VALUING DIFFERENT LOBLOLLY PINE PLANTATION REGIMES CONSIDERING TRADITIONAL AND NON-TRADITIONAL TIMBER PRODUCTS AND PRICE UNCERTAINTIES

by

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(Under the Direction of Michael B. Kane)

ABSTRACT

Loblolly pine (*Pinus taeda*) is widely planted in the southern US due to its adaptability, growth rate and suitability for timber markets. It is the premier species in a region that contributes a significant portion of industrial roundwood to the U.S. and the world. This research used three installations (sites) of the Plantation Management Research Cooperative (PMRC) Culture Density Study from the Lower Coastal Plain of Georgia and Florida as case studies to examine loblolly pine timber yields and financial returns from traditional and integrated (including bioenergy feedstock) forest product mixes and a feedstock only scenario for combinations of site class, cultural regime, and density management (planting density and thinning). Financial returns were determined using the Black and Scholes model under the real options analysis approach (ROA) and the traditional discounted cash flow approach of net present value (NPV). Management regimes were ranked using the equivalent annual annuity (EAA) approach for both ROA and NPV due to varying optimum rotation age as influenced by site class, planting density, cultural regime, and thinning scenario. Conclusions regarding best management regimes were the same using ROA and NPV; however, ROA returns were higher as it captured the value from product price volatilities which NPV did not. Financial returns for integrated forest products were greater than for traditional timber product due to the addition of bioenergy feedstock revenues. For the traditional product mix, the optimum regime for low and average site classes was 600 TPA planting density with intensive culture and two thinnings while that for the high site was 900 TPA, operational culture, and two thinnings. Optimum regimes for the integrated forest product mix were similar with the exception that the 600 and 900 TPA densities provided similar returns for each site class. Financial returns for the integrated products mix regimes were generally much less than for bioenergy feedstock dedicated regimes but the feedstock dedicated regime returns reflected unusually high historical prices.

INDEX WORDS: traditional timber products, non-traditional timber products, bioenergy, optimal rotation, net present value, real options analysis, price volatility, planting density, cultural intensity, site class.

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## DEDICATION

I'd like to dedicate this work to my parents, Bali Ram Chaudhari and Basmoti Chaudhari, and to my wife Bhawana Chaudhary for their sacrifice and encouragement for my higher education.

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# CHAPTER 1

# INTRODUCTION AND LITERATURE REVIEW

## 1.1 Purpose of the Study

Loblolly pine (*Pinus taeda* L.) is one of the most widely studied tree species in the southeastern United States due to its commercial and ecological significance. Many studies (Switzer et al., 1966; Teskey et al., 1987; Schultz, 1997; Sedjo and Botkin, 1997; Jokela et al., 2004) have examined the effects of silvicultural practices and cultural intensities on the productivity of loblolly pine over the past several decades. However, few reported studies include a range of site productivity classes, tree densities, and cultural intensities. This study explores the biological potential and economic outcome from three site productivity classes, planting densities ranging from 300 to 1800 trees per acre and two cultural intensities.

The economics of loblolly pine plantations impacted by site classes, densities, thinning regimes, and cultural treatments using real options analysis (ROA) and net present value (NPV) capital budgeting techniques has not been reported (Chaudhari et al., 2016). Timber price plays a vital role in decision making. Price variation in the market creates volatilities that conventional discounted cash flow techniques, such as NPV, do not capture. ROA can be used as a forest valuation tool that accounts for price volatility. This study examines two capital budgeting techniques (i.e., NPV and ROA) to assess forest stand value and optimal rotation age for stands given price uncertainty scenarios and identifies their advantages and limitations.

Traditional timber products, such as pulpwood, chip-n-saw, and sawtimber remain the major drivers for profitable forest plantations in the southeastern U.S. (Wear and Greis, 2002). More recently a non-traditional market for bioenergy feedstock has gained momentum due to demand for wood pellets in the European Union. The southern U.S. have become a major exporter of wood pellets to several European countries (Goetzl, 2015; Dwivedi et al., 2016). This study values different plantation regimes considering both traditional and non-traditional forest products using ROA and NPV approaches.

Various studies (Fox, 2000; Borders and Bailey, 2001; McKeand et al., 2006) show that intensive plantation management generally yields greater biomass and higher return; however, it is important to understand impacts of intensive culture regimes for a given site. Researchers have recommended different levels of tree densities. Bowling (1987), Vardaman (1989), and Caulfield et al. (1992) recommend planting of 300 to 400 trees per acre, while others (Bailey, 1986; Borders et al., 1991) recommend planting up to 1200 trees per acre. Managers often base planting density decisions on expected maximum financial return given site productivity and market assumptions. It is important to understand what level of stand density provides maximum financial return given site productivity and markets. It may be tempting to think that greater total biomass production can be obtained by planting higher densities which will provide greater financial return. This study investigates whether that is the case.

The research reported here addresses a clear need for a comprehensive analysis of key factors, such as site quality, density management, cultural regimes, product mix and uncertainty in stumpage values that impact financial return from loblolly pine plantation. The main objectives of the study are to:

1. Quantify loblolly pine stand yield for silvicultural regimes differing in planting density, cultural intensity and thinning for a range of site indices in the Lower Coastal Plain.
2. Evaluate financial return of traditional and non-traditional forest products from different plantation regimes using NPV and ROA approaches.
3. Identify optimum plantation regimes for different site classes and product mixes.
4. Identify advantages and limitations of NPV and ROA approaches.

## 1.2 Dissertation Structure

The remainder of Chapter 1 consists of a literature review of the main topics addressed in this dissertation. An in-depth literature review of use of ROA in forestry investment decisions is presented in Chapter 2. Research on the effects of site class, management regimes including planting density, cultural intensity, and thinning, on the economic returns from traditional timber products using NPV and ROA valuation approaches is presented in Chapter 3. Economic returns using NPV and ROA approaches for an integrated timber product mix (combination of traditional timber product and bioenergy feedstock) and a plantation dedicated to bioenergy regime only are presented in Chapter 4. Main conclusions from Chapters 2, 3, and 4 are presented in Chapter 5.

## 1.3 Literature Review

*Loblolly Pine Management in the Southern USA*

Loblolly pine (*Pinus taeda* L.) occupies more than 32 million acres of land in the southern USA (Schultz, 1997; Fox et al., 2004) and is the preeminent commercial pine species (Baker and Langdon, 1990; Harms et al., 2000; Vance and Sanchez, 2006). It is well adapted to a wide range of soils, sites, and environments that occur over its natural range, which extends from southern New Jersey south to central Florida and west to eastern Texas (Harms et al., 2000). Loblolly pine has been favored for commercial production on private lands, because this species typically reaches economic maturity faster than other pine species and lends itself, perhaps more than any other species in the world, to silvicultural flexibility (Baker et al., 1996). It can be managed as either even-aged or uneven-aged natural stands, or it can be regenerated artificially and managed in plantations (Burns and Barbara, 1990). The even-aged stands are obtained from clearcutting, seed-tree, and shelterwood methods. The selection method creates and maintains uneven-aged stands.

While many non-industrial private landowners manage their planted pines with minimum silvicultural input, commercial growers generally favor more intensive plantation management on shorter rotation of 30 to 35 years (Wear and Greis, 2002). Intensively managed plantations generally use genetically improved stock matched to the site and silvicultural treatments targeted at amending resource limitations (Allen et al., 2005). The overall objective of intensive plantation management is to maximize net present value by employing economically efficient treatments that promote higher net production, often of higher value product classes in relatively short rotations. While applied and process-level research has been conducted over the past few decades with loblolly pine (Switzer et al., 1966; Teskey et al., 1987; Schultz, 1997; Sedjo and Botkin, 1997; Jokela et al., 2004), our understanding of the effects of operational and intensive management regimes for a broad range of densities, site qualities, and thinning scenarios has been less documented, particularly from a forest valuation perspective.

Loblolly pine plantation regimes contain a suite of silvicultural treatments, the optimum combination and timing depending on site and markets. Chemical site preparation is often important to eliminate and control unwanted woody vegetation. A planting density of 500 to 600 trees per acre are commonly planted by the commercial timber growers in the U.S. (Lang et al., 2016). Post planting control of herbaceous competitions is often warranted and, in some cases, herbicide applications are made to control woody competition in established stands. Thinning is carried out to manage stand density and provide adequate growing space (Fox et al., 2007b). It is often done once or twice with timing dependent on planting density, growth rates, and market opportunities. Normally, on sites of moderate to high productivity, first thinning is carried out at 14 to 16 years of age and second thinning at 20 to 24 years of age (Lang et al., 2016). Fertilization, typically with nitrogen (N) and phosphorous (P) is often done to ameliorate soil nutrient limitations (Fox et al., 2007b). If the trees receive enough care and management, they typically reach their maturity at 30 to 36 years of age (Lang et al., 2016). Final harvest at such ages usually ensures tree size meeting sawtimber specifications.

Pine plantation management in the U.S. South has become dominant due to the high economic returns that can be obtained in a short period of time, and these gains can be attributed to improved genetics, fertilization, competition control, density management, and other cultural practices (Fox, 2000). Historically, most forest landowners focused on minimizing per acre costs associated with plantation establishment and tending which resulted in growth rates averaging less than the 5 tons/ac/year (Allen et al., 2005; Fox et al., 2007a. 2007b). Technology developments have led some landowners to plant genetically improved seedlings and use more intensive silviculture that have helped them double timber volume (10 tons/ac/year) and cut the rotation length by a half (Fox et al., 2004; Allen et al., 2005; Fox et al., 2007a, 2007b). Although the cost associated with intensive management can be higher, financial returns from such plantations may be higher because of the much greater growth rates and shorter rotations (Allen et al., 2005). The plantation stands in this study received slightly higher end of operational and intensive culture regime. This study explores whether higher cost of intensive management justifies the newer approach.

*New Market Opportunities and Risks*

Landowners are adapting forestry practices to developing market opportunities. Forests of the southern U.S. offer considerable promise for sustainable production of wood for traditional and developing industries, and number of non-timber forest products. These forests cover merely 2% of the world's forest but produce more timber than any other country in the world (Prestemon and Abt, 2002). Southern forests alone supply 60% percent of all wood products (industrial roundwood, sawn wood, and wood pulp production) in the U.S. (Wear and Gries, 2002) which is over 12% of global production of these products. This large supply of timber from the U.S. South is mainly due to forest expansion from 1953 to 1997. Wear and Greis (2002) forecasted that timber production in the United States will increase by about one-third between 1995 and 2040 and that nearly all of this growth will come from the South, where production is forecasted to increase 56 percent for softwoods and 47 percent for hardwoods.

