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Evaluation of harvesting disturbance and establishment practices on early height growth of loblolly pine (Pinus taeda L.)

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EVALUATION OF HARVESTING DISTURBANCE AND ESTABLISHMENT PRACTICES ON EARLY HEIGHT GROWTH OF LOBLOLLY PINE (*PINUS TAEDA* L.)

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Land for forest plantations is declining while demand for forest products is increasing, creating concern over sustainable forest management. Maintenance of site productivity is fundamental to forest sustainability, and an assessment of cumulative height growth is a useful index of productivity. Loblolly pine height data were used from four research plantations installed by the project Cooperative Research in Sustainable Silviculture and Soil Productivity from Texas to Georgia. The sites vary in soil characteristics, management history, nutrient status at time of planting, and age (from 4 to 9 years). Each site is a randomized complete block design with a factorial treatment arrangement of harvesting practices (minimum and maximum disturbance) and different establishment practices (e.g., bedding, fertilization, herbaceous weed control, herbaceous weed control plus fertilizer, and burning). An integrated statistical analysis using the change in height with age was used for the evaluation of longer-term treatment effects. Harvesting practices had a significant treatment effect on the change in height with age ($p < 0.03$) at one site, but did not significantly affect early height growth at the other three sites ($p > 0.37$). On the other hand, establishment practices had a significant effect on the change in height with age ($p < 0.01$), independent of accompanying harvesting practice.

INTRODUCTION

Application of intensified cultural practices are expected to significantly increase productivity of pine plantations (Yin and Sedjo 2001). Combinations of intensive silvicultural treatments enable forest managers to grow more wood fiber faster on fewer acres (Martin and Shiver 2002). Because fewer acres will be needed for wood production, intensively managed plantations can play an important role in providing for our wood needs in a sustainable and environmentally sound manner (Seymour and McCormack 1989). Intensively managed plantations are only one part of a triad forest allocation plan. In a triad forest allocation plan, intensively managed plantations would coexist with reserves, and the rest of the landscape would be managed by alternative silvicultural systems.

Sustainable Forest Management

Concerns about providing for wood and other natural resources originated in Europe in the 18th century (Speidel 1972 and Huuri et al. 1989, as cited in Fox 2000). The establishment of the national forest system in the United States arose from concerns over sustainable water and timber supplies toward the end of the 19th century (Pinchot 1947, Frome 1984). The Multiple Use Sustained Yield Act of 1960 and the National Forest Management Act of 1976 were enacted as the debate over water and timber supplies continued in the United States. The guiding principle of the Multiple Use Sustained Yield Act (Public Law 86-217) is the achievement and maintenance in perpetuity of a high-level annual or regular periodic output of the various renewable resources provided by National Forests without impairing the productivity of the land. The National Forest Management Act (Public Law 94-588) mandates that the USDA Forest Service manage

public forest lands without permanently damaging their productivity. In Australia and New Zealand, where plantation management is practiced on considerably short rotations, Keeves (1966) reported a decline in the growth of second rotation radiata pine in southern Australia raising questions of long-term site productivity. New Zealanders enacted the Resource Management Act of 1991 to ensure forest management practices do not degrade on or off-site environmental values in New Zealand.

The concept of sustainable forestry has gained increasing international focus over the last decade. A series of international meetings were conducted that generated a general consensus on how sustainable forestry should be defined and how it should be assessed through a process of criteria and indicators. Criteria set forth general principles that express agreed upon objectives, and indicators are metrics for assessing whether these criteria are being met (Brand 1997). The year following the Rio De Janeiro Earth Summit in 1992, representatives from various countries decided that sustainable forestry would be defined on two fronts: (1) Europe and (2) other temperate and boreal countries. European countries could establish criteria and indicators under the European Ministerial Conference on Forests, i.e., the Helsinki Process. An informal working group was created in April 1994 to complete the work for other temperate and boreal countries, i.e., the Montreal Process. In June 1994, the Helsinki Process accepted six criteria. During 1995, criteria and indicators were presented in Santiago, Chile, as part of the Santiago Declaration; the document outlining the Montreal Process. Six criteria are common to the Helsinki and Montreal Processes including the maintenance of forest productivity and the conservation and maintenance of soil and water resources. The Santiago Declaration,

however, includes a seventh criteria—the development of a legal, institutional, and economic framework for sustainability.

Although the criteria in the Santiago Declaration outline the objectives of sustainable forestry, the current set of indicators only provides a broad assessment framework without clear standards or baselines (Brand, 1997). Researchers and forest managers must define and interpret indicators of sustainable forestry on their own. Therefore, foresters need tools, guidelines, or management systems to enable them to turn subjective sustainability goals into outcomes that can be measured quantitatively (Smith et al. 2001). Montreal Process Criteria 2, maintenance of productive capacity of forest ecosystems, dictates an assessment of trends in growth and yield over time. In plantation forestry, management effects on site productivity are linked with the conservation and maintenance of soil and water resources.

Although there is a general consensus on criteria for sustainable forest management, there is still much discussion on how to evaluate each criterion and how to interpret the findings (e.g. Burger and Kelting, 1999, Columbe 1995). Several indicators of forest sustainability and methods of maintaining forest sustainability have been proposed (Burger and Kelting 1999, Kimmins 1996, Noss 1993). Kimmins (1996) proposed a qualitative and subjective approach to describe forest sustainability: he judged the sustainable nature of a forest on its ability to provide landscape level benefits under the influence of periodic disturbances. Noss (1993), however, proposed several indicators to monitor the forest landscape condition including forest age, forest structure, patch size and isolation, fire regime, roads, and sensitive species.

Site Productivity as an Indicator of Forest Sustainability

Site productivity can be measured indirectly with soil quality indicators. Soil quality is the capacity of the soil to support tree growth and consists of two parts: the inherent capacity of the soil to support tree growth, and a dynamic part influenced by the manager (Carter et al. 1997). Soil quality indicators, analogous to agriculture's soil tilth, have been proposed for forest soils. Kelting et al. (1999) argue that soil quality concepts and methods within the agricultural community should form the basis for more soil-based assessments of management effects on the long-term productivity of forests. Schoenholtz et al. (2000) conclude that indices of soil quality would be better adopted if they were sensitive to management changes and if they can be linked to measurements of desired values such as productivity and biodiversity. Smith et al. (1993) state that soil quality may be defined in several different ways such as productivity, sustainability, environmental quality, and effects on human nutrition. Further, Smith et al. (1993) argue that because assessing soil quality is complex, individual soil quality indicators need to be integrated to form a soil quality index.

Burger and Kelting (1999) developed a soil quality index that measures the effects of management practices on changes in key growth-determining aspects of forest soils. The five key growth-determining attributes of forest soils are that the soil must (1) promote root growth; (2) store, supply, and cycle nutrients; (3) accept, hold, and supply water; (4) promote gas exchange; and (5) promote biological activity (Burger and Kelting 1999). The effects of intensive management on soil quality and subsequent tree growth can be positive, neutral, or negative (Fox 2000). An example of direct effects of silvicultural treatments that increase soil quality can be illustrated with phosphorus

fertilizer applications. Elevated levels of available phosphorus in the soil, and the continued growth response in subsequent rotations to the original phosphorus applications, clearly demonstrate a long-term increase in soil quality (Gentle 1986, Harding and Jokela 1994).

Site productivity can also be assessed with aboveground, plant-based measurements. Measurements that are direct indicators of productivity such as basal area, volume, and biomass are sensitive to stand density (Evans 1984). A common indirect measure of productivity is site index, the average height of a sample of the tallest trees in a stand at a base age, e.g., 25 years. Height growth is a good indicator of site productivity because it is sensitive to differences in site quality, strongly correlated with volume growth, and weakly correlated with density and species composition (Lanner 1985). Height growth is the average of influences from more than one year and is not affected by weather fluctuations to the degree diameter growth is affected (Oliver and Larson 1990). Furthermore, early differences in stand development due to management practices, e.g., harvesting, site preparation, and residue management treatments, may be indicative of rotation-length outcomes (Westfall et al. 2004) and longer-term effects on productivity (Roberts et al. 2005).

Effects of Silvicultural Treatments on Site Productivity

Silvicultural treatments can positively or negatively effect (1) site resource availability, (2) the allocation resources to crop trees (Oliver and Larson 1990), or (3) the ability of crop trees to acquire and use site resources (Allen 2001). Much of silviculture is either reallocating growing space to desirable species or giving desirable species a competitive advantage (Oliver and Larson 1990). Growing space can be defined as the

sum of the factors necessary for growth (Oliver and Larson 1990). Growing space may be reduced by cultural management practices when the practices damage the soil structure, increase soil bulk density, or reduce soil nutrients by leaching, volatilization, or relocation. Some cultural treatments such as bedding or fertilization, however, can increase the total growing space by increasing rooting depth, or reducing nutrient deficiencies, respectively (Oliver and Larson 1990).

Silviculturists are concerned with positive or adverse permanent site changes to growing space. Tillage treatments, such as bedding, discing, or ripping can ameliorate soil physical limitations but can also have adverse effects by increasing erosion. Intense site preparation fires can decrease nitrogen and sulfur through volatilization and phosphorus and other micronutrients through ash loss (Flinn et al. 1979, Vose and Swank 1993). Terry and Hughes (1975) report an instance where land drainage has resulted in a long-term, positive change in site production in a 35-year rotation.

Effects of Harvesting Disturbance on Site Productivity

Harvesting practices have the potential to affect site productivity. Equipment used in whole-tree harvesting may decrease site productivity through soil compaction from harvesting equipment and organic matter removal. More nutrients are removed in mechanical whole-tree harvesting operations than when trees are hand-felled and only the bole is removed (Kimmins 1977, Freedman et al. 1981, Johnson et al. 1982). Harvest residues left on the site can significantly increase soil moisture, especially during the first two years after harvest when the trees are getting established (O'Connell et al. 2004). Further, harvest residues can also affect nutrient dynamics—increasing nutrient availability and reducing nutrient loss from leaching (Jurgensen et al. 1992, Carlyle et al.

1998, Blumfield and Xu 2003). Other studies report little or no effect of residue retention on nutrient availability (Proe and Dutch 1994). Johnson and Todd (1998) reported that leaving logging residues on site for 15 yr after harvest provides no benefits to stand productivity.

