Urea fertilizer increases growth of 20-year-ole thinned Douglas-fir on a poor quality site. Res. Note PNW-291. Portland, OR: USDA Forest Service, PNW station. 8p.

Miller, R.E. and Tarrant, R.F. 1983. Long-term growth response of Douglas-fir to ammonium nitrate fertilizer. Forest Science 29:127-137.

Miller, R.E., Barker, P.R., Peterson, C.E. and Webster, S.R. 1986. Using nitrogen fertilizers in management of coastal Douglas-fir I. Regional trends of response. *In* Douglas-fir: Stand management for the future. *Edited by* C.D.Oliver, D.P. Hanley and J.A. Johnson. College of forest resources, University of Washington, Seattle. Contrib. No.55. 290-303

Miller, R.E.; Hazard, J.W. and Bruce, D. 1991. Response of western Oregon stands to nitrogen fertilizer. Interagency Agreement PNW 88-557. Portland, OR.

Miller, R. E., Obermeyer, E. L. and Anderson, H. W. 1999. Comparative effects of precommercial thinning, urea fertilizer, and red alder in a site II, coast Douglas-fir plantation. Res. Pap. PNW-RP-513. Portland, OR: U.S. Department of Agriculture, Forest Service, PNW Research station. 25p.

Miller, R. E., Smith, J. and Anderson, H.W. 2001. Detecting response of Douglas-fir plantations to urea fertilizer at three locations in the Oregon Coast Range. Res. Pap. PNW-RP-533. Portland, OR: USDA, Forest Service, PNW station. 20p.

Peterson, C.E.; Webster, S.R.; Barker, P.R. and Miller, R.E. 1986. Using Nitrogen fertilizers in management of coast Douglas-fir: II future informational needs. *In* Douglas-fir: Stand management for the future. *Edited by* C.D.Oliver, D.P. Hanley and J.A. Johnson. College of forest resources, University of Washington, Seattle. Contrib. No.55. 304-309.

Reukema, D.L. 1972. Twenty-one-year development of Douglas-fir stands repeatedly thinned at varying intercals. Res. Pap. PNW-141. Portland, OR: USDA Forest Service, PNW station. 23p.

Reukema, D.L. and Bruce, D. 1977. Effects of thinning on yield of Douglas-fir: Concept and some estimates obtained by simulation. Gen. Tech. Rep. PNW-58. Portland, OR: USDA, Forest Service, PNW station. 36p.

Sjolte-Jorgensen, J. 1967. The influence of spacing in the growth and development of coniferous plantations. Int. Rev. For. Res. 2: 43-94.

Smith, H. J. and Reukema, D. L. 1986. Effects of plantation and juvenile spacing on tree and stand development. *In* Douglas-fir: Stand management for the future. *Edited by* C.D.Oliver, D.P. Hanley and J.A. Johnson. College of forest resources, University of Washington, Seattle. Contrib. No.55. 239-245.

Staebler, G.R. 1956. Evidence of shock following thinning of young Douglas-fir. Journal of Forestry. 54(5): 339.

Stegemoeller, K.A. and Chappel H.N. 1991. Effects of fertilization and thinning on 8-year growth responses of second-growth Douglas-fir stands. Canadian Journal of Forest Research. 21: 516-521.

Williamson, R. L. and Curtis, R.O. 1980. Estimating merchantable volumes of second growth Douglas-fir stands from total cubic volume and associated stand characteristics. USDA Forest Service Research Note, PNW-353. 1