Urbanization is one potential reason for conversion from forest in the eastern part of the southeastern U.S. by 2040, but it will also create a demand for traditional forest commodities like sawtimber, chip-n-saw, and pulpwood and non-traditional forest commodities like bioenergy feedstock for energy and green areas for wildlife habitat, clean water, and fresh air (Wear and Greis, 2002). An increased demand for bioenergy feedstock particularly from European countries has been observed recently, (Goetzl, 2015; Dwivedi et al., 2016). European energy companies use feedstock in the form of pellets for heat and electricity generation. The demand for bioenergy can be fulfilled to some extent by fast growing short rotation woody crops and planted pine small diameter sized trees and harvest residuals (e.g., tops, limbs).

Although European and some Asian countries buy wood pellets for energy, southern US forest growers are concerned about appropriate pricing and legislative uncertainty regarding bioenergy feedstock markets. Bioenergy feedstock price has been subject to government policy changes as indicated by high prices during the 2007 to 2009 period and price decreases thereafter. Recent studies by Nesbit et al. (2011) and Dwivedi et al. (2012) show the price of the bioenergy feedstock ranging from $1 - $5 may not financially justify plantations dedicated to bioenergy, particularly on poor sites or plantations with minimal operational treatment. Besides selling the whole tree as bioenergy feedstock, tops and limbs of trees can be sold as a bioenergy feedstock if there is appropriate market.

Viable feedstock markets provide many advantages in addition to direct monetary returns. Thinned material may in the future be used for cellulosic ethanol and thinning may reduce the risk of wildfire in the forests by reducing fuel load (White, 2010). Biofuel is regarded as an alternative to fossil fuel and a way for reducing carbon emission (Lippke et al., 2012). Use of forest biomass alleviates pressure on agricultural land for biofuel productions (National Research Council, 1999) and provides raw material for electricity and heat generation. Biotechnologies using woody biomass for cellulosic ethanol are still in development and demonstration phases. However, several energy companies in the U.S. South do buy harvest residues and small diameter-sized trees in the southern US for energy and heating purposes. Increased demand for wood pellets from European and Asian countries and appropriate woody feedstock price may encourage forest landowners to opt for higher density tree plantations. The future stumpage price and demand for biomass feedstock will determine the role of this potential market in plantation management, but current demand for wood pellets from abroad and energy needs in domestic markets is a promising sign for development of markets (Goetzl., 2015; Dwivedi et al., 2016).

*Price Uncertainties and Financial Tools*

Most forest management financial decisions are based conventional discounted cash flow (DCF) techniques such as net present value (NPV), soil expectation value (SEV), equivalent annual annuity (EAA), benefit-cost analysis (BCA), and internal rate of return (IRR) (Klemperer, 1996). All of these methods' emphasis is on maximizing financial return considering the time value of money and some level of risk adjustment through the discount rate. There are other methods for valuing a project like accounting rate of return (ARR) and payback period which are not based on discounted cash flow.

The conventional approach to valuing investment projects, based on NPV, essentially involves discounting the expected net cash flows from a project at a discount rate that reflects the risk of those cash flows (the "risk-adjusted" discount rate) (Schwartz and Trigeorgis, 2004). The DCF techniques are easy to follow as they require essentially two financial variables: discount rate and deterministic price. Unfortunately, the implementation of conventional DCF analyses does not properly capture the value of investments whose cash flow streams are conditional on future outcomes and managerial actions, and which thus have complex risk profiles (Triantis, 2003). Also, the conventional DCF analyses are based on the assumption that future cash flows follow a constant pattern that in the case of forestry can be accurately predicted from regeneration to the rotation age (Duku-Kaakyire and Nanang, 2004). However, future timber prices are uncertain and timber management may need future actions before the final harvest which violates the DCF assumption. The uncertainty that is inherent in an afforestation or reforestation project and management's reactions to changes in the assumptions are only dealt with superficially (Morck et al., 1989). A European call option, an option valuation technique, for non-dividend paying real assets is an extension to conventional discounted cash flow techniques which addresses the issues of managerial decision by deferring, expanding, contracting, staging, or abandoning a project. Last but not the least, ROA captures the value of uncertainty (or volatility) in timber product prices which conventional NPV (or DCF) does not, which makes ROA superior to conventional NPV for capital budgeting.

A real option is a right – not an obligation – to take an action (e.g., defer, expand, contract, abandon, stage) on an underlying nonfinancial asset at a predetermined cost on or before a predetermined date (Schwartz and Trigeorgis, 2004; Damodaran, 2005). Black and Scholes (1973) and Merton (1973) pioneered a formula for valuing a financial option and laid the foundation for research on the pricing of financial assets. The idea was later applied to real assets by Myers (1977) who proposed the idea that a firm's non-obligatory investment opportunities can be viewed as a call option on real assets similar to the financial call option providing decision rights on financial assets (Tee et al., 2012).

There are numerous advantages of using real options valuation over the conventional NPV approach. In forest investment analyses, it explicitly allows for managerial flexibility in forest harvesting timing in case of timber market fluctuations. If timber prices are low at the anticipated time of harvest, forest owners may delay harvest and wait-and-see before making a harvesting decision. Conventional NPV misses the extra value associated with deferral because it assumes the decision cannot be deferred (Dixit and Pindyck, 1995; Luehrman, 1998). Likewise, if timber prices are remarkably high before the expected time of harvest, profit oriented forest managers decide to harvest earlier than planned (Tee et al., 2012). Tree plantations can be sold should the timber price fall below the landowner's expected rate of return. The salvage value in terms of timber and land sales and the resale value of capital equipment usually more than offsets the exit cost (Trigeorgis, 1996). In addition, ROA does not require the estimation of a risk-adjusted discount rate and uses the risk-free rate of interest as the discount rate. When market (e.g., future) prices exist, it avoids the need to make assumptions about the trajectory of spot prices in the future since it uses the information contained in futures prices (Schwartz and Trigeorgis, 2004).

### 1.4 Summary

The research purpose and literature review above provide a setting in which the research of Chapters 2 -4 occurs. A detailed analysis of key literature, growth, and trends in usages of ROA in forestry investment decisions is lacking. Many researchers have explored the impact of site indices due to genetic improvement, fertilization and soil nutrient, competition control, and tree densities. However, many studies of these studies are limited to either early ages or only explored the biological perspectives. Financial evaluations are carried out mostly using conventional NPV. ROA in forestry investment decisions is not a new idea; however, it has not been applied in a larger scheme of site productivity levels, multiple densities and management intensities. Few studies in forestry have used both ROA and NPV comparing financial return from both approaches. Research on traditional timber market dominates the forestry literature, and a study on non-traditional timber products, such as bioenergy feedstock, is valuable given current and potential bioenergy feedstock.

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# CHAPTER 2

# THE KEY LITERATURE OF, AND TRENDS IN, FORESTRY INVESTMENT DECISIONS USING REAL OPTIONS ANALYSIS[1]

[1] Chaudhari, U.K., M.B. Kane, and M.E. Wetzstein. 2016. *International Forestry Review*. 18(2):146-160. Reprinted here with permission of the publisher.

**Abstract**

This chapter presents trends and development of real options analysis (ROA) in the field of forestry investment decision making. A literature review was conducted similar to Newman's (2002), which presented the Faustmann framework of optimal forest rotation literature in forestry investment decisions. Eighteen forestry and non-forestry journals, along with significant books on ROA, are reviewed. Although real options applications in the field of forestry are relatively new, as compared to Faustmann's discounted cash flow technique, numerous journals contain articles on ROA in forest investment decisions. The application of real options in forestry investment decisions developed during the late 1980s from the simple topic of nature preservation employing a quasi-option value. This analysis method has recently been applied to much larger problems of timber cutting contracts employing Monte Carlo simulation approaches. In addition, geometric Brownian motion and mean reversion, two of the most prevalent continuous-time stochastic price models in ROA, are discussed. The number of publications slowly but steadily increased from the early 1980s to the late 1990s and has remained steady since the early 2000s, with an average of 2.7 articles annually. Although real options analysis has garnered attention lately, the discounted cash flow technique remains the major tool supporting forestry investment decisions.

Key Words: Faustmann model, real options, investment, optimal rotation, stochastic timber price

## 2.1 Introduction

Forest managers generally employ traditional discounted cash flow (DCF) techniques such as net present value (NPV), land expectation value (LEV), benefit/cost ratio (BCR), and internal rate of return (IRR) in forest investment decisions. Faustmann's work (1849), "on the determination of the value which forest land and immature stands pose for forestry" was a significant contribution to forest investment decision making and how we look at forests as an investment opportunity (Newman 2002). Subsequently, many authors have contributed articles on optimal time to harvest a stand. More than 300 published works on this topic have appeared in books and over sixty journals (Newman 2002). Given the assumptions of a constant price, discount rate, and growth rate of trees based on growth and yield models, Faustmann's deterministic method yields a reasonable approximation of an optimal rotation and the forest values. However, future timber prices are uncertain and hence can be treated as stochastic variables. Discount rates are related to the way future prices behave; applying Faustmann's formulae may yield misguided conclusions, both in terms of optimal rotation periods and the value of the bare land (Gjolberg and Guttormsen 2002). In addition, Zinkhan (1995) and Thorsen (1999) maintain that the conventional discounted cash flow technique ignores the importance of flexibility for the evaluation of forest resources management and may result in erroneous conclusion in the making of wrong forest management planning.

Real options analysis (ROA) is an augmentation of static NPV, which offers a robust approximation of future values considering price uncertainties and managerial flexibility (Olafsson 2003). Relatively few articles have been published using this approach in forestry investment decisions as compared to NPV and other discounted cash flow techniques. Brazee and Newman's (1999) editorial on recent developments in risk and uncertainty research touched on the application of ROA in forest economics but did not discuss it in great detail. Hildebrandt and Knoke (2011) explored the usage of ROA in various fields of forestry and discussed the major ROA solution methods (i.e., Black and Scholes and binomial tree method). Most ROA related articles provide a brief literature review on ROA usage in forestry but usually emphasize one particular application of ROA. A synthesis of historical perspective, growth and development of ROA in forestry investment decisions has not been reported. The main objective of this article is to fill this gap. In addition, the aim of this article is to present an outlook of ROA solution methods common in forestry investment decisions, application of ROA methods in varying investment decisions, and to present a discussion on continuous-time stochastic price models (i.e., geometric Brownian motion and mean reversion) and their use in ROA articles to solve forestry problems associated with investment decision making.

The articles presented in this review illustrate a wide range of ROA application in forestry investment decisions. This review serves as a reference for forestry professionals, scientists, and students interested in forestry investment decision making. It follows the review by Newman (2002) who demonstrated the dominance of the use of DCF and the Faustmann model as forest investment criteria. The bibliography of ROA application in forestry is a valuable resource to readers interested in applications and methods. In addition, this article identifies common continuous-time stochastic price models used in ROA application. This information will aid understanding of appropriate continuous-time stochastic price models in research design and analysis.