Effects of Establishment Practices on Site Productivity

Plantation establishment practices can be grouped into at least two categories: those that manipulate the soil's physical properties and those that control competition (Morris and Lowery 1988). Activities that influence the soil's physical properties such as soil tillage including bedding, discing, or even machine planting, may increase growth of seedlings (Wheeler et al. 2002). The predominant treatment for controlling competition is chemically with herbicides — less common treatments include scalping, root raking, shearing, chopping, harrowing, burning, dragging, and mulching (Long et al. 2004).

Soil properties that may be improved by soil tillage are moisture availability, nutrient availability, or increased rooting volume for seedlings (Lowery and Gjerstad 1991, Morris and Lowery 1988). Bedding creates an elevated, well-drained, and aerated rooting zone (Terry and Hughes 1975), and it improves surface-drainage, controls competition to some extent (Williams 1988), and increases nutrient availability (Haines et al. 1975, Broerman et al. 1983). Bedding tends to increase P levels in the soil and concentrates organic matter, K, Ca, Mg, and Mn near seedling roots in the bed (Terry and Hughes 1975).

Tillage treatments affect tree growth in various ways. Bedding increased loblolly pine height growth over the control on poorly drained soils, but not on very poorly drained soils where phosphorus was severely deficient (Terry and Hughes 1975). On a

moderately drained site, bedding increased tree heights by 33%, 2 yr after planting, but it increased height by only 7% 10 yr after planting (McKee and Wilhite 1986). Tiarks and Hayward (1996), however, reported that discing and bedding reduced slash pine tree growth following two rotations at the same site. Wheeler et al. (2002) contended that tillage in combination with fertilization and competition control can be used to maximize stand growth rate, but also noted that the longevity of the tillage response will probably be site specific.

Herbaceous competition for light, water, and nutrients severely limits growth of pine seedlings and saplings (Bacon and Zedaker 1987, Nelson et al. 1981, Tiarks and Haywood 1986, Zutter et al. 1986). Soil moisture was negatively related to herbaceous weed cover in loblolly pine plantations (Zutter et al. 1986). Increased radiata pine growth with herbaceous weed control has been attributed to an increase in water available to pines (Smethurst and Nambiar 1989), and when water was not limiting, an increase in the mineral N available to the trees (Ellis et al. 1985).

Fire is used in southern pine management for site preparation prior to seeding or planting and during the rotation to reduce woody competition, lower the risk of wildfire, and restore or maintain certain fire-dependent ecosystems (Van Lear and Waldrop 1989). McInnis et al. (2004) reported that of prescribed fire, alone or in combination with other treatments, did not increase basal area growth and sometimes even decreased it. Potential reasons for reduced growth after prescribed burning are as follows: direct injury to tree stems, crowns, or roots; reduction in microorganisms such as mycorrhizae, with concurrent reductions in nutrient availability; reduced photosynthetic capacity; and changes in carbon allocation (Landsberg 1994). Carter and Foster (2004) report that

burning results in a short-term increase in soil available nitrogen and other nutrients immediately after burning, stimulating the growth of understory vegetation; a desirable effect in some settings but also a source of competition for newly planted pine seedlings.

Fertilizer treatments can benefit the trees or the site (Miller 1981). Miller (1981) proposed that fertilizers generally benefit the trees, not the site. For a fertilizer treatment to affect the site, the amount of the nutrients applied must be large in relation to the soil capital. Miller (1981) also reported that prior to canopy closure, tree growth is very dependent on soil nutrient concentrations and that response to various nutrients can be expected. Response to fertilizer treatments has been described as acceleration through time (Miller and Cooper 1973), and fertilizer response is best described as a reduction in rotation length.

Fertilization has positive effects on pine production that have been linked to an increase in foliage production or an increase in photosynthetic rate. The growth of new foliage, and therefore increased leaf area, has been found in conifer trees after fertilization (Albaugh et al. 1998, Gholz et al. 1991, Jokela and Martin 2000). Nitrogen fertilization has been shown to influence both foliage mass and photosynthesis per unit foliage for Douglas-fir (Brix 1981) and for Corsican pine (Miller and Miller 1976). Brix (1983) also reported the major growth response to fertilizer treatments over a 7-year period was caused by an increase in the amount of foliage and an increase in photosynthetic rate. Other studies, however, indicate fertilizer had little (Thompson and Wheeler 1992) to no effect (Teskey 1994) on tree photosynthetic rates.

Response Types

Three general response curves have been discussed in the literature to describe the duration of treatment effects and how a treatment response trend may be an indicator of long-term forest productivity. The three response curves were originally depicted by Hughes et. al (1979), and further explored by Morris and Lowery (1988). The general response curves are labeled as type A, type B, and type C. The type A response occurs when the site is improved and growth gains continue to increase throughout the rotation (Figure 1a). The type B response is described as growth gain that is achieved early and is maintained at a constant level throughout the rotation (Figure 1b). The type C response occurs when there is a transient increase in growth that is partially or completely gone by the end of the rotation (Figure 1c).

Whether a treatment affects the longevity of the response depends on the resource manipulated by the treatment. For example, a type A response may be seen in response to phosphorus application on a P-deficient site. Not only is there an early growth gain, but the growth advantage of fertilized trees over unfertilized trees continues to increase with age. An example of a type B response is when there is a short-term increase in the availability of resources to trees that would have been lost had it not been utilized (Albaugh et al. 2004). A type C response may be the result of an early short-term increase in existing site resources or to the allocation of these existing site resources to the crop trees early in the rotation (Albaugh et al. 2004) and the growth increase continues to increase with age. An example of a type C response may be seen with an operational treatment that controls competing herbaceous vegetation.

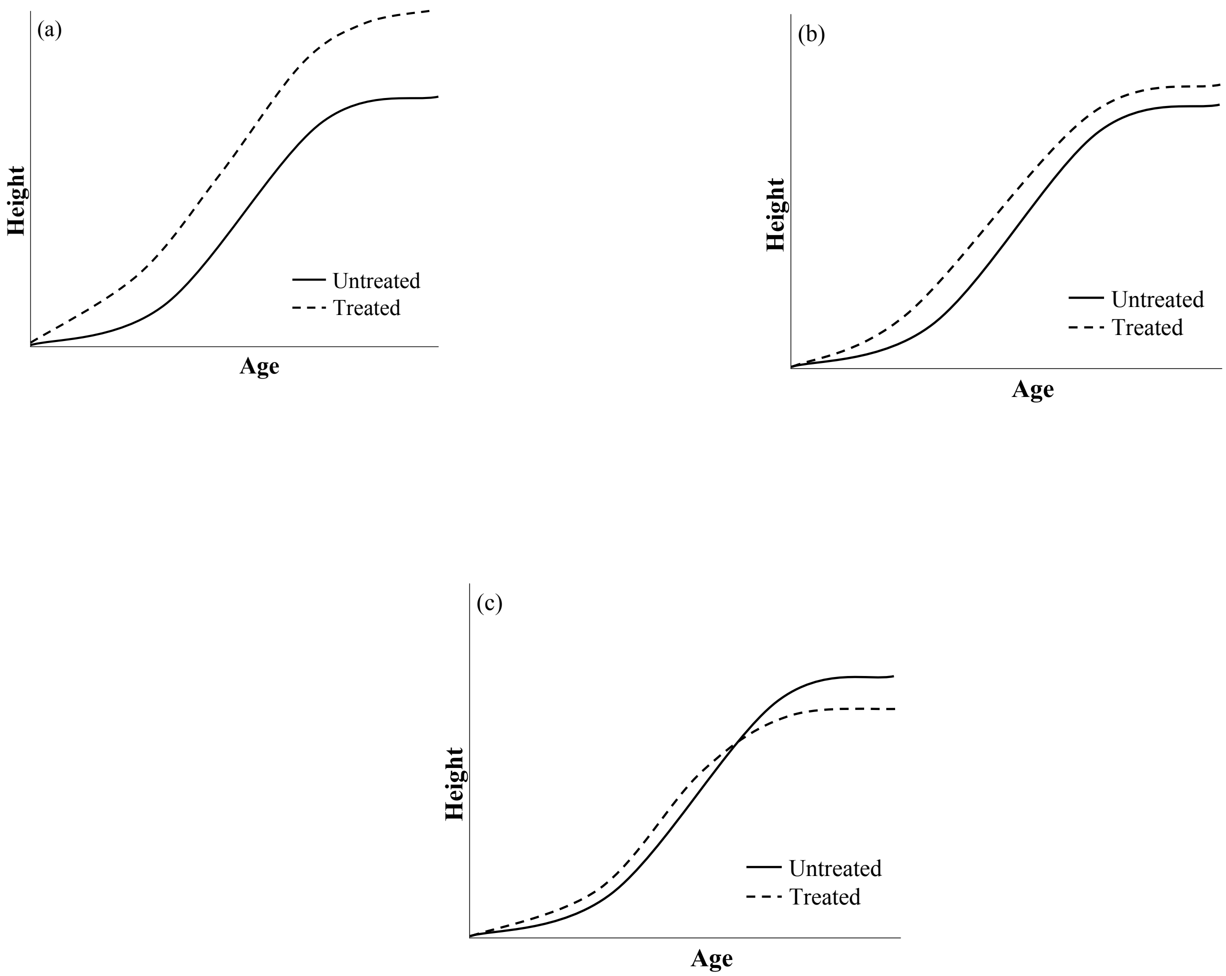

Figure 1. Potential changes in patterns of stand growth resulting from regeneration practices at plantation establishment: (a) type A response, (b) type B response, and (c) type C response (redrawn from Morris and Lowery 1988).

Current Studies

To address concerns over long-term forest sustainability, the Long-Term Site Productivity (LTSP) study, established by the USDA Forest Service in 1989, addresses the maintenance of soil productivity (Powers and Avers 1995). The LTSP study was initiated in response to the National Forest Management Act of 1976. The LTSP is designed to investigate the effects of compaction and organic matter removal on soil properties and growth of subsequent plantations. The experimental design for the long-term site productivity study manipulates soil porosity and residual organic matter separately in hopes of creating a response surface of tree growth to gradients in these variables.

A companion to the Long-term Site Productivity study, Cooperative Research in Sustainable Silviculture and Soil Productivity (CRiSSSP), was initiated in 1993. The objectives of CRiSSSP are similar to those of the LTSP study but from an operational perspective. While the LTSP tries to detect individual effects of soil porosity and residual organic matter on tree growth, the CRiSSSP analyzes the effect of conventional, whole-tree harvesting on tree growth and determines whether effects correspond with changes in soil porosity and organic matter removal resulting from the harvest. The CRiSSSP study also includes additional establishment practices to evaluate possible ameliorative effects of harvesting effects on tree growth.

Objectives

Determining and quantifying the relationships in forest sustainability as assessed by site productivity of the site is important for the future of plantation forestry. In this study, height growth was used as an indicator of site productivity because it is relatively

unaffected by competition. The main objectives of this study were to determine whether harvesting disturbance and establishment practice affect early height growth of loblolly pine in the Gulf coastal plain. Another objective is to determine the duration of the treatment effects.

MATERIALS AND METHODS

Study Sites

The study sites are part of the Cooperative Research in Sustainable Silviculture and Soil Productivity (CRiSSSP) study. All sites are located in humid-temperate-subtropical ecoregion provinces 231 or 232 (Bailey 1997) in the Gulf Coastal Plain of the U.S.A.

Fred – The site is located near Fred, Texas, in Tyler County on property owned by Temple Inland Forest Products Corporation. The soil is Kirbyville series, a fine-loamy, siliceous, semiactive, thermic Oxyaquic Paleudult. The study site has no history of post-Columbian cultivation. The mean annual temperature at this site is 10º C and 27º C in January and July, respectively, with a mean annual precipitation of 136 cm/yr. Initial stand hand planting of 1-0 improved bare root, seed orchard stock, seedlings took place in March of 1995, and after severe mortality from pales weevil (*Hylobius pales* (Herbst)), the installation was replanted in February 1996. Trees at Fred were 9-yr old at last measurement.

Bainbridge – This site is located on a broad terrace of the Flint River in Decatur County, Georgia, on property owned by International Paper Company. The soil series is Hornsville, a fine, kaolinitic, thermic Aquic Hapludult. There is a long history of agricultural use on the site. The mean annual temperature at this site is 10º C and 27º C in January and July, respectively, with a mean annual precipitation of 167 cm/yr. Planting of 1-0 bare root seedlings took place in the winter of 1996. One-half of each plot was planted with first rotation families while the other half of the plot was planted with a family exhibiting superior growth. Trees at Bainbridge were age 9 at last measurement.

Bryceland – This site is located in Bienville Parish, Louisiana, on property owned by Weyerhaeuser Company. The soil series is Mahan, a fine, kaolinitic, thermic Typic Hapludult. Slope on the site ranges from 5 to 10%. There is no evidence of severe erosion that would indicate a history of cultivation. The mean annual temperature at this site is 7º C and 27º C in January and July, respectively, with a mean annual precipitation of 137 cm/yr. Bare root seedlings (1-0) grown from seed orchard stock were planted in December of 1996. Trees at Bryceland were 9-yr old at last measurement.

Pine Grove – This site is located in St. Helena Parish, Louisiana, on property originally owned by International Paper Company. These soils formed in a moderately thick deposit of loess over loamy Coastal Plain sediments. The taxonomic classification is a fine-silty, siliceous, thermic Typic Fragiudult. The site was likely cultivated and abandoned sometime prior to the 20^{th} century. The mean annual temperature at this site is 9º C and 27º C in January and July, respectively; with a mean annual precipitation of 168 cm/yr. Hand planting of 1-0 bare root seedlings grown from seed orchard stock took place in December of 1996. Trees at Pine Grove were 4-yr old at last measurement because a fire killed most of the trees.

Experimental Design

Each of the four study sites was a randomized complete block design with a factorial combination of harvest disturbance and establishment practices randomly assigned to plots within each block. In the study, each of the sites was blocked on surface drainage or topography. Three blocks were installed at Bainbridge, Fred, and Pine Grove, and four blocks were installed at Bryceland. The sites were blocked to control site variation and thus, minimize experimental variation.

Number of treatment plots, planting description and spacing, and plot size vary by location. There are 24 treatment plots with 14 rows of 14 trees with 2 x 3 m spacing at Fred and Bryceland. Each 0.12-ha treatment plot contains a central 0.06-ha measurement plot. At Pine Grove, there were 18 treatment plots with 14 rows of 14 trees with 2 x 3 m spacing. Each 0.12-ha treatment plot contains a central 0.06-ha measurement plot. At Bainbridge, there are 18 treatment plots with 7 rows of 36 trees with 2.44 x 2.44 m spacing. Each 0.15-ha treatment plot at this site was also the measurement plot.

Treatments

Table 1 shows the treatment specifications for all the sites. At Fred, a 2x2x2 factorial combination of harvesting disturbance (2 levels), bedding (2 levels), and fertilization (2 levels) was established. At the Pine Grove, Bainbridge, and Bryceland sites, treatments are a 2x3 factorial combination of harvesting disturbance (2 levels) and various, site-specific, establishment practice (3 levels). Although fertilizer was a separate factor at the 2x2x2 site, fertilization was included as one of the establishment practices at one of the 2x3 sites.

To assure minimal competition control, each installation site was aerially sprayed with site-specific combinations of herbicides and applications rates. At Fred, the aerial spray was a combination of broadleaf herbicides of imazapyr plus triclopyr at the rates of 0.5 plus 2 kg/ha a.i. The aerial spray application at Bainbridge was a combination of imazypyr plus triclopyr, at a rate of 0.5 plus 2 kg/ha a.i. At Bryceland, the aerial spray application was a combination of imazypyr plus glycophosphate at a rate of 0.5 plus 4 kg/ha a.i. At Pine Grove, the aerial spray applied was a combination of imazypyr plus glycophosphate at a rate of 0.25 plus 2 kg/ha a.i.

Table 1. Harvesting and establishment practices used at the 4 study sites. The harvest treatments were the same at all locations: Min: minimum harvesting disturbance (hand felling with bole-only removal); Max: maximum harvesting disturbance (mechanical harvesting with whole tree removal). Aerial sprays were applied by helicopter prior to planting of pine seedlings. Bedding and ripping were also conducted prior to planting. Herbaceous weed control and fertilizer were applied with hand equipment after planting pine seedlings (adapted from Carter et al. 2006).

Location	No. of Blocks	Aerial Spray	Factors	Harvest Disturbance	Establishment Practice	Fertilizer
Fred	3	Imazapyr + triclopyr, 0.5 + 2 kg/ha a.i.	2x2x2	Min	None	None
				Max	Ripped and bedded	DAP (diammonium phosphate, 250 kg/ha, broadcast by hand after planting)
Bainbridge	3	Imazapyr + triclopyr, 0.5 + 2 kg/ha a.i.	2x3	Min	None	
				Max	HWC (herbaceous weed control - 2 applications of sulfometuron + imazapyr, 0.14 + 0.28 kg/ha a.i., in 2% aqueous solution of glyphosphate as directed spray)	
					HWC + F (HWC + complete fertilizer with minor elements @ 56 kg N / ha in a circular band around each seedling after planting)	
Bryceland	4	Imazapyr + glyphosphate, 0.5 + 4 kg/ha a.i.	2x3	Min	None	
				Max	HWC (herbaceous weed control - a single application of hexazinone + sulfometuron + metsulfuron @ 3.5 + 0.07 + 0.07 kg/ha in a 1.1 m band over the row of planted pines)	
					Burn (broadcast slash burning 1 yr after harvest, 3 mo after aerial spray)	
Pine Grove	3	Imazapyr + glyphosphate, 0.25 + 2 kg/ha a.i., hand broadcast	2x3	Min	None	
				Max	HWC (herbaceous weed control - a single application of imazapyr + sulfometuron, 0.25 + 0.5 kg/ha a.i., in a 1.1 m band over the row of planted pines)	
					Bedded	

Two extremes of harvesting disturbance were applied to all sites (Table 1). The minimum harvesting disturbance consisted of hand-felling, limbing and topping the trees in place, and lifting the merchantable portion of the bole from the plot. The maximum harvesting disturbance consisted of cutting trees with a saw shear and removing the entire tree from the plot with rubber-tired, grapple skidders. Mechanical whole-tree harvesting significantly increased the soil bulk density in the surface 30 cm of the soil by 0.1 Mg/m^3 at Fred (from 1.14 to 1.24 Mg/m^3) and Bainbridge (from 1.41 to 1.51 Mg/m^3) (Carter et al. 2006). At Pine Grove, the soil bulk density was not significantly affected by mechanical whole-tree harvesting. There was no significant difference on soil bulk density between hand-felled and whole-tree harvested plots at Bryceland (Carter et al. 2006).

The second factor at the Fred site was the presence or absence of bedding (Table 1). Bedded sites at Fred were ripped and bedded before planting in October 1994. The third factor at Fred was the presence or absence of fertilization. The fertilizer treatment was accomplished by hand-broadcasting diammonium phosphate at the rate of 250 kg/ha in May 1996.

At the Bainbridge, Bryceland, and Pine Grove sites, the second factor was a series of establishment practices. An establishment practice common to all three sites was a site-specific herbaceous weed control treatment. At Bainbridge, the herbaceous weed control treatment was applied twice in the summer of 1995 by direct spray with a mixture of sulfometuron and imazapyr at the rates of 0.14 and 0.28 kg/ha a.i. in 2% aqueous solution of glyphosphate. The herbaceous weed control treatment at Bryceland was accomplished in a single application March 1997 by direct spray with a mixture of

hexazinone, sulfometuron, and metsulfuron at the rates of 3.5, 0.07, and 0.07 kg/ha a.i., respectively, in a 1.1-m band over the row of planted pines. At Pine Grove, an herbaceous weed control treatment was applied in a band 1-m wide over the row of planted pines with a combination of imazapyr plus sulfometuron at the rates of 0.25 plus 0.5 kg/ha a.i. in March of 1997.

The next level of establishment practice varied across the three sites. At Bainbridge, the third establishment practice was herbaceous weed control plus complete fertilizer treatment. Complete fertilizer with minor elements was applied to the seedlings in a circular band around each seedling at a rate of 56 kg N/ha. Broadcast burning was the third level of establishment practice at Bryceland, performed three months after aerial spray in October of 1996. The third level at the Pine Grove site was bedding with a 3-m interval. The site was bedded in October 1995.

Measurements

Height data were collected using a height pole or hypsometer on all trees in the measurement plots at varying time intervals. Trees at Fred, Bryceland, and Pine Grove were measured every year. At Bainbridge, height data were not collected for the first year after planting, but were collected every year for three years, and then collected every other year.