The development of literature building on the seminal work of Black and Scholes (1973) and Myers (1977) is reviewed and documented. The growth in use of dynamic programming developed by Richard Bellman (Bellman 1957) and contingent claim (Morck 1989) in ROA application in forestry is presented. Numerical solution methods such as binomial tree (Cox *et al*. 1979), Monte Carlo simulation (Boyle 1977), implicit finite difference and explicit finite difference methods are also described and documented. The breakthrough of ROA in forestry occurred in the 1980s, with broader applications during the 90s and later. This review explores the advances of ROA in forestry investment decisions from 1985 to July 2014.

The article is organized as follows. The method section details the tools and techniques for developing and organizing the bibliography. It describes criteria for selecting specific journals and subject areas in forestry. The result section details chronology and statistics of ROA articles in forestry. It is followed by a description of ROA solution techniques commonly applied in forestry investment decisions. Common continuous-time stochastic price models used in ROA are presented in the next section. The article concludes with the discussion on historical perspective, growth and developments, general trends, management implications of ROA and stochastic price models and their likely development in the future.

## 2.2 Methods

To assess the trends in the development of ROA for forestry investment decisions, relevant publications were surveyed with emphasis on stochastic prices, timber growth, interest rates, market uncertainty, and most importantly, ROA. Publications from 1985 to July 2014 were considered because most of the development in ROA occurred since the late 1980s. Brazee and Newman (1999) and Newman (2002) noted an abundance of risk and uncertainty articles in forest economics that apply ROA methods published after the late 1980s. Included in this survey were 18 forestry-relevant journals; various non-forestry journals; selected books such as Dixit and Pindyck (1994), Guthrie (2009), Hull (2012), and Trigeorgis (1996); and some thesis works. Generally, the articles cited were obtained through an online library search (Web of Science and Agricola) and from the University of Georgia library archives. Key words employed in the search engine include real options, option, stochastic price, volatility, uncertainty, optimization, forest valuation, dynamic programming, Black and Scholes (hereafter, Black-Scholes), and binomial tree, generating the list of articles containing these key words either in their title or abstract. In addition to the key word search, an issue-by-issue and article-by-article survey of selected journals was employed in an online library search. The data were compiled into a database using the bibliographic software Endnote version X7.0.

Not all articles covering real options and stochastic price models were included in this review. The determination of whether or not to include a work depended on factors such as content, relevance, importance, and interest. Generally, research articles on forestry investment decisions using ROA in leading forestry journals were included. Some of the leading journals published no ROA articles (e.g., *Forestry, Silva Fennica,* and *Land Use Policy*) but contained articles on stochastic price models in the application of NPV and LEV. In addition to major forestry and environmental journals, many finance, advancement in simulation, and policy related journals were also explored. Articles employing stochastic price processes in the model but not utilizing a real options model were excluded from the list of tables and figures but are mentioned in the text and bibliography. In this analysis, articles are included that describe real options or its use as a tool in investment decision making in forestry but not in fisheries and wildlife management (e.g., Ewald 2013, Nøstbakken 2006, Willis 1989) in order to confine interest to the timber sector, placing reasonable limits on the bibliography. Articles from other sources such as conference proceedings and non-selected journals received little attention. They are mentioned in the text because of their importance but are not presented in tables and figures, as they were not part of the 18 journals surveyed. The information recorded about each article included publication date, journal, type of technique(s) described or demonstrated, and the problem-solving approach emphasized. The journals considered were: *American Journal of Agricultural Economics, Biomass and Bioenergy, Canadian Journal of Forest Research, Ecological Economics, Environmental and Resource Economics, Forest Ecology and Management, Forest Policy and Economics, Forest Science, Forestry, Journal of Economic Dynamics and Control, Journal of Environmental Economics and Management, Journal of Forest Economics, Journal of Forestry, Land Economics, Land Use Policy, Natural Resource Modeling, Silva*

*Fennica,* and *The Journal of Finance.* ROA articles were grouped by solution method, type of stochastic price process, and the investment decision criterion.

## 2.3 Results

*Journals and Publication Contributions*

A simple chronology of publications on ROA and its applications in forestry investment decisions are provided. The theory of modern option pricing was established by Black and Scholes (1973) and extended by Merton (1973). Myers (1977) coined the term real options with the idea that a firm's discretionary investment opportunities can be viewed as a call option on real assets in much the same way as a financial call option (Tee *et al*. 2012). Pindyck (1984) then applied option pricing to a renewable resource in property rights appraisals and, later in the same year, Shaffer (1984) reported on valuation of long-term timber cutting contracts using the Black-Scholes model. Brennan and Schwartz (1985) subsequently applied a real options approach to value non-renewable natural resources.

The number of publications employing ROA in forestry investment decisions increased since 1985 (Figure 1). The contribution of each journal by percentage, number of publications, first, and last publication using ROA is shown in Table 1. In the review period, the first ROA articles of interest were published in *Land Economics* in 1985 and 1986. These articles do not exclusively mention the topic of forestry investment decisions but discuss supply uncertainty, option price, and option value of environmental public goods. These articles demonstrate the development of ROA applications in topics (e.g. environmental public goods) closely related to forestry and likely influenced subsequent publications in forestry. Smith (1987) mentioned the topic of environmental welfare measures under uncertainty and Fisher and Hanemann (1987) explained the net benefit of nature preservation with an approach of quasi-option value. Both articles were published in the *Journal of Environmental Economics and Management.* Although *Forestry, Silva Fennica,* and *Land Use Policy* are leading forestry journals, this review did not find ROA articles relevant to forestry applications in these journals. However, these journals have published articles on the DCF approach using stochastic prices (e.g., O'Donnell *et al*. 2013, Pukkala and Kellomäki 2012).

The *Journal of Environmental Economics and Management* published 14 ROA articles during the review period, more than any other journal (Figure 2 and Table 1). It actively published such articles in forestry throughout the 1980s, 90s, and 2000s. Their latest ROA article was published in 2009. *Forest Policy and Economics* was the second leading journal with 12 ROA articles and has a consistent publication record on the topic from 1999 to 2013. *Land Economics* and *Forest Science* each contributed by publishing eight articles. *Land Economics* published comparatively more articles in the late 1980s and early 1990s whereas *Forest Science* published more articles in the late 1990s and early 2000s. The *Journal of Environmental Economics and Management* and *Forest Policy and Economics* were particularly active in forestry related ROA publications after 2001. These temporal changes indicate that it is possible for journals to quickly establish prominence in specialized topic areas such as this.

The ROA publication data indicate an intermittent temporal pattern (Figure 2). However, publication level over time has increased when the publications are grouped into ten-year periods. There were 17 articles published from 1985 to 1994, 24 articles from 1995 to 2004, and 27 articles from 2005 through July of 2014.

*ROA Methods in Forestry Investment Decisions*

Prior to discussing real option solution methods, it is important to differentiate the term quasi-option value coined by Arrow and Fisher (1974), Fisher and Hanemann (1987), and Henry (1974) with ROA as defined by others. Generally, authors (Arrow and Fisher 1974, Chambers *et al*. 1994, Cochrane and Cutler 1990, Fisher and Hanemann 1987, Hanemann 1989, Lund 1991) interpreted an option value as the expected value from benefits of future improved knowledge about an environmental resource which would have been lost due to irreversible development. Arrow and Fisher (2000) termed this as quasi-option value and consider it as equivalent to real option value, the value of delay or deferral of development until new knowledge becomes available over time. However, Mensink and Requate (2005) distinguish between real option and quasi-option value. They argued that the Arrow-Fisher-Henry-Hanemann quasi-option value reflects only the value of delaying a decision due to the expected value of obtaining more information in the future whereas option value as per Dixit and Pindyck (1994) can be decomposed into the informational option value, which is equivalent to Arrow-Fisher-Henry-Hanemann option value, plus a pure value of delay which exists in the absence of uncertainty.

Various types of groupings and classes of approaches have been presented to solve option problems reflecting the underlying business context (Rigopoulos 2015). Rigopoulos (2015) and Schulmerich (2010) presented a detailed taxonomy of ROA methods for a broad context of applications (Figure 3). Trigeorgis (1996) presented a categorization of numerical and analytical solution methods with emphasis on different types of options (i.e., option to defer, option to shut down or abandon, option to exchange, option to switch, and compound options) and use of a numerical solution when no analytic closed-form solution is possible. Trigeorgis (1996) stated that there are inherent flaws in analytical solution methods. Analytic models are used mostly for simplified cases and may not be useful when the project value has an opportunity cost or a dividend payout where the closed-form solution does not exist (Schulmerich 2010). Dixit and Pindyck (1994) presented detailed analytical methods, particularly dynamic programming and contingent claim analysis. Numerical methods are employed to handle rather complex option problems. The numerical solution methods are usually the approximation of the stochastic process or partial differential equations (PDE) (Trigeorgis 1996). In many cases when there is no analytic solution, numerical solution methods are employed to approximate PDE (Hull 2012, Trigeorgis 1996, and Dixit and Pindyck 1994). These authors discuss the numerical procedures in their respective books in detail.

The current review discusses analytical and numerical solution methods applied in forestry investment decisions. The following classes of solution methods are presented.

1. Analytical methods
    a. Closed form solutions in the form of Black – Scholes model
    b. Dynamic programming (optimal stopping, approximation of stochastic process)
    c. Contingent claim
2. Numerical methods
    d. Approximation of stochastic process (binomial tree, Monte Carlo simulation)
    e. Approximation of the PDE (implicit and explicit finite difference methods)

1. Analytical Methods

Analytical solution methods use the solving of PDE. One of the most commonly used analytical methods in financial options is the Black-Scholes model. Fischer Black and Myron Scholes first proposed an equilibrium option pricing model in 1973 and it was later extended by Robert Merton in the same year in several important ways (Cox *et al*. 1979). The Black-Scholes model is a continuous-time model usually applied to value complex contracts in which the holder has the right but not the obligation to buy or sell a stock at a predetermined date (Amram and Kulatilaka 1999). The model is based on the assumption that stock price follows a geometric Brownian motion (GBM). Usually in forestry, the PDE form of the Black-Scholes model is solved to a continuous-time model for a call option (without dividends) and is used in forest valuation problems (Hildebrandt and Knoke 2011). It is practiced as a European type option. A European option can only be exercised at the end of its life. The analogous form of a European option in forestry would be an option exercised at the end of the rotation of a stand.