Statistical Analysis

Description – A model describing the change in tree height with plantation age is used to test how harvesting and establishment practices affect the pattern of height growth at early plantation ages. If there is a treatment effect, then there will be different patterns of height growth, suggesting that one curve is not sufficient and multiple curves

are needed to describe the pattern of height growth. In a mixed model analysis with random coefficients regression, treatment effects can be added to simple equations that describe height with age.

A mixed model includes both fixed and random regression coefficients; the fixed coefficients describe the shape of the typical growth curve over the entire population, whereas the random coefficients that individualize the curve describe tree-specific characteristics of the growth pattern (Hall and Bailey, 2000). In this study, the coefficients for the equation and the treatments are fixed, and the random effects are blocks, locations, and trees. Random coefficient regression estimates an error term for each of these components and adds additional error terms representing the variability in intercepts and slopes for the plots. This new source of random variation is used as an error term for testing treatment differences.

In general, a plot of height versus age resembles a sigmoid curve with an inflection point (Chen and Klinka 2000). For these young trees, however, height has yet to exhibit a reflection point in the curve; consequently, much simpler functions may be used to describe height accumulation with age. Three simple linear functions were fit to the pairs of height (H) and age (A): simple linear, exponential (linearized as $\ln(H) = b + (mA)$, and power (linearized as $\ln(H) = b + m[\ln(A)]$). Analyses of the back-transformed residuals (Figure 2) and evaluation of the Fit Index (similar to R^2) showed that the linearized power function provided the best fit to the height-age data over the entire range of data.

Statistical Models - Two mixed model analyses were conducted because of the difference in the experimental designs: one for Fred and one for the combined data from

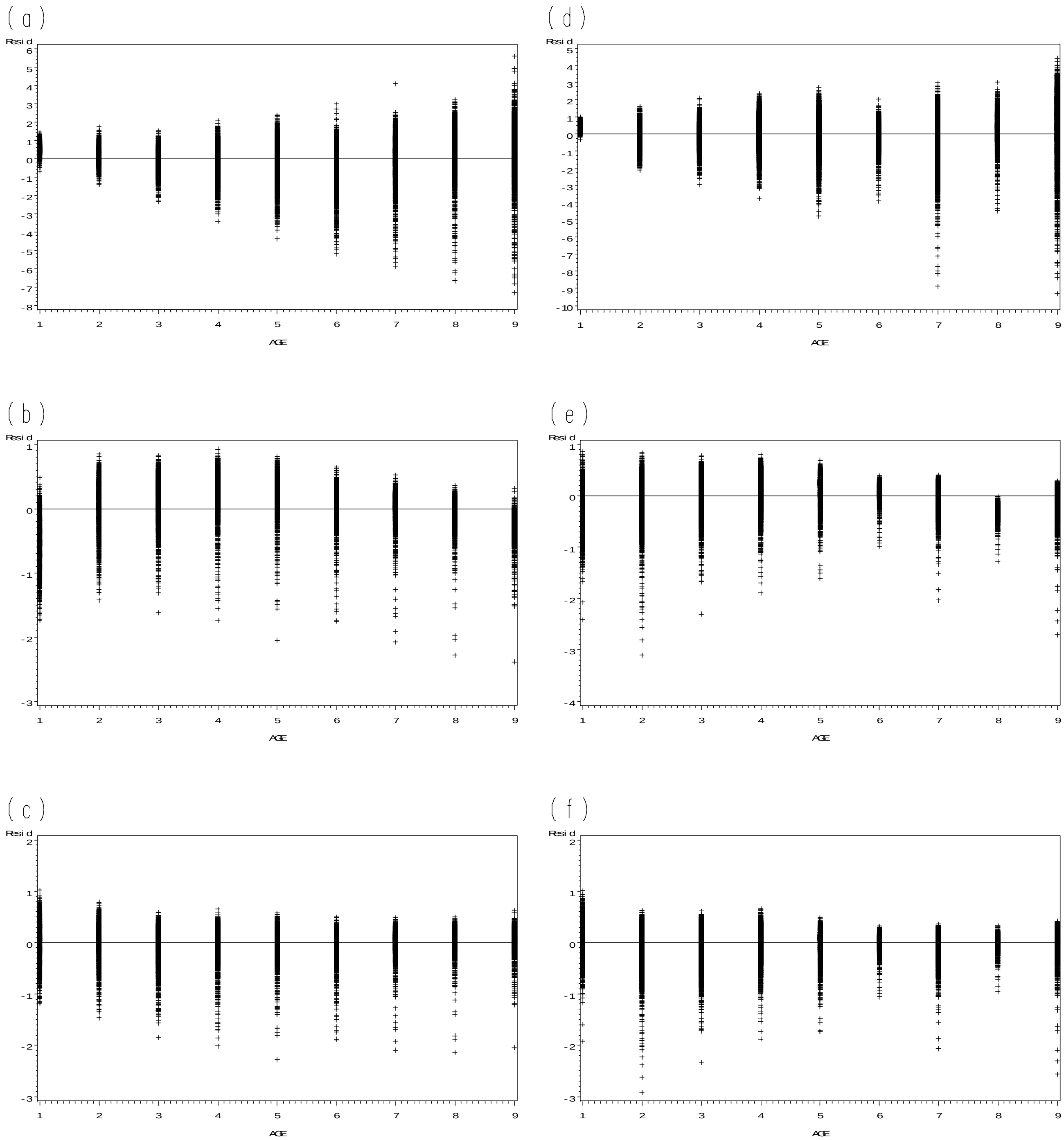

Figure 2. Plots of back-transformed height residuals (m) on age after fitting a linear (a and d), linearized exponential (b and e), or linearized power (c and f) function to the data at Fred (a,b and c) and Bryceland, Bainbridge and Pine Grove (d, e, and f).

Bainbridge, Bryceland, and Pine Grove. The dependent variable was ln(height) and ln(age) was the independent variable. At Fred, the linear model was

$$\mathbf{Y_{ijklm} = (\beta_0{+}c) + (\beta_1{+}c)\, X_i + \varepsilon_{ijklm}},$$

where $\mathbf{Y_{ijklm}}$ = ln(H_{ijklm});

$\mathbf{H_{ijklm}}$ = average plot height, in meters, of the i^{th} age, j^{th} block, k^{th} harvesting disturbance, l^{th} establishment practice, and m^{th} fertilization treatment;

$\boldsymbol{\beta_0}$ = regression coefficient;

$\boldsymbol{\beta_1}$ = regression coefficient;

$\mathbf{X_i}$ = ln(A_i);

$\mathbf{A_i}$ = value (in years) of the i^{th} age, (i=1, 2,…, t), where t = 9;

$\mathbf{c = B_j + H_k + E_l + F_m + HE_{kl} + HF_{km} + EF_{lm} + HEF_{klm}}$;

$\mathbf{B_j}$ = j^{th} block, (j=1, 2, 3);

$\mathbf{H_k}$ = effect of the k^{th} harvesting disturbance, (k=1 or 2);

$\mathbf{E_l}$ = effect of the l^{th} establishment practice, (l=1 or 2);

$\mathbf{F_m}$ = effect of the m^{th} fertilization treatment, (m=1 or 2);

$\mathbf{HE_{kl}}$ = interaction effect between harvesting and establishment practice;

$\mathbf{HF_{km}}$ = interaction effect between harvesting disturbance and fertilization;

$\mathbf{EF_{lm}}$ = interaction effect between establishment practice and fertilization;

$\mathbf{HEF_{lmn}}$ = interaction effect between harvesting disturbance, establishment practice, and fertilizer; and

$\boldsymbol{\varepsilon_{ijklm}}$ = error term.

At Bainbridge, Bryceland, and Pine Grove, the linear model was

$$\mathbf{Y_{ijklm} = (\beta_0{+}c) + (\beta_1{+}c)\, X_i + \varepsilon_{ijklm}},$$

where $\mathbf{Y_{ijklm}} = \ln(H_{ijklm})$;

$\mathbf{H_{ijklm}}$ = average plot height, in meters, of the i^{th} age, j^{th} location, k^{th} block, l^{th} harvesting disturbance, and m^{th} establishment practice;

$\boldsymbol{\beta_0}$ = regression coefficient;

$\boldsymbol{\beta_1}$ = regression coefficient;

$\mathbf{X_i} = \ln(A_i)$;

$\mathbf{A_i}$ = value (in years) of the i^{th} age, (i=1, 2,…, t), where t = 4 or 9;

$\mathbf{c} = L_j + B_k + H_l + E_m + HE_{lm}$

$\mathbf{L_j}$ = effect of the j^{th} location, (j=1, 2, 3);

$\mathbf{B_k}$ = effect of the k^{th} block, (k=1, 2, 3, 4);

$\mathbf{H_l}$ = effect of the l^{th} harvesting disturbance, (l=1 or 2);

$\mathbf{E_m}$ = effect of the m^{th} establishment practice, (m=1, 2, 3);

$\mathbf{HE_{lm}}$ = interaction effect between harvesting disturbance and establishment practice; and

$\boldsymbol{\varepsilon_{ijklm}}$ = error term.

Statistical Hypotheses - The overarching null hypothesis was that one curve would be sufficient to describe the change in height with plantation age. This hypothesis could be rejected one of two ways, by rejecting either or both of the following null hypotheses: (1) no treatment effect on the constant and (2) no interaction between a treatment and the fitted coefficient for $\ln(H_{ijklm})$. Rejection of the first null hypothesis would indicate that more than one curve offset by constants would be necessary to adequately describe height accumulation. Rejection of the latter would indicate multiple

lines of varying slopes would be necessary to describe height accumulation. The probability of making a Type I error was set to 0.10.

RESULTS AND DISCUSSION

Treatment Effects

There were no interactions at Fred between harvesting disturbance, bedding, and fertilizer (Table 2). At Fred, harvesting disturbance, bedding, and fertilizer treatment all had a significant effect on the change in height with age. Two curves are needed to describe the data, based on how the plot was disturbed during harvesting, e.g., minimally or maximally. There was a harvesting disturbance treatment effect on the β_0 coefficient ($p = 0.03$), but not on the β_1 coefficient ($p = 0.53$). The effect on the β_0 coefficient is indicated in the table as the Harvest effect, while an effect on the β_1 coefficient is indicated by the ln (age) x Harvest effect. Two curves are also needed to describe the early height growth of trees planted on bedded plots versus trees planted on unbedded plots. There was not a bedding effect on the β_0 coefficient ($p = 0.26$) but there was a bedding effect on the β_1 coefficient ($p < 0.01$). Separate curves were also needed to describe the pattern of height growth of fertilized and unfertilized trees. Fertilizer did not have a treatment effect on the β_0 ($p = 0.25$) but did have an effect on the β_1 ($p = 0.05$).