A number of articles (e.g., Burnes *et al*. 1999, Gjolberg and Guttormsen 2002, Hildebrandt and Knoke 2011, Hughes 2000, Manley and Niquidet 2010, Susaeta *et al*. 2009, Yin 2001, and Zinkhan 1991) have employed the Black-Scholes model. Shaffer (1984) first applied the Black-Scholes model in timber cutting contracts followed by Burnes *et al*. (1999). Burnes *et al*. (1999) modified the problem formulation to obtain a closed-form solution for a harvest contract with the simplifying assumption that the contract holder would make the decision to harvest the stand based on the market conditions near the end of the contract period. Zinkhan (1991) applied this model in valuing timberland and evaluating more economically attractive options such as conversion to different management regimes. Gjolberg and Guttormsen (2002) described the consequences of mean reversion (MR) on tree cutting problems using the Black-Scholes model. Hughes (2002) and Manley and Niquidet (2010) employed this model to value plantation forests of New Zealand from an optimal rotation standpoint. Susaeta *et al*. (2009) used the model to estimate forestland values of slash pine forests in the southern United States under thinning and non-thinning scenarios. Hildebrandt and Knoke (2011) did not use this model for analytical solutions, but explained the theory of option valuation along with other investment decision methods addressing uncertainty employed in forestry investment decision studies.

Thomson (1991) stated that the forest rotation optimization cannot be determined using the Black-Scholes method because not all of the requisite inputs are available for a timber valuation problem. However, in his subsequent article (1992), he commented that the forest rotation problem can be solved using a closed form solution of the Black-Scholes model if the stumpage price follows the lognormal diffusion process (i.e., GBM) along with other financial market assumptions. Insley (2002) and Hull (2012) also confirmed that once exercise price or the cost of management is explicitly included, the option can no longer be solved analytically in an American-type call option on a dividend-paying asset allowing it to be solved as a European type option. Luehrman (1998) also explained the usage of Black-

Scholes models in a step by step process comparing it with traditional NPV approach for a non-dividend paying assets such as forest.

Most of the analytical solution methods of option pricing use stochastic dynamic programing (Thomson 1992) and contingent claim analysis. Dynamic programming was developed by Richard Bellman in the 1950s (Bellman 1957). Although both approaches are closely related and lead to identical results in many applications, they are based on different assumptions about financial markets and discount rates that firms use to value future cash flows (Dixit and Pindyck 1994). The term "Bellman equation" is generally regarded as the dynamic programming equation associated with discrete-time optimization problems. The analogous equation is a PDE which is called the Hamilton-Jacobi-Bellman (HJB) equation commonly used in continuous-time optimization problems. The dynamic programming option problems using a HJB equation follow a backward induction process to value an asset using a discount rate, which reflects the opportunity cost of capital for investments of similar risk (Insley and Wirjanto 2010).

Norstrøm (1975) was one of the pioneers to use stochastic timber prices to find the optimal harvest age using dynamic programming. Most forestry investment decision problems addressing uncertainty have been formulated using dynamic programming (Figure 4). Brazee and Medelsohn (1988), Clarke and Reed (1989), Haight and Holmes (1991), Insley and Wirjanto (2010), Musshoff (2012), Rocha *et al*. (2006), Schatzki (2003), Thorsen (1999), Yin and Newman (1997), and many others followed after Norstrøm (1975).

Stochastic dynamic programming utilizing the stochastic price process is an important approach. Norstrøm (1975), and Haight and Holmes (1991) used it for harvest decisions by incorporating price fluctuations as a source of uncertainty. Provencher (1995) used a stochastic dynamic programming algorithm within a maximum likelihood routine in timber harvest decisions for slash pine plantations in southeast Georgia. Plantinga (1998) demonstrated optimal timber rotation determination using dynamic programming with reservation price policies which act as a mechanism for incorporating the option value.

Manley and Niquidet (2010) followed Norstrøm (1975) and compared stochastic dynamic programming with the binomial tree approach and found very similar results in evaluating harvest, defer or never harvest options.

Optimal stopping is a particular class of dynamic programming in which the decision choices are binary (Dixit and Pindyck 1994). The basic idea of optimal stopping is that, for a given binary choice, one alternative corresponds to stopping the process to take the termination payoff, and the other entails continuation for at least one period, when another similar binary choice will be available (Dixit and Pindyck 1994). The optimal stopping problem is formulated such that when there is no profit moving forward, the investment is stopped and asset/equipment is sold for its scrap value whereas continuation correspond to wait for the next period. In terms of forestry, it is an approach where the decision to harvest the stand of trees is formulated as an optimal stopping problem in which the owner can decide in each period whether it is better to harvest immediately in a favourable market situation, salvage harvest in case of natural calamities, or continue to wait until the next year for favourable market. The optimal stopping method is basically an American option because the model is formulated to exercise the right to buy (or sell) the underlying asset at a predetermined price at any time before or at the expiry date. Clarke and Reed (1989) and Reed and Clarke (1990) analysed optimal harvest time in a single and ongoing rotation using a continuous-time stopping problem. They found that it was optimal to harvest a biological asset at fixed age with the size of the asset and its price at harvest time being lognormally distributed random variables. For the ongoing rotations, they found the optimal harvest is a result of stand age and size of the asset. The application of optimal stopping can also be found in articles by Di Corato *et al*. (2013), Insley (2002), Insley and Rollins (2005), Insley and Wirjanto (2010), Kassar and Lasserre (2004), Reed (1993), Thorsen (1999), Yin (2001), and Yin and Newman (1997).

Contingent claim analysis has developed from the premise of Black-Scholes (1973) and Merton (1973). It is a generalization of option pricing theory of the Black-Scholes model. A contingent claim is any financial asset whose future payoff depends on the value of another asset. Morck *et al*. (1989) presented a contingent claim approach to find optimal rotation age within the context of Merton's (1973) intertemporal capital asset pricing model to value a hypothetical, leased, white pine forest in Canada assuming stochastic timber prices and tree inventories. Insley and Wirjanto (2010) found contingent claim with risk neutral valuation a preferred approach to dynamic programming using a constant risk adjusted discount rate especially when important data, such as future prices, exists. Khajuria *et al*. (2009) used the same approach to value timber harvesting options for the forests of Ontario, Canada testing real option values with various stochastic price process. Khajuria *et al*. (2012) used contingent claim analysis to estimate appropriate discount rate. Chambers (1994), Guthrie and Kumareswaran (2009), and Insley and Lei (2007) also used the contingent claim approach in various forestry investment decisions.

2. Numerical Methods

While analytical solution methods are quite applicable in simple options problems, numerical methods become essential for large and complex option problems where model derivation is not possible and closed form solutions are difficult to find (Rigopoulos 2015). Numerical solution methods can be subdivided into two categories: stochastic process application and approximation of the PDE.

Binomial tree methods of option pricing are considered numerical solution methods of ROA (Richardson 2009, Schulmerich 2010, Vidić 2012). Proposed and developed by Cox, Ross, and Rubinstein (1979), this approach uses a discrete time model of the changing price over time of the underlying financial instrument. The binomial tree approach to valuation makes the assumption that the price of the under-lying asset can only either increase or decrease in two discrete time periods until the option expires and is worthless. It is in fact a simple version of an explicit finite difference scheme (Insley and Rollins 2005). Thomson (1992) employed the binomial tree model, compared it with the Faustmann's model, and found the binomial approach as superior due to its flexibility in determining optimal rotation, given the potential upside of higher prices along with the option to abandon forestry if the potential downside occurs. Duku-Kaakyrie and Nanang (2004) analyzed multiple scenarios of managerial flexibility using the same approach. The authors used the binomial tree approach to evaluate an option to delay reforestation, to expand the size of a wood processing plant, to abandon the plant if timber prices fell below a minimum value and a combination of those three options. Manely and Niquidet (2010) used a two-state binomial model developed by Cox *et al*. (1979) and applied by Thomson (1992) to value different options such as harvest or defer and harvest or never harvest options. Khajuria *et al*. (2012) employed a binomial tree approach using price forecasts generated from the Kalman-filter algorithm. Tee *et al*. (2014) employed a two-price variable binomial tree model to explore possible higher returns from carbon forestry vs. timber-forestry only alternatives. They found the combination of carbon and timber business feasible and that the combination can be delayed until the optimal future combination is realized.

Insley (2002), Insley and Rollins (2005), and Rocha *et al*. (2006) employed finite-difference methods under continuous-time dynamic programming and numerical solution techniques. Insley (2002) applied the fully implicit finite difference method combined with a penalty method to determine the optimal harvest time of a single rotation stand with harvest decision being independent of timber price. Insley and Rollins (2005) applied the HJB methodology to a harvesting problem that is solved numerically using the fully-implicit finite difference method to estimate the value of a stand in Ontario's boreal forest. They considered complete flexibility in harvesting decisions over infinite rotations along with limitations due to government policies and mill supply requirements. Rocha *et al*. (2006) employed the explicit finite difference method to value Brazilian forests with a forest management concession policy. The authors state that the explicit finite difference method is faster and easier than the implicit finite difference method or the Monte Carlo simulation approaches, especially when there is a low number of state variables. In addition, the authors emphasized the significance of their model over the traditional DCF stating that option pricing indicated at least 50% higher value for the forest management concession policy.

Numerical solution methods using binomial tree and finite-difference methods are practical and intuitive for solving option pricing problems where there are one or two sources of uncertainty. However, in situations with multiple sources of uncertainty, binomial tree and the finite-difference models are impractical and simulation may be employed (Longstaff and Schwartz 2001). Monte Carlo simulations are extensively used in finance to calculate the value of an option with multiple sources of uncertainty. Boyle (1977) first introduced Monte Carlo simulation as a way of obtaining numerical solutions to option-value problems. Multiple applications of Monte Carlo simulation are employed in financial economics but its applications in the field of forestry utilizing ROA approach are not extensive. Petrasek and Perez-Garcia (2010) employed least square Monte Carlo (LSM) simulation in valuing timber cutting contracts in the presence of stochastic timber prices, flexibility in harvest timing, and penalty clauses. They determined the LSM method is better suited to timber cutting contracts than the European style option as described by Burnes *et al*. (1999). Similarly, Mei and Clutter (2013) employed LSM simulation as an alternative to the Black-Scholes model to value timber contracts as a high-dimensional American call option.

Most authors applying ROA in forestry investment decisions employed stochastic dynamic programming (Figure 4). This approach was used in approximately 62% (count = 37) of the articles reviewed. The Black-Scholes model was applied to forest valuation problems in about 14% (count =8) of the articles. Binomial tree and contingent claim approaches were each used in 8% of the articles reviewed. A main reason for general use of dynamic programming is that it is relatively easy to express exact solution differential equations and if no closed-form solution exists, it can be approximated by numerical methods (Trigeorgis 1996). The usage of explicit and implicit finite difference methods to solve option problem in forestry is quite infrequent. Very few articles (count =2) on ROA using Monte Carlo simulation were published.