There were no interactions between harvesting disturbance and the various establishment practices for the combined data from Bainbridge, Bryceland, and Pine Grove (Table 2). In contrast to the results observed at Fred, one curve is sufficient to describe the change in height growth with age, independent of the degree of harvesting disturbance on the plot. Harvesting disturbance had no significant effect on the change in height with age ($p = 0.37$). Several curves are needed to describe the early height growth of trees, depending on the specific establishment practice at Bainbridge, Bryceland, and

Table 2. Results of a random coefficient regression mixed model analysis test for effects of treatment on early height with age for four loblolly pine plantations in the Gulf coastal plain. The fit index[1/] was 0.909 for Fred and 0.908 for Bainbridge, Bryceland, and Pine Grove.

	Treatment Design					
	2x2x2			***2x3***		
Effect	df	F-Value	Pr>F	df	F-Value	Pr>F
Harvest (H)	1	5.22	0.03	1	0.82	0.37
Establish (E)	1	1.29	0.26	4	4.93	<0.01
Fertilizer (F)	1	1.36	0.25			
HxE	1	0.14	0.71	4	0.17	0.95
HxF	1	0.03	0.87			
ExF	1	0.01	0.94			
HxFxE	1	0.01	0.93			
Error	35			41		
ln(Age)	1	8913.00	<0.01	1	2598.40	<0.01
ln(Age)xH	1	0.39	0.53	1	0.00	0.97
ln(Age)xE	1	13.75	<0.01	4	9.23	<0.01
ln(Age)xF	1	3.92	0.05			
ln(Age)xHxE	1	0.39	0.53	5	<0.01	0.99
ln(Age)xHxF	1	0.46	0.50			
ln(Age)xExF	1	<0.01	0.95			
ln(Age)xHxExF	1	0.68	0.41			
Error	40			50		

[1/] Fit Index = $1-\frac{\sum_i (y_i-\hat{y}_i)^2}{\sum_i (y_i-\bar{y})^2}$; where $\hat{y}_i$ = predicted value of y_i and $\bar{y}$ = mean value of y_i.

Pine Grove, however. Establishment practice had a significant effect on both the β_0 and β_1 coefficients for Bainbridge, Bryceland, and Pine Grove ($p < 0.01$).

Since no interactions were detected between harvesting disturbance and the various site preparation and establishment practices used in regenerating the plots, the statistical models can be reduced to simple power functions to describe height at a given age for each treatment factor. The power function was fit to the tree data depending on whether the treatment significantly affected b_0, the intercept, or whether the treatment affected b_1, the coefficient for ln (A):

$$H = b_1 A^{b_2} \tag{1}$$

where $b_1 = b_{10} + b_{11} Z$;

$b_2 = b_{20} + b_{21} Z$; and

Z = the effect of a particular treatment factor.

The model was refitted with b_{11} or b_{21} set to zero depending on which coefficients were not significantly different from zero. The model was fit with curvilinear regression. Curves were graphed to visualize treatments effects on cumulative height within the measurement period.

The harvesting effect at Fred results in only a small difference in the value of b_1 and consequently, only a small height gain of the trees planted after maximum harvesting disturbance compared to the trees planted after minimum harvesting disturbance (Figure 3a). Bedding at the Fred site results in only a small effect on b_2, which also only translates into a small height advantage of the trees on the bedded plots compared to the trees on the unbedded plots (Figure 3b). Fertilization resulted in much larger differences

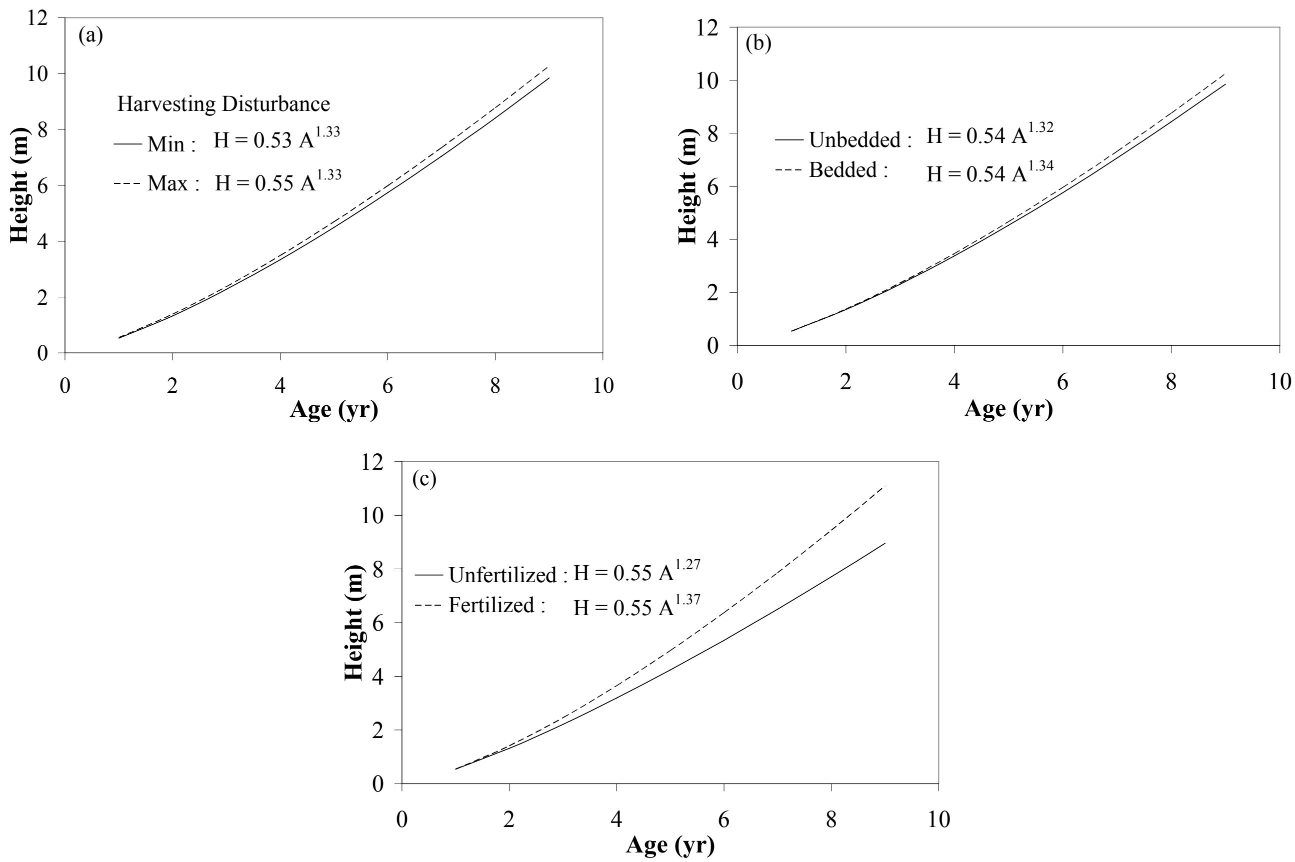

Figure 3. Predicted height (H) versus age (A) for three factors of silvicultural treatment at Fred: (a) harvesting disturbance (Min: minimum harvesting disturbance (hand felling with bole-only removal); Max: maximum harvesting disturbance (mechanical harvesting with whole tree removal)), (b) bedding, and (c) fertilizer.

in b_2, which is seen as a substantial height increase over unfertilized trees when the fitted power function is plotted (Figure 3c). At age 9, the mean height of fertilized trees was 24 % taller than the mean height of the unfertilized trees; at the same age, whole-tree harvesting (maximum disturbance) and bedding both produced a 4 % increase in mean height compared to the hand-felled, bole-only (minimum disturbance) and unbedded treatments.

Faster height growth of trees planted on maximum disturbance and bedded plots at Fred may be related to nutrient release. Lister et al. (2004) reported that disturbance tended to enhance soil biological activity as measured by decomposition rates, microbial biomass, and N mineralization. On a similar note, Proe et al. (1997) suggested that harvesting may increase N availability due to effects associated with soil compaction, changes in microclimate, and altered weed competition. Carter et al. (2002), however, reported that harvesting disturbance method did not affect net N mineralization at Fred, whereas bedding did affect mineralization. Bedding is reported to increase nutrient concentrations and N mineralization (Burger and Pritchett 1984, Fox et al. 1986, Carter et al. 2002).

The effect of herbaceous weed control at Bainbridge, Bryceland, and Pine Grove was an increase of b_1 and a slight decrease of b_2. The end result was a small height gain of the trees on the herbaceous weed control plots compared to the trees without herbaceous weed control (Figure 4a).

Herbaceous weed control plus fertilizer treatment at Bainbridge increased b_1 and lowered b_2 (Figure 4b). The combined effects was that trees in the herbaceous weed

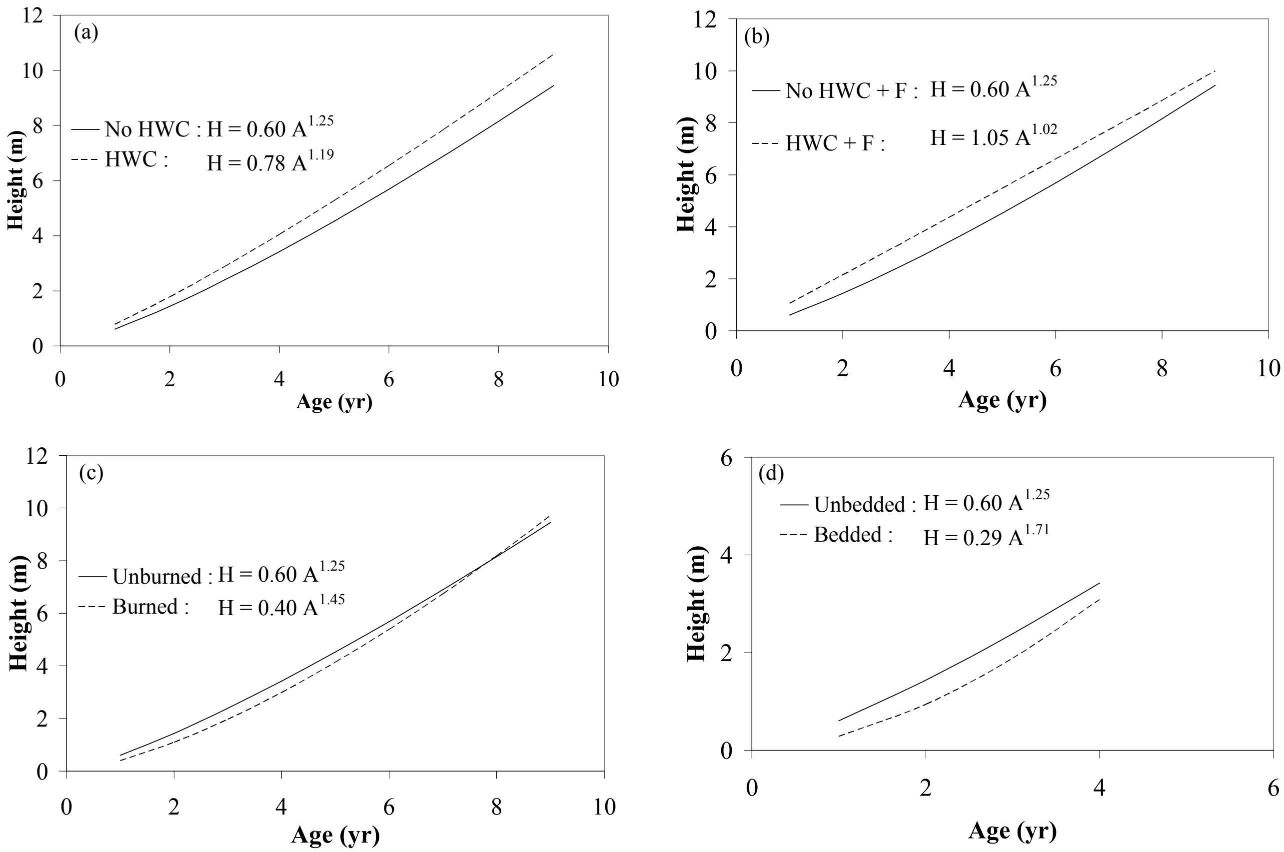

Figure 4. Predicted height (H) versus age (A) for four levels of the establishment factor at Bainbridge, Bryceland, and Pine Grove: (a) herbaceous weed control (HWC) at all three sites, (b) herbaceous weed control plus fertilizer (HWC+F) at Bainbridge, (c) broadcast burn at Bryceland, and (d) bedding at Pine Grove.

control plus fertilizer treatment had a small height gain over trees that were not in the herbaceous weed control plus fertilizer plots.

Broadcast burning at Bryceland had a negative effect on b_1 and a positive effect on b_2 (Figure 4c). Trees on burned plots were shorter than trees on unburned plots until around age 8 yr.

Bedding at Pine Grove also decreased b_1 and increased b_2 (Figure 4d). These effects translated into shorter trees on bedded plots as compared to trees on unbedded plots within the range of the data (4 yr).

Nine yr after treatment, trees in the herbaceous weed control, herbaceous weed control plus fertilizer, and broadcast burning treatments were 1.6 m, 0.29 m, and 0.26 m taller than their respective control plots, respectively (Figure 4a-c). Conversely, trees in the bedding treatment at Pine Grove were 0.32 m, 0.50 m, 0.51 m, and 0.34 m shorter than those in the control at 1, 2, 3, and 4 yr after treatment (Figure 4d).

Annual Height Growth

The first derivative of the power functions (equation 1) fitted to these data is the instantaneous slope between height and age for a particular age. The change in this slope as a function of age for those treatments that exhibited significant effects on height provides some insight into the actual duration of the effect on height. Some physiological insight may be gained when the instantaneous slope between height and age is analyzed in relation to the mean height at that age, i.e. relative height growth.

At Fred, treatments increased annual height growth by various degrees throughout the duration of the study (Figure 5). One yr after planting, trees planted in the maximally

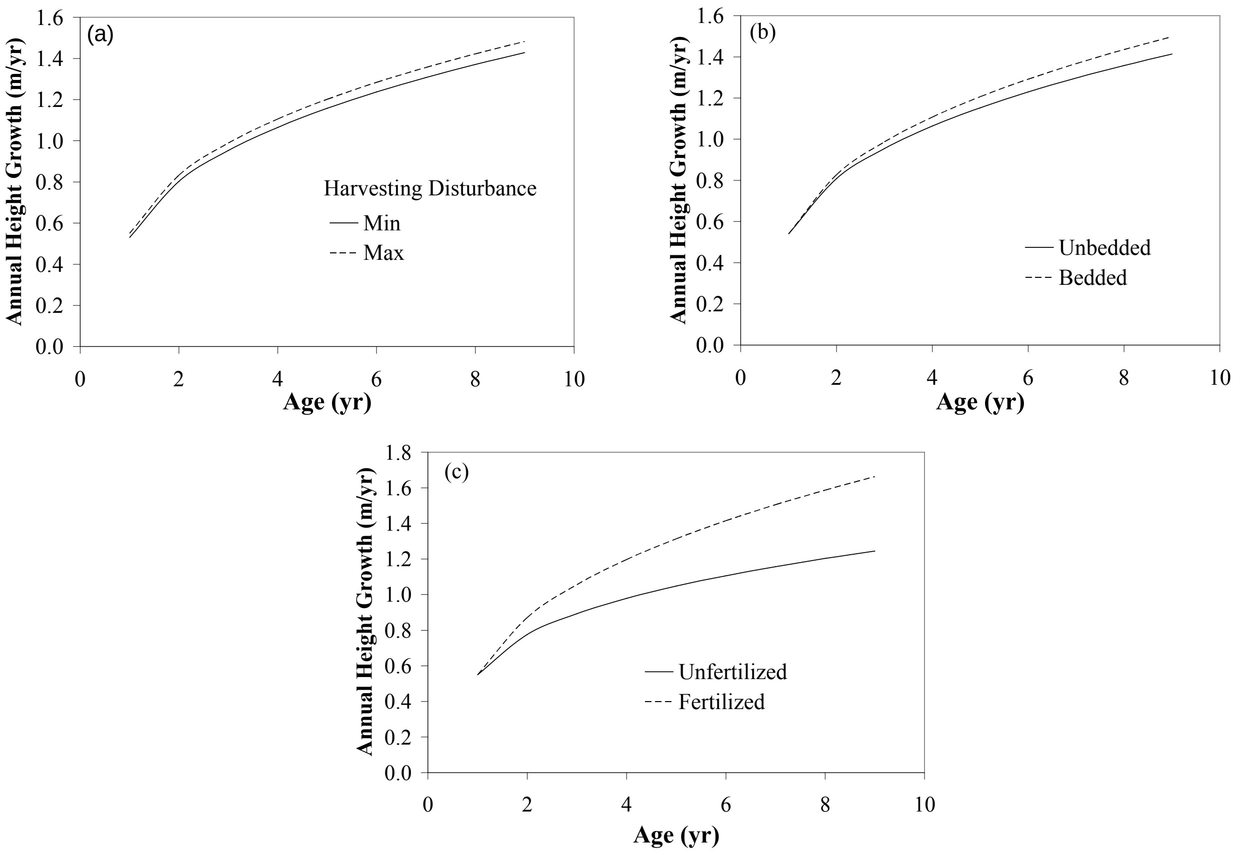

Figure 5. Annual height growth by age for three treatments at Fred: (a) harvesting disturbance (Min: minimum harvesting disturbance (hand felling with bole-only removal); Max: maximum harvesting disturbance (mechanical harvesting with whole tree removal)), (b) bedding, and (c) fertilizer.

disturbed plots grew 0.03 m/yr faster than trees planted in the minimally disturbed plots (Figure 5a). Nine yr after planting, there was still a slight treatment effect, and trees in the maximally disturbed, whole-tree harvested plots grew 0.06 m/yr faster than those in the minimally disturbed, hand- felled, bole-only removed plots. Less brush and slash were left on the site after whole-tree harvesting, making more light available for shade intolerant pines, perhaps explaining the more rapid growth of the trees planted after whole-tree harvesting (Dougherty and Gresham 1988). Fleming et al. (1998) proposed that increased height growth may be due to an increase in nutrient availability from accelerated decomposition of the forest floor at a time when demand for nutrients from newly planted trees is relatively small. Previous N mineralization analyses conducted at the Fred site, however, do not support this hypothesis. There were no N mineralization differences between harvesting intensities (Carter et al. 2002), and soil respiration rates and soil temperature were not significantly affected by harvesting methods (Carter et al. 2002).

Bedding at Fred did not influence the annual height growth initially (Figure 5b). After age 1, however, trees on bedded plots started growing 0.01 m/yr faster than trees on unbedded plots. From age 2 to age 5, trees on bedded plots grew about 0.02 m/yr faster than trees on unbedded plots. At age 6, through age 9, trees on bedded plots grew slightly faster than trees on unbedded plots at about 0.03 m/yr. Although trees were bedded to improve drainage and to elevate the seedlings out of water, and therefore increase root production, it is possible that a different resource was affected by bedding. Accelerated growth after about 2 yr may have resulted from a short-term increase in organic matter decomposition and greater nutrient availability (Morris and Lowery 1988).

Annual height growth at Fred for fertilized was 0.05 m/yr quicker than annual height growth for unfertilized trees initially (Figure 5c). By age nine, fertilized trees were growing 0.42 m/yr greater than unfertilized trees. According to foliar analysis of trees sampled prior to harvesting, the Fred site is phosphorus deficient (Carter et al. 2006). The substantially higher annual height growth of fertilized trees is likely a response to the addition of phosphorus fertilizer to the site. Other studies have shown similar responses to phosphorus additions (e.g., Gent et al. 1986, Snowdon 2002). Phosphorus fertilization on phosphorus-deficient clay soils in the southern United States and New Zealand has significantly increased long term productivity (Gentle et al. 1965, Pritchett and Comerford 1982).

Establishment practices at Bainbridge, Bryceland, and Pine Grove also affected annual height growth of the trees. Trees in the plots treated for herbaceous weeds grew 0.17 m/yr faster than those in the plots without herbaceous weed control 1 yr after planting (Figure 6a). Two yr after planting, there is a decelerating rate of annual height growth for trees in the herbaceous weed control plots compared to trees in plots without herbaceous weed control that continues through to age 9 where treated trees were only growing 0.07 m/yr faster than untreated trees.