*ROA Applications in Forestry Investment Decisions*

Major categories of forestry investment decisions and applications using ROA and associated citations are presented in Table 2. Generally, all ROA articles consider the time value of money in an uncertain world with varying risks. Investment decision categories are *optimal harvest decision/rotation period, optimal value from management option switch or conversion, optimal investment timing,* and *optimal value of timber cutting contracts*.

Many articles explored optimal harvest decision (Table 2). The optimal harvest decision category includes articles on optimal rotation and decision on variables such as where and how much to cut (i.e., harvesting rule/policy problems). It includes articles similar to Brazee and Bulte (2000) on optimal thinning strategies (i.e., when and how much) at various stage of a rotation and Malchow- Møller *et al*. (2004) on adjacency constraints to harvesting, which have major impacts on harvest planning.

Articles on optimal harvest decision or optimal rotation determination are presented in Table 2. Brazee and Mendelshon (1988) used a reservation price approach in optimal rotation determination and found that a flexible price harvest policy significantly increases the present value of expected returns as compared to a rigid Faustmann model. Reed and Clarke (1989) and Clarke and Reed (1990) used optimal harvest decisions on biological assets using optimal stopping problem formulation for single and multiple rotations with stochastic timber pricing and timber growth. In contrast to the above articles that used continuous-time stochastic price models, Haight and Holmes (1991) and Thomson (1992) used non-stationary random walk price models and considered that a discrete time is a better representation of harvest decisions. Recent articles by Chladná (2007) and Tee *et al*. (2014) used optimal rotation criteria for studies on carbon sequestration using different ROA techniques. Manley and Niquidet (2010) used stochastic dynamic programming, binomial tree, and Black-Scholes model approaches to value harvest or defer and harvest or never harvest alternatives. Despite different approaches, these authors significantly contributed to the optimal harvesting decision making field and provided the foundation for many subsequent publications.

Zinkhan (1991) developed an ROA model for the conversion of forestland and noted that it may be optimal to preserve old growth timber in the process of optimally timing conversion to another land use. Similarly, Conrad (1997), Di Corato (2012), and Reed (1993) employed ROA to evaluate alternatives of conserving old-growth forest for amenity value and harvesting for immediate return given the risk of catastrophic destruction by natural calamities. Forsyth (2000) pointed out that the decision to preserve or harvest timber may exclusively depend on the dynamics of timber prices and amenity values. Kassar and Lasserre (2004) emphasized the value of species diversity and how a perfectly substitutable pool of species can create value under a ROA framework.

Abildtrup and Strange (1999) found higher option value by switching from natural to semi-natural forest to Christmas tree production even though there was an irreversible risk of watershed contaminating due to fertilization. Di Corato (2013), Musshoff (2012), and Schatzki (2003) showed the higher option value of energy forestry if converted from agriculture. However, Girma *et al*. (2012) showed that ignoring the stochastic nature of forests leads to suboptimal value particularly when there is a risk of climate change. They found that higher interest rates (>5%) favoured the deforestation and conversion to urban landscape scenario. Guo and Castello (2013) showed two alternatives of timber management for the California timber industry using the option value of adaptation to climate change program. Rahim *et al*. (2007) also showed an economic incentive to land-use conversion.

ROA has been used to evaluate the optimum investment timing option (Table 2). Yin and Newman (1996) analysed the risk of entry or exit in the presence of catastrophic risk on forest investment decisions. Thorsen (1999) discussed the optimal investment timing due to the effects of subsidies to the landowners to initiate afforestation. Duku-Kaakyire and Nanang (2004) used binomial tree methods to analyse various investment timing options and managerial flexibility.

Very few authors have analysed timber cutting contracts using ROA methods. Shaffer (1984) was the first to analyse timber cutting contracts using the Black-Scholes model. Burnes *et al*. (1999) applied the same approach using the USDA Forest Service timber sale data to present harvest bids on federal lands. Mei and Clutter (2013) and Petrasek and Perez-Garcia (2010) used a more advanced least-square Monte Carlo simulation to determine optimal timber cutting contracts.

*Stochastic Price Models in ROA*

The literature on continuous-time stochastic price models is presented to provide insight of their application in ROA. The relevance of option valuation is very sensitive to the assumptions of the underlying price model (Manley and Niquidet 2010). Haight and Holmes (1991) and Plantinga (1998) also state that optimal harvest decisions largely depend on the nature of price processes. Norstrøm (1975) was one of the first to use stochastic timber prices to determine optimal harvest age using dynamic programming. A number of articles discuss the choice of stochastic price process (e.g., Chladná 2007, Haight and Holmes 1991, Insley 2002, Lohmander 1988, Mei and Clutter 2013, Morck *et al*. 1989, Yin 2001). These authors, in their real options studies, assume that the underlying asset price followed either a GBM or MR. More than half of the articles surveyed used GBM (e.g., Clarke and Reed 1989, Conrad 1997, Di Corato 2013, Jacobsen 2007, Lundgren 2003, Malchow-Møller *et al*. 2004, Reed 1993) whereas the remaining articles used MR (e.g., Gjolberg and Guttormsen 2002, Insley 2002, Insley and Rollins 2005, Plantinga 1998, Rocha *et al*. 2006, Schmit *et al*. 2009, Schwartz 1997, Tee *et al*. 2014). Only Khajuria *et al*. (2009) used the MR process with a slight variation in which structural breaks and jumps were included in the model to show price changes resulting from unexpected events such as political decisions and natural catastrophes.

There has been increasing interest in modelling natural resource prices with a continuous-time stochastic process with the development of ROA and its applications (Saphores *et al*. 2002). Optimal harvest decisions depend strongly on the nature of the price process (Plantinga 1998) and the argument over the appropriate price model is an ongoing debate (Hildebrandt and Knoke 2011). The GBM is widely used in finance theory and economics literature (e.g., Clark and Reed 1989, Dixit and Pindyck 1994, Mei and Clutter 2013, Morck *et al*. 1989, Reed and Clarke 1990, Reed and Haight 1996). It is a continuous-time stochastic process in which the logarithm of the random variable follows a generalized Wiener process. The drift parameter in the GBM is used to model deterministic trends (a constant mean increment) and the volatility term in the model is used to measure the unpredict-able events occurring during the motion. Under the MR assumption it is assumed that the prices tend to revert to a fixed long-run trend (Insley 2002, Insley and Rollins 2005, Yin 2001) which in economics is referred to as stationarity. A MR process differs from a GBM in the drift parameter—it is positive when current price is below the long-run equilibrium price and negative when the current price is above the long-run equilibrium (Mei *et al*. 2010, Mei and Clutter 2013). A MR is represented by a process called Ornstein-Uhlenbeck, which is another special case of the ItÔ process, a generalized Wiener process in which the mean and variance of the model are characterized by the price process and, in some cases, time as well. Dixit and Pindyck (1994) and Hull (2012) provide more information on the generalized Wiener process and ItÔ process.

More articles have reported the use of GBM than MR as the stochastic price process (Table 3). GBM has been used extensively in ROA studies since the late 1980s while application of MR in timber price forecasts increased since 2005. Before using either GBM or MR price models, the data series should be tested for stationarity. The test of stationarity indicates the appropriate price model to use for future price forecasts. The Augmented Dickey-Fuller (ADF) test (Hamilton 1994), the ADF-generalized least square (GLF) test (Elliot *et al*. 1996), and the Kalman-filter algorithm (Khajuria *et al*. 2012) can be used for the test of stationarity. Many authors opined that longer time series can give a better picture of whether the price series is or is not stationary (Khajuria *et al*. 2009). Authors such as Clarke, Reed, and Thorsen tend to favour GBM while Insley, Yin, Newman, Khajuria, Mei, and Clutter offer positive views on the application of MR. All authors advise careful use of either price model, however.

Mei and Clutter (2013) warned that the choice of stochastic price process has to be considered in a serious manner as it may produce bewildering results. Mei *et al*. (2013) and Schwartz (1997) emphasize long-run natural resources prices should be mean reverting, reflecting the marginal costs of production in equilibrium. In contrast, in the short run, the random walk or the GBM assumption may be a better choice, given that random walk timber prices have a wider range of values and higher contract values in good times can be realized by simply exercising the options (Mei and Clutter 2013). Gjolberg and Guttormsen (2002) indicated that timber prices do not change randomly but follow a mean-reverting development which provides a plausible explanation for common pricing with low discount rates in forestry. Rocha *et al*. (2006) conclude that considering forest management and uncertainty about the current timber volume, the option value was considerably higher (eight times) for the GBM approach and times higher for the MR approach as compared with the value using the traditional NPV approach. They recommended a more conservative MR process for a natural resource commodity which have longer management horizons. Insley and Lei (2007) found similar result where their ROA approach with the MR model produced considerably higher stand values than the Faustmann model. Insley and Rollins (2005) found MR has a significant impact on optimal rotation. They suggested that the MR approach indicates an earlier optimal rotation when the forest is not fully mature. Insley (2002) considered the MR process as more realistic for the behaviour of commodity prices, while Clarke and Reed (1989) believed that price and volume growth of a trees are better represented by GBM for a single rotation stand. Haight and Holmes (1991), Washburn and Binkley (1999) also note that a random walk model is consistent with an efficient market which is generally accepted for most assets including stumpage.

Manley and Niquidet (2010) found it difficult to statistically distinguish between option values for a random walk model with GBM and MR process using 30 years of data. They concluded one must often rely on theoretical considerations (for example, intuition concerning the operation of equilibrating mechanisms) more than statistical tests when deciding whether or not to model a price or other variable as a MR process. Gjolberg and Guttormsen (2002) and Guthrie and Kumareswaran (2009) suggested that the assumption of GBM in timber prices or wood growth seems to be made more for mathematical convenience rather than based on studies of the actual process. Dixit and Pindyck (1994) suggest it is not always wise to depend on stochastic processes based on the stationarity assumption and that theoretical factors should be considered.

## 2.4 Discussion and Conclusion

The modern option pricing theory has been extensively used in financial options and derivatives since the development of the Black-Scholes model (1973). The first use of the Black-Scholes model in forestry came after a decade. Real option pricing, a term coined by Myers (1977) to value real assets in a similar manner as financial assets and derivatives, has been used in valuing non-renewable natural resources such as coal, oil, gold and renewable natural resources such as forests and agriculture. Although Cox *et al*. (1979) claimed the binomial model as a much simpler approach than the Black-Scholes model, its forestry application is much more limited. Binomial models are not very effective when the multiple sources of uncertainty and adjacency constraints are introduced in the model (Longstaff and Schwartz 2001). To address such large problems, Monte Carlo simulation methods are preferred. The initial concept of stochastic dynamic programming was developed by Richard Bellman (Bellman 1957) resulting in a Bellman equation associated with discrete-time optimization problems. The Hamilton-Jacobi-Bellman (HJB) equation is used in a continuous-time model. Dynamic programming has been a major analytical solution tool used in forestry decision making employing ROA. Although many dynamic programming problem formulations have analytical solutions, some solutions are not closed-form and a numerical solution is required. This is especially true when the expiry date has a finite-horizon (Jacobsen and Thorsen 2003).

The application of ROA in forestry investment decision making has advanced considerably over the last 30 years. During the early 1990s, forestry researchers examined inclusion of stochastic timber prices in the Faustmann model and the incorporation of different price models into the real options model. The seminal articles on optimal rotation by Brazee and Mendelsohn (1988), Reed and Clarke (1989), Clarke and Reed (1990), Zinkhan (1991), and Thomson (1992) applied various stochastic price models in ROA methods to test whether ROA approaches produced a higher return than the conventional Faustmann model. ROA has been applied not only in determining optimal time to harvest the trees, but also in determining optimal time to switch management alternatives or optimal time for converting forestry into more profitable business initiatives or vice versa. Many authors such as Abildtrup and Strange (1999), Chambers *et al*. (1994), Di Corato (2012), Girma *et al*. (2012), Guo and Costello (2013), Kassar and Lasserre (2004), Leroux *et al*. (2009), Musshoff (2012), Rahim *et al*. (2007), Schatzki (2003), Thomson (1992), and Zinkhan (1991) evaluated the optimal value generated from switching to different land-use practices including biodiversity conservation in the face of species extinction and climate change.

There have been many applications of ROA in forestry with major work in optimal rotation determination of even-aged forests. Other areas of application are in land-use con-version (e.g., Abildtrup and Strange 1999, Girma *et al*. 2012, Musshoff 2012, Rahim *et al*. 2007, Reed 1993, Schatzki 2003, and Zinkhan 1991), preservation of old-growth forest (e.g., Conrad 1997, Di Corato 2012, Reed 1993, and Zinkhan 1991), amenity value (e.g., Di Corato 2012, Kassar and Lasserre 2004 and Leroux *et al*. 2009), bioenergy and carbon sequestration (Chladná 2007, Musshoff 2012, and Susaeta *et al*. 2009), risk of natural catastrophe such as fire and insects (Insley and Lei 2007, Reed 1993, Sims 2011, Susaeta *et al*.

2009, and Yin and Newman 1996) and climate change (Jacobsen and Thorsen 2003). Few or no articles were found addressing the risk of stochastic flood and drought events in forests, fast growing species (e.g., Eucalyptus, Casuarina, Leucaena) and their impact on energy forestry. The impact of wood pellet and biofuel industries on forest rotation determination and the impact of pulp and paper industries on fast growing softwood plantations applying ROA methods have not been explored. Timber cutting contracts play a vital role in growing timber but the application of ROA in this area is limited. Many forest landowners make timber cutting decisions based on reservation price or threshold prices. Few authors (Brazee and Mendelsohn 1988, Khajuria *et al*. 2012, Tee *et al*. 2014) have investigated the optimal investment time and effect of threshold prices.

The stochastic price process and associated models have long been debated. The GBM has been most widely used. Several authors (e.g., Abildtrup and Strange 1999, Clarke and Reed 1989, Conrad 1997, Hughes 2000, Mei and Clutter 2013, Reed 1993, Schatzki 2003, Thomson 1992, Yin and Newman (1995, 1996, 1997, 2006) have used GBM for various types of investment analysis in forestry. Similarly, MR models have been applied in various option problems but less extensively (e.g., Brazee and Mendelsohn 1988, Gjolberg and Guttormsen 2002, Guthrie and Kumareswaran 2009, Haight and Holmes 1991, Insley 2002, Insley and Rollins 2005, Mei and Clutter 2013, Plantinga 1998, Tee *et al*. 2014, Yin 2001) as compared to GBM. One of the main reasons for GBM being so widely used is that quarterly timber prices, often used by researchers, follow more of a non-stationary pattern than a MR pattern (Haight and Holmes 1991, Manley 2013) or for the sake of mathematical convenience (Guthrie and Kumareswaran 2009).

What will be the role of ROA in forestry investment decision making in the near future? The historical development and usage of ROA suggests a continuous but rather intermittent application. Real options values were generally compared to net present values and many authors made positive assertions about the relative values of using ROA. In particular, ROA provides managerial flexibility in valuing irreversible investment such as forestry later in investment period while the NPV approach does not take account of managerial options signifying now or never proposition (Hyde and Machir 2000). Stochastic dynamic programming was commonly employed in real options analysis. Binomial tree and the Black-Scholes approaches are very common options valuation methods, but their use in forestry is limited. The use of least square Monte Carlo simulation approach is limited in forestry investment decision making. Only two articles (Mei and Clutter 2013, Petrasek and Perez-Garcia 2010) were found that applied LSM with Monte Carlo simulation.

Journals such as *Journal of Environmental Economics and Management*, *Forest Policy and Economics*, *Land Economics*, and *Forest Science* are the prominent journals most active in publishing articles on ROA in forestry investment decision making since the late 1980s. The publication of ROA articles in forestry investment decision shows an increasing trend with time. This indicates that forest economists and financial specialists are evaluating and using this methodology to complement traditional methods of the Faustmann model and other discounted cash flow techniques.

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Table 2. 1. The 18 forestry and finance journals publishing ROA literature in forestry and their contribution.

| Journals | Count | % of total | 1st article published | Most recent |
|---|---|---|---|---|
| Journal of Environmental Economics and Management | 14 | 14% | 1987 | 2009 |
| Forest Policy and Economics | 12 | 12% | 1999 | 2013 |
| Land Economics | 8 | 8% | 1988 | 2014 |
| Forest Science | 8 | 8% | 1985 | 2010 |
| Natural Resource Modeling | 5 | 5% | 1991 | 2013 |
| Journal of Forest Economics | 5 | 5% | 2006 | 2012 |
| Environmental and Resource Economics | 4 | 4% | 2003 | 2009 |
| Ecological Economics | 3 | 3% | 1993 | 1997 |
| Canadian Journal of Forest Research | 2 | 2% | 2007 | 2012 |
| Journal of Environmental Dynamics and Control | 2 | 2% | 1989 | 2007 |
| American Journal of Agricultural Economics | 2 | 2% | 2002 | 2005 |
| Biomass and Bioenergy | 1 | 1% | 2012 | 2012 |
| Journal of Finance | 1 | 1% | 1990 | 1997 |
| Forest Ecology and Management | 1 | 1% | 2003 | 2003 |
| Journal of Forestry | 1 | 1% | 1995 | 1995 |
| Forestry | 0 | 0% | | |
| Silva Fennica | 0 | 0% | | |
| Land Use Policy | 0 | 0% | | |
| Others | 33 | 33% | | |
| | 102 | 100% | | |

Note: (Contribution includes ROA articles in forest investment decisions from 18 journals published from 1985 to July 2014 with reference to only ROA articles/books/thesis in bibliography). Percent values are rounded to zero decimals.

Table 2. 2. Major decision criteria involved in choosing ROA articles in forestry and finance journals from 1985-July, 2014.

| Citations | Investment decision primarily based on |
|---|---|
| Brazee and Mendelsohn (1988), Clarke and Reed (1989), Thomson (1992), Zinkhan (1991), Haight and Holmes (1991), Reed (1993), Provencher (1995), Yin and Newman (1995),Yin and Newman (1997), Plantinga (1998), Brazee and Bulte (2000), Gjolberg and Guttormsen (2002), Hughes (2000), Insley (2002), Jacobsen and Thorsen (2003), Saphores (2002), Malchow-Møller et al. (2004), Insley and Rollins (2005), Alvarez and Koskela (2006), Chladná (2007), Jacobsen (2007), Guthrie and Kumareswaran (2009), Khajuria et al. (2009), Susaeta et al. (2009), Insley and Wirjanto (2010), Manley and Niquidet (2010), Sims (2011), Manley (2013), Tee et al. (2014) | Optimal harvest decision |
| Zinkhan (1991), Thomson (1992), Chambers et al. (1994), Abildrup and Strange (1999), Schatzki (2003), Kassar and Lasserre (2004), Rahim et al. (2007), Leurox et al. (2009), Girma et al. (2012), Musshoff (2012), Di Corato (2012), Guo and Costello (2013) | Optimal value from management options switch (conversion) |
| Zinkhan (1991), Yin and Newman (1996), Thorsen (1999), Yin and Newman (1999), Yin (2001), Lundgren (2003), Duku-Kaakyire and Nanang (2004), Isik (2004), Rahim et al. (2007) | Optimal investment timing |
| Burness et al. (1999), Petrasek and Perez-Garcia (2010), Mei and Clutter (2013) | Optimal value of timber cutting contracts |
| Khajuria et al. (2012), Tee et al. (2014) | Optimal investment time and threshold prices |

Table 2. 3. GBM vs MR models used in major journal articles from 1985-July 2014.

| | Geometric Brownian Motion | Mean Reversion |
|---|---|---|
| **Year** | Citation | Citation |
| **1988** | | Brazee and Mendelsohn (1988) |
| **1989** | Clarke and Reed (1989), Haneman (1989) | |
| **1991** | | Haight and Holmes (1991), Zinkhan (1991) |
| **1992** | Thomson (1992) | |
| **1993** | Reed (1993) | |
| **1994** | Chambers (1994) | |
| **1995** | Provencher (1995), Yin and Newman (1995) | |
| **1996** | Yin and Newman (1996) | |
| **1997** | Conrad (1997), Yin and Newman (1997) | |
| **1998** | | Plantinga (1998) |
| **1999** | Abildtrup and Strange (1999), Burnes (1999),Thorsen (1999), Yin and Newman (1999) | |
| **2000** | Hughes (2000) | Brazee and Bulte (2000) |
| **2001** | Yin (2001) | Yin (2001) |
| **2002** | Insley (2002), Saphores (2002) | Gjolberg and Guttormsen (2002), Insley (2002), |
| **2003** | Jacobsen and Thorsen (2003), Lundreen (2003), Schatzki (2003) | |
| **2004** | Duku-Kaakyire and Nanang (2004), Kassar and Lasserre (2004), Malchow-Møller et al. (2004), Isik (2004) | |
| **2005** | | Insley and Rollins (2005) |
| **2006** | Rocha et al. (2006), Yin and Newman (2006) | Rocha et al. (2006) |
| **2007** | Chladná (2007), Jacobsen (2007), Rahim et al. (2007) | Chladná (2007), Insley and Lei (2007) |
| **2008** | Seifert et al. (2008) | |
| **2009** | Susaeta et al. (2009) | Gurthie and Kumareswaran (2009), Zinkhan (2009) |
| **2010** | Insley and Wirjanto (2010), Manley and Niquidet (2010) | Petrasek and Perez Garcia (2010) |
| **2011** | Hildebrandt and Knoke (2011), Sims (2011) | Hildebrandt and Knoke (2011) |
| **2012** | Girma et al. (2012), Musshoff (2012), Di Corato (2012) | Khajuria et al. (2012), Musshoff (2012) |
| **2013** | Manley (2013), Mei and Clutter (2013) | Mei and Clutter (2013) |
| **2014** | | Tee et al. (2014) |