At Bainbridge, trees in the herbaceous weed control plus fertilizer plots had a higher annual height growth and grew 0.32 m/yr faster than trees not in herbaceous weed control plus fertilizer plots 1 yr after planting (Figure 6b). By age 5, however, trees in the herbaceous weed control plots were growing 0.01 m/yr slower than trees in plots without herbaceous weed control plus fertilizer. At age 9 trees in the plots treated with

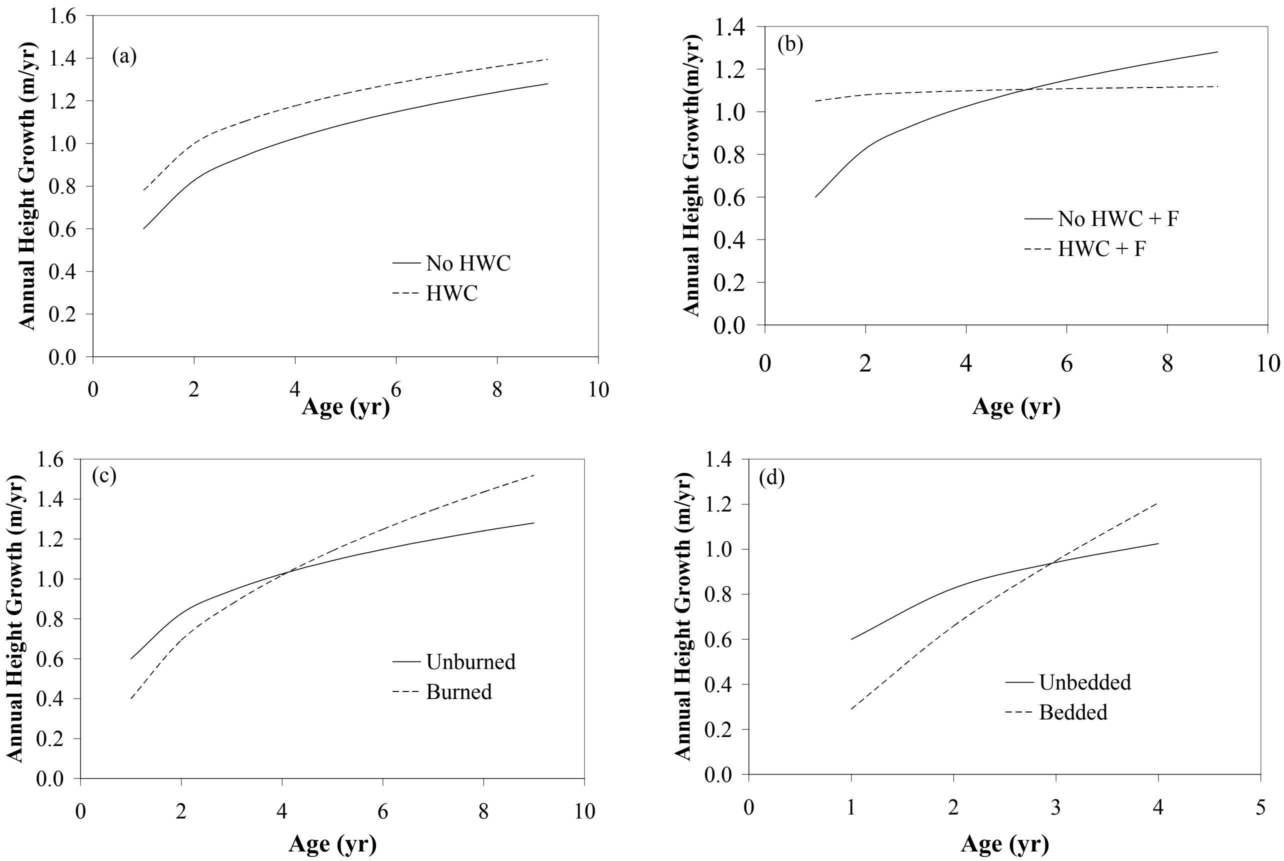

Figure 6. Annual height growth versus age for four levels of the establishment factor at Bainbridge, Bryceland, and Pine Grove: (a) herbaceous weed control at all sites, (b) herbaceous weed control plus fertilizer at Bainbridge, (c) broadcast burn at Bryceland, and (d) bedding at Pine Grove.

herbaceous weed control plus fertilizer still had a lower annual height growth than trees in the plots without herbaceous weed control plus fertilizer.

It is unclear as to why trees in the herbaceous weed control plus fertilizer treatment had a lower annual height growth than untreated trees by age 5, although many trees in the herbaceous weed control plus fertilizer plots were infected with fusiform rust (*Cornartium quercuum* (Berk.) Miyabe ex Shirai f. sp. fusiforme). Sites with soils that are moderately to well drained and have good to excellent tree growth, e.g., Bainbridge, are considered high hazard sites for fusiform rust infection (Froelich and Snow 1986).

Trees in the herbaceous weed control plus fertilizer treated plots may have been more susceptible to fusiform rust infection than trees in plots without herbaceous weed control plus fertilizer treatment because they were growing taller faster. There is increased incidence of fusiform rust infection in weeded (via cultivation or herbicides), fertilized, and weeded and fertilized slash pine (Balthis and Anderson 1944, Boggess and Stahelin 1948). Balthis and Anderson (1944) proposed that a higher rate of growth of cultivated slash pine, when compared to uncultivated trees, probably produced susceptible growth for longer periods of time. Boggess and Stahelin (1948) disagreed with Balthis and Anderson (1944) and suggested that increased incidence is not because of rapid tree growth, but due to an early break of winter dormancy during peak production of fusiform sporidia. Froelich et al. (1983) reported that tall slash pine seedlings became infected with fusiform rust more often than shorter ones, but shorter ones were still infected, a finding also supported by Burton et al. (1985). Froelich et al. (1983) further concluded that rust infection is not solely dependent on the quantity of tissue or the amount of shoots produced in a season.

At Bryceland, trees in burned plots were initially growing 0.18 m/yr less than trees in unburned plots (Figure 6c). Around 4 yr after planting, trees in the burned plots exhibit a higher annual height growth of 0.01 m/yr. This difference between the annual height growth of trees in burned and unburned plots increases with age, and nine yr after planting, trees in the burned plots were growing 0.26 m/yr more than trees in unburned plots. Nutrients such as phosphorus and potassium may have been released after burning (Allen et al. 2005), but these nutrients may have gone to the competing vegetation instead of the trees (Carter et al. 2004). Burning increased soil NH_4^+ which stimulated nitrifying bacteria leading to a decline in NH_4^+ and an increase in NO_3^- (Covington et al. 1991). However, nitrate levels eventually returned to pre-burn levels as a result of plant uptake, leaching, and microbial immobilization. This trend may have occurred on the burned plots in the study.

Trees in bedded plots at Pine Grove were initially growing 0.27 m/yr slower than trees that were not bedded (Figure 6d). By age three, trees on the bedded plots were growing faster than trees on the unbedded plots by 0.08 m/yr. Trees on bedded plots continued to exhibit higher annual height growth than trees on unbedded plots at age 4, growing 0.25 m/yr faster than trees on the unbedded plots. Because bedding was implemented to help with drainage and there was not an initial response to bedding, it is unclear as to what resource the bedding treatment might have manipulated at this site.

At Fred, the relative height growth of the trees in various treatments varied (Figure 7). Trees that were planted on the maximally disturbed, whole-tree harvested plots were more vigorous than trees planted on the minimally disturbed, hand-felled plots (Figure 7a). But, the difference between the relative height growths of the trees planted in

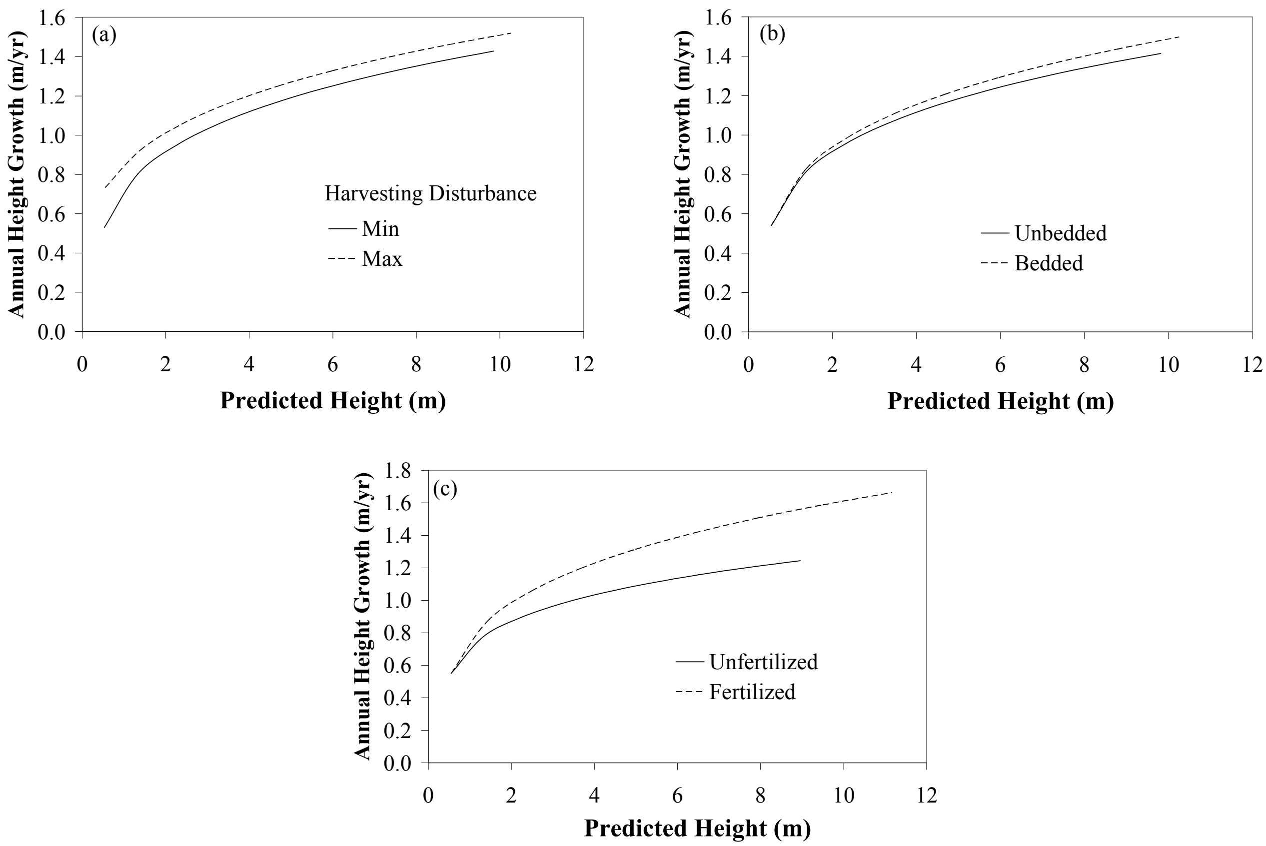

Figure 7. Annual height growth versus predicted height for three factors of silvicultural treatment at Fred: (a) harvesting disturbance (Min: minimum harvesting disturbance (hand felling with bole-only removal); Max: maximum harvesting disturbance (mechanical harvesting with whole tree removal)), (b) bedding, and (c) fertilizer.

the maximum and minimum disturbed plots remained nearly constant across the range of heights.