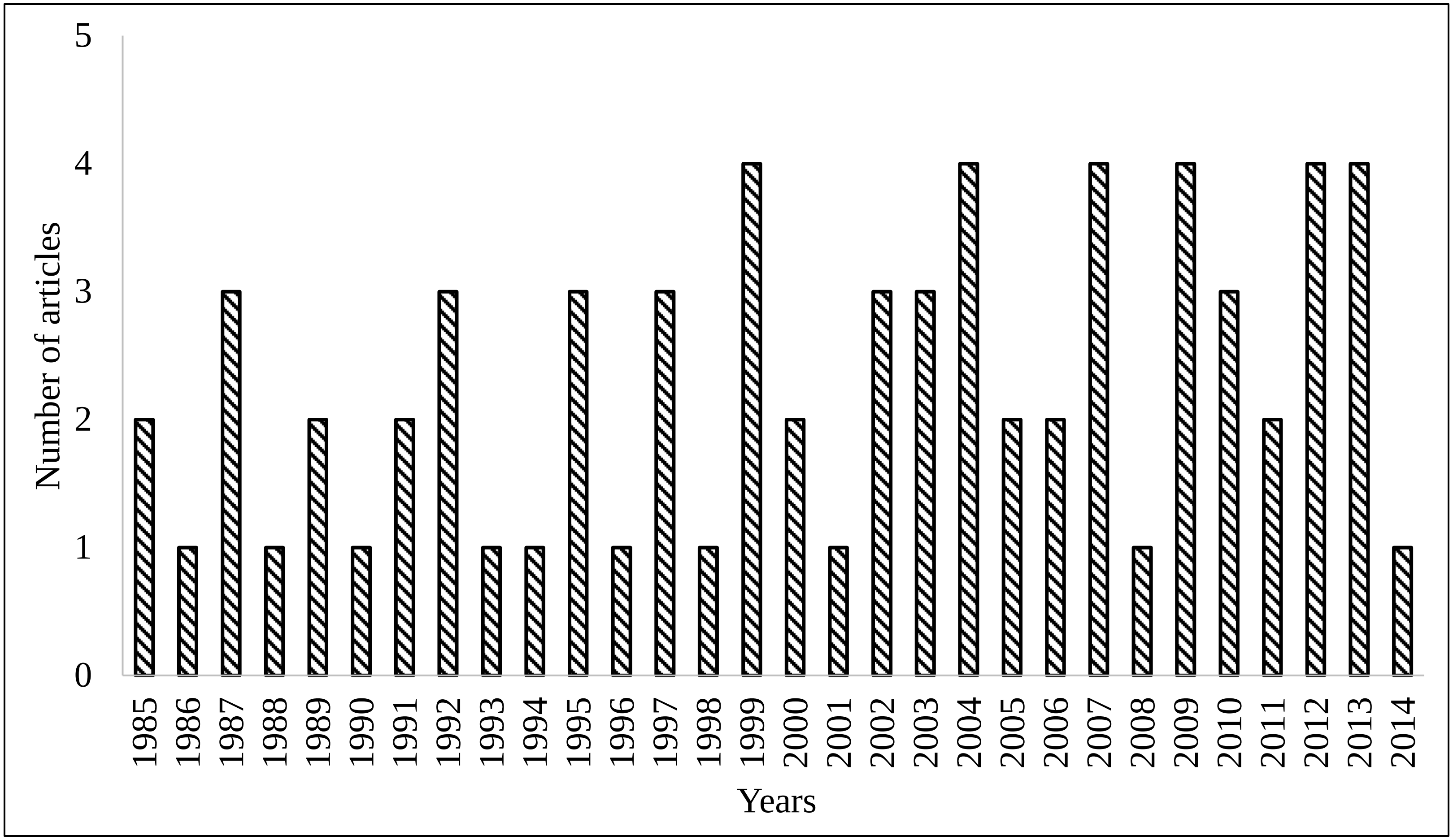
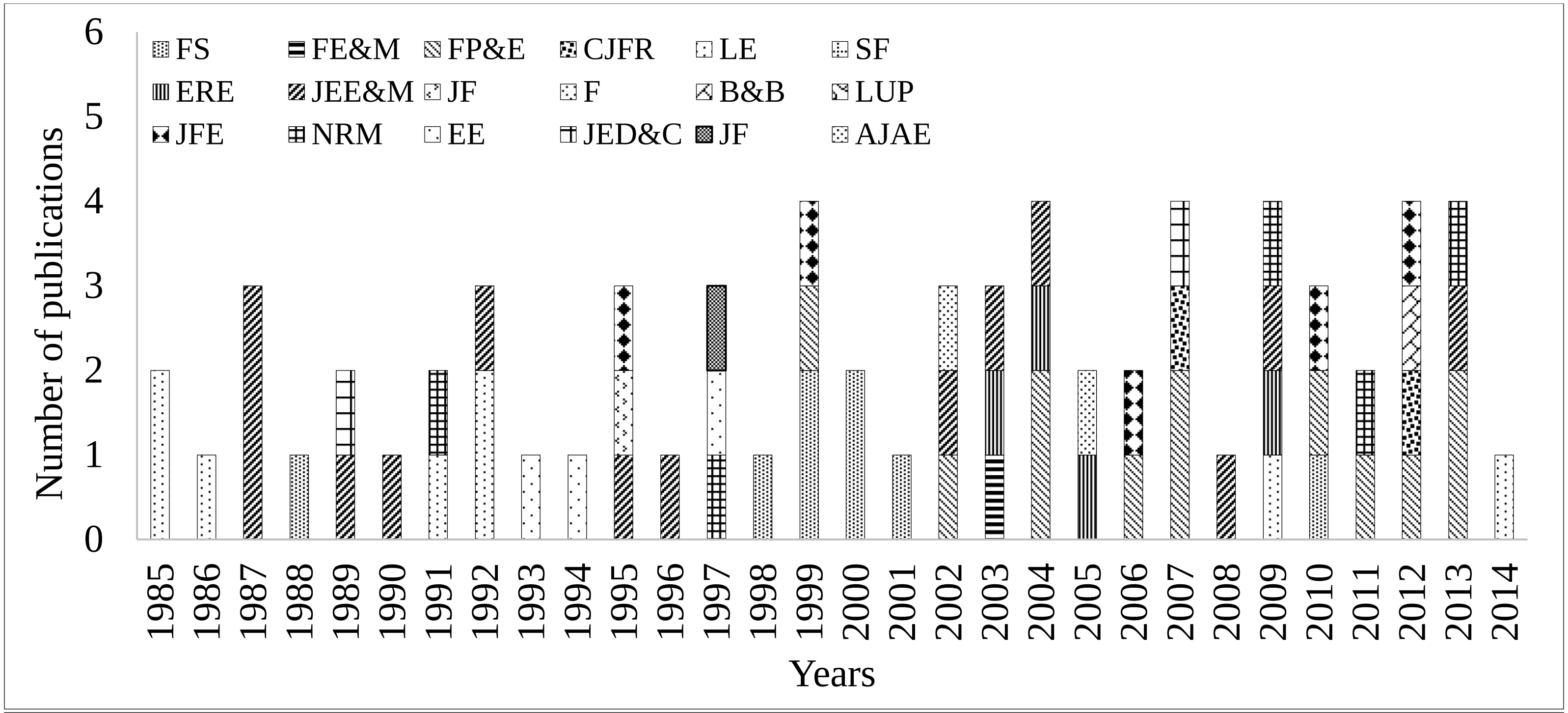



Figure 2. 1. Number of peer-reviewed ROA articles in 18 forestry and finance journals. Note: 2014 values are only through July.




FS = Forest Science
FE&M = Forest Ecology & Management
FP&E = Forest Policy and Economics
CJFR = Canadian Journal of Forest Research
LE = Land Economics
SF = Silva Fennica
ERE = Environmental & Resource Economics
JEE&M = Journal of Environmental Economics & Management
JF = Journal of Forestry
F = Forestry
B&B = Biomass and Bioenergy
LUP = Land Use Policy
JFE= Journal of Forest Economics
NRM= Natural Resource Modeling
EE = Ecological Economics
JED&C = Journal of Economic Dynamics & Control
JF = Journal of Finance
AJAE = American Journal of Agricultural Economics

Figure 2. 2. Source of peer-reviewed ROA articles, by year and name of their journals available through field of forestry and finance. Note: 2014 values are only through July.