Trees in bedded plots at Fred, when compared to trees on unbedded plots, exhibited a different relative height growth trend (Figure 7b). Trees in the bedded plots started out growing at the same annual height growth per year, initially. But, after the trees were about 2 m tall, and the heights of the trees that were bedded increased, the difference between relative height growth of the trees on bedded plots and trees on unbedded plots began to increase.

Fertilized and unfertilized trees at Fred had the same relative height growth initially (Figure 7c). Fertilized trees had a substantially higher relative height growth than their unfertilized counterparts after they grew 2 m tall. This indicates that fertilized trees are much more vigorous than the unfertilized trees. When the trees were about 9 m tall, the unfertilized trees had a relative height growth of about 1.26 m yr^{-1} m^{-1}, whereas the fertilized trees had a relative height growth of about 1.5 m yr^{-1} m^{-1}.

Trees in treated plots at Bainbridge, Bryceland, and Pine Grove all exhibited different relative height growth trends (Figure 8). Trees in the herbaceous weed control treated plots had a higher relative height growth than trees not receiving herbaceous weed control (Figure 8a), which could indicate that the trees in the herbaceous weed control plots were more vigorous than those not released from herbaceous weed competition. Increased light and water that may have been available to the seedlings initially may have contributed to the longer term vigor of the trees.

Trees in the herbaceous weed control plus fertilizer treated plots had a higher relative height growth than their counterparts until 4 yr after treatment when trees in the

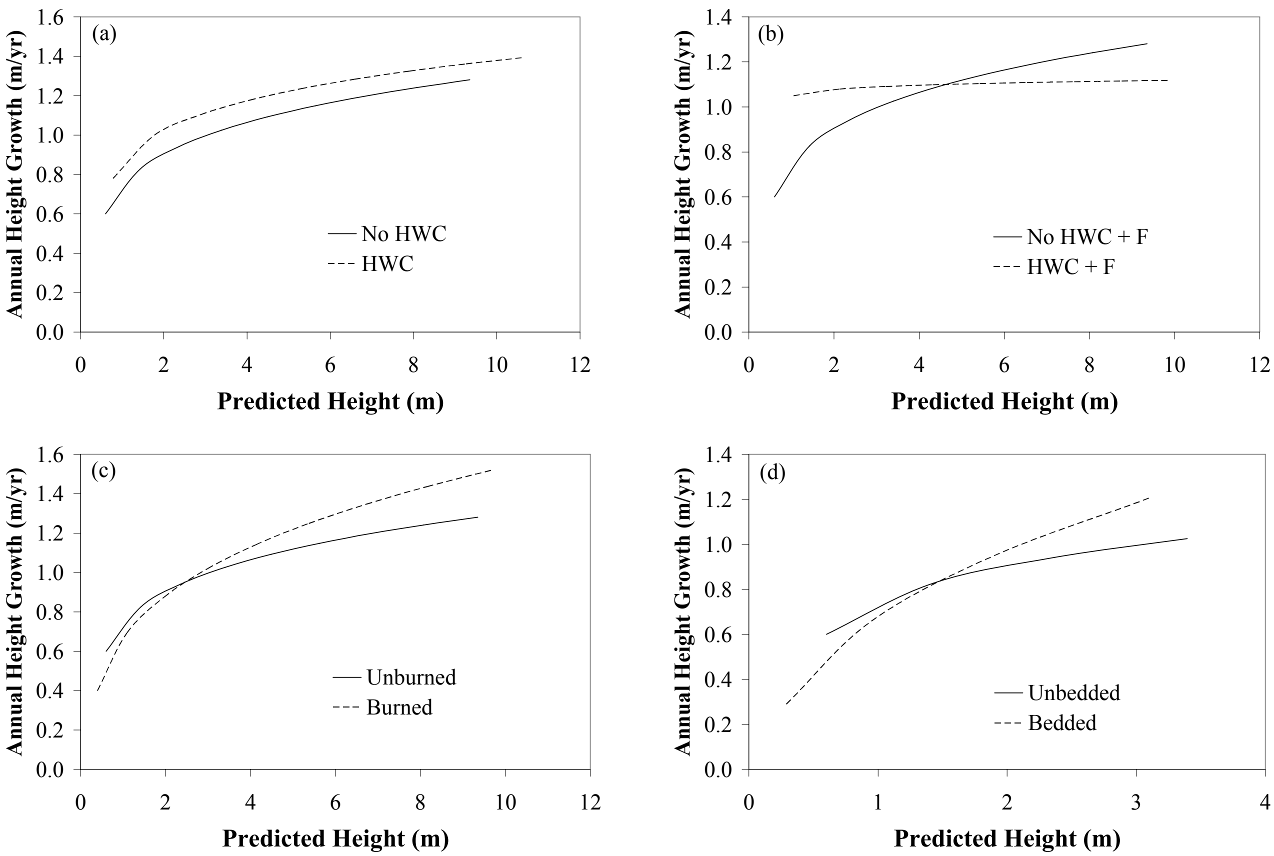

Figure 8. Annual height growth versus predicted height for four establishment practices at Bainbridge, Bryceland, and Pine Grove: (a) herbaceous weed control at all sites, (b) herbaceous weed control plus fertilizer at Bainbridge, (c) broadcast burn at Bryceland, and (d) bedding at Pine Grove.

plots without herbaceous weed control and fertilizer had a higher relative height growth (Figure 8b). Fusiform rust infection on the trees may have caused this decrease in vigor of the herbaceous weed control plus fertilizer treated trees. After slash pine was infected with rust, their height growth decreased, relative to pines that were not infected with rust (Froelich et al. 1983). Moreover, the magnitude of the decrease was greater when the main stems were infected in the first two yr of growth. Froelich et al. (1983) found that fusiform rust stimulated the growth of branches, and as a result the dominant stem seemed to grow more slowly than those without the increased branches.

Trees in burned plots (Figure 8c) grew much slower at earlier heights than their counterparts. Trees in burned plots, however, started growing at a greater relative height growth after they were about 2 m tall. This would indicate that the trees have some how gained vigor and they are more able to obtain the resources necessary for substantial growth gains.

Trees on bedded plots at Pine Grove had a much lower relative height growth than their unbedded counterparts initially (Figure 8d). However, when the trees on bedded plots were about 2 m tall, their relative height growth, as compared to trees on unbedded plots, was greater. This higher relative height growth continues as the trees on bedded plots got taller.

Management Implications

The early height growth treatment response to the harvesting treatments and establishment practices included in this study can be examined by describing them by the type A, B, and C growth responses (Figure 1). A type A response shows a positive growth gain that increases throughout rotation; the type B response shows an early

increase in growth that is maintained but not increased throughout the rotation; and the type C response shows an early growth gain that declines toward the end of rotation age. Although these data only represent the juvenile stages of growth, systematic response patterns have emerged.

Fertilized trees are exhibiting a type A growth response. Monotonic increases in growth gains from phosphate fertilization has been reported previously in the literature, (e.g., Pritchett and Comerford 1982). This early growth response suggests that the annual height growth rates of the fertilized trees will continue to diverge from the annual height growth rate of unfertilized trees. Furthermore, the higher relative height growth of the fertilized trees may provide insight into what type of regeneration treatments substantially increase site productivity; if a regeneration practice substantially affects the physiology of the tree or increases the soil capital of the site, it may exhibit a type A growth response.

Trees planted on maximally disturbed, whole-tree harvested plots at Fred appear to exhibit a type B growth response. Trees on bedded plots at Fred also exhibited a type B growth response through age 9. These type B early growth responses suggest that the faster rate of annual height growth will be maintained.

Herbaceous weed control response at Bainbridge, Bryceland, and Pine Grove can be likened to the Type B or C responses (Figure 1b-c) The shift in resource allocation to the trees in the herbaceous weed control treatments at Bainbridge, Bryceland, and Pine Grove, rather than to a change in total site resources, suggests that the response probably will not affect, i.e., increase, long-term site productivity (Morris and Miller 1994).

Herbaceous weed control plus fertilizer treatment at Bainbridge also appears to follow a type C growth response (Figure 1c).

Trees on burned plots at Bryceland exhibit a type C response curve through age 8 yr, although it may be described as a 'reverse' type C response. The treated trees, in this case, exhibited the type of response depicted by the untreated curve in Figure 1c -- the treated trees were growing slower than the untreated trees early on, but by the end of the range of data, they were growing faster than untreated trees. In a similar fashion, trees that were on bedded plots at Pine Grove also exhibited a reverse type C response. Extended observations of burning at Bryceland and bedding at Pine Grove suggest that neither one of these practices has a negative affect on the long term productivity of the sites contrary to what early observations would indicate.

CONCLUSIONS

Multiple curves were needed to describe the change in tree height with plantation age. At the Fred site, two curves were needed to describe the effect of the harvesting disturbance on early height growth. Furthermore, trees that were on plots that were bedded (at Fred and Bryceland) required a separate height growth curve when compared to trees on unbedded plots. Fertilized trees also required a separate growth curve than unfertilized trees. Likewise, trees that were treated with herbaceous weed control needed a separate height growth curve than trees that were not treated with herbaceous weed control. Additionally, trees treated with herbaceous weed control plus fertilizer treatment exhibited a different early height growth than trees that were not treated with herbaceous weed control plus fertilizer, therefore it required a separate curve. Trees on burned plots required a separate growth curve than trees on unburned plots as well.

Data suggest that most of the forest regeneration practices in this study do not negatively affect productivity. An herbaceous weed control plus fertilizer treatment, on sites with good to excellent growth, however, may be an exception due to increased vulnerability to rust infection.

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