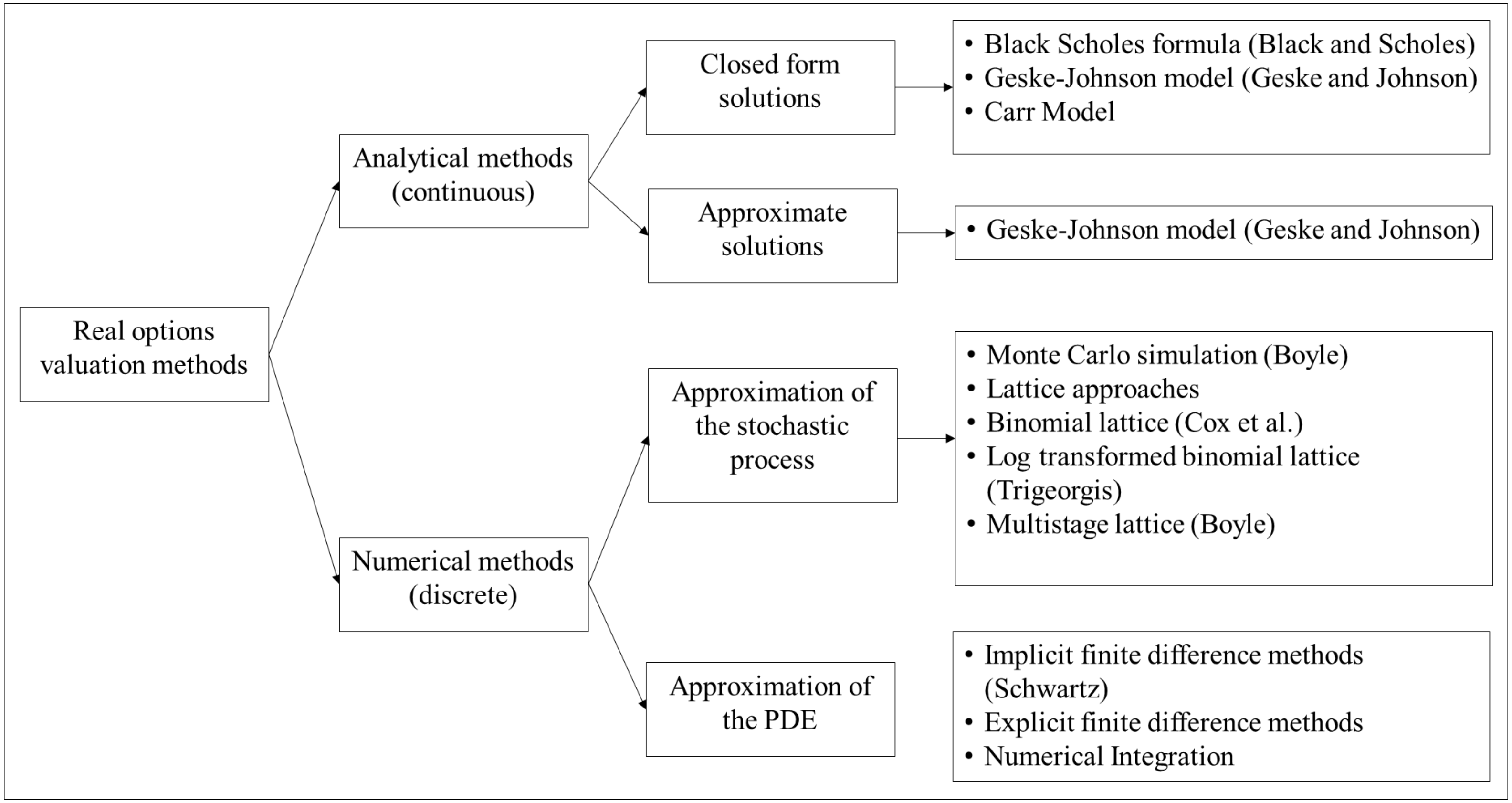


Figure 2. 3. Real option solution methods (Rigopoulos, 2015).

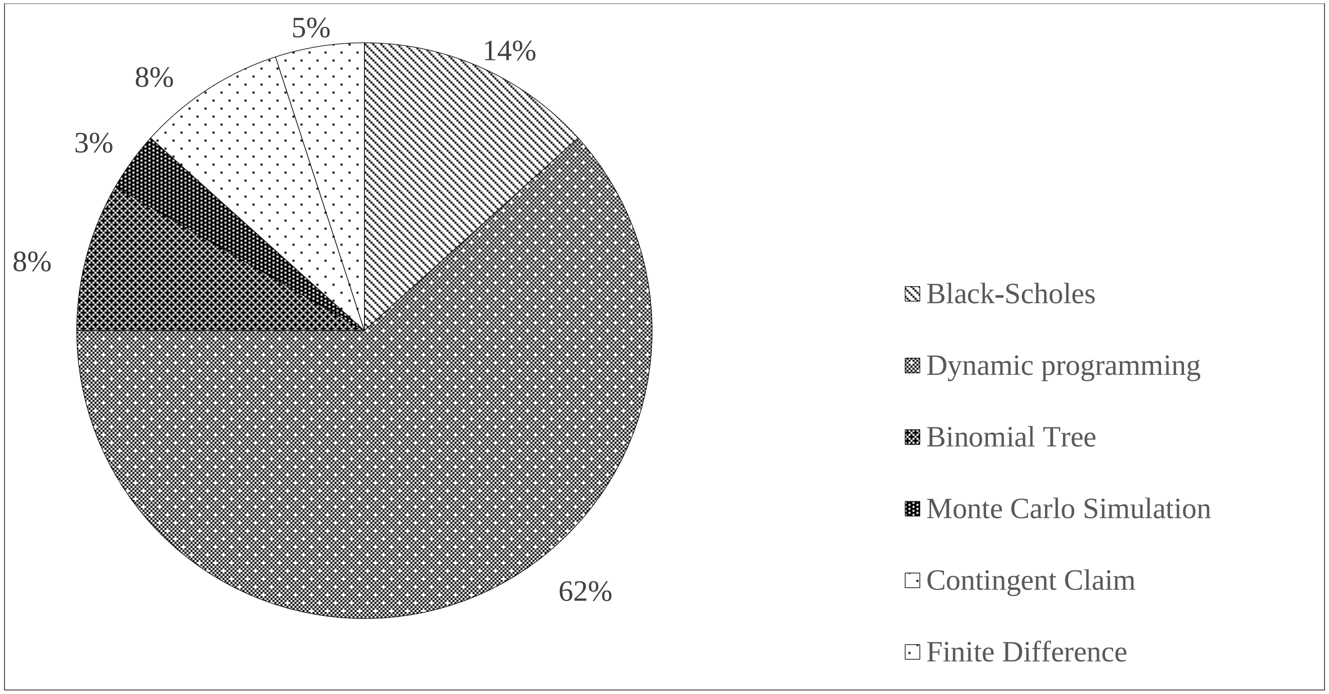


Figure 2. 4. Most common ROA solution methods used in forestry investment decisions: Note. Values are only through July 2014.

# CHAPTER 3

# SITE QUALITY, PLANTING DENSITY, CULTURAL INTENSITY, AND THINNING IMPACTS ON LOBLOLLY PINE YIELD OF TRADITIONAL TIMBER PRODUCTS AND ECONOMIC RETURN USING DISCOUNTED CASH FLOW AND REAL OPTIONS APPROACHES[2].

[2] . Chaudhari, U.K., Kane, M., Wetzstein, M. To be submitted to Journal of Forest Economics

ABSTRACT

Loblolly pine (*Pinus taeda*) is widely planted in the southern U.S. due to its adaptability, growth rate, and suitability for timber markets. It is the premier species in a region that contributes a significant portion of industrial roundwood to the U.S. and the world. This case study of three research sites examined timber yields and financial returns from traditional timber products for combinations of site class, cultural intensity, and density management (planting density and thinning) in the Lower Coastal Plain of Florida and Georgia. The three research sites were selected to illustrate low, average, and high site index sites. Financial returns were determined using both the real options analysis approach (ROA) using the Black and Scholes model and the traditional discounted cash flow approach of net present value (NPV). Conclusions regarding best management regimes were the same using ROA and NPV; however, ROA returns were higher as it captured the value from price volatilities which NPV did not. Optimal rotation age for the no-thin scenario was minimally influenced by planting density, site class, and culture and averaged 24 years. Optimal rotation age for thinning scenarios varied considerably by site class, planting density, and cultural regime. Generally lower densities (300 to 600 trees per acre) produced greater financial return for no-thinning scenarios on all site types and with operational culture. Two thinnings resulted in greater financial return for stand densities 600 trees per acre and above, particularly on average to high sites and stands receiving intensive culture. Intensive culture increased returns on the low site class and reduced returns on the high site. Optimum returns on low and average sites occurred with the 600 TPA planting density, intensive culture, and two-thin regime. Optimum return on the high site occurred with 900 TPA planting density, operational culture, and either one- or two- thin regime.

## 3.1 Introduction

Southern forests of the U.S. support the premier sustainable wood fiber industry in the world. Southern timberland which occupies only 2% of the world's forest contributes about 17% of global roundwood production (Prestemon et al., 2015). Loblolly pine (*Pinus taeda* L.) is the major species in the southern U.S. sold as roundwood for various industrial uses (e.g., sawlogs and veneer logs, pulpwood and other industrial roundwood). Due to its commercial success and ecological significance, it has been planted on over 32 million acres (Baker and Langdon, 1990; Schultz 1997) providing about 24 billion cubic feet of standing timber (Wear and Greis, 2002).

Loblolly pine is a fast-growing species. Significant gains in loblolly pine productivity occurred over recent decades due to continuous effort of scientists and growers that studied the effects of genetics and site index (Neary et al., 1990; Yin and Sedjo, 2001; McKeand et al., 2006a; McKeand et al., 2006b), planting density (Bailey, 1986; Vardaman, 1989; Borders et al., 1991; Caulfield et al., 1992; Baldwin et al., 2000; Harms et al., 2000; Sharma et al., 2002), fertilization (Bailey et al., 1989; Neary et al., 1990; Borders and Bailey, 2001; Allen et al., 2005) and thinning (Cao et al., 1982; Reisinger, 1985; Baldwin and Busby 1993; Huang and Kronard, 2002). Loblolly pine plantation research has led to significant increases in commercial plantation areas employing intensive culture in the U.S. South and countries such as Argentina, Brazil, Australia, China, New Zealand and South Africa (Evans, 1992; Borders and Bailey, 2001). Most commercial growers utilize treatment regimes that provide economic returns given biological response and markets for timber products.

The effect of pine plantations due to planting density (Bailey, 1986; Hotvedt and Straka, 1987; Borders et al., 1991; Caulfield et al., 1992), site index increment or genetic improvement (Huang and Kronard, 2002; McKeand et al., 2006b), intensive fertilization regime (Borders and Bailey, 2001; Allen et al., 2005; Fox et al., 2007a), thinning (Hotvedt and Straka, 1987; Baldwin and Busby, 1993; Huang and Kronard, 2002) and competition control (Oppenheimer et al., 1989; Allen et al., 2005) have been reported; however, reports are lacking on economic returns for a comprehensive set of regimes including different planting densities, cultural treatments, and thinnings on different site productivity classes.

A historical paradigm of cost minimization associated with plantation establishment and tending has been replaced, in the case of many commercial growers, by spending relatively more on genetically improved seedlings and more intensive silviculture. More intensive loblolly pine plantation silviculture has helped landowners, in some cases, double timber volume and shorten the rotation by half (Fox et al., 2004; Fox et al., 2007b; Aspinwall et al., 2012). The resulting increases in total production may reduce the production cost per ton and shorten the rotation length, providing landowners the potential for greater returns. The extra volume gains in a shorter rotation often increased returns as compared to the cost minimization approach.

Forest management financial decisions are mainly based on discounted cash flow (DCF) techniques such as net present value (NPV), soil expectation value (SEV), and internal rate of return (IRR) (Klemperer, 1996). Unfortunately, the conventional implementation of DCF analyses does not properly capture the value of investments whose cash flow streams are conditional on future outcomes and managerial actions, which have complex risk profiles (Triantis, 2003). Also, the conventional DCF analyses are based on the assumption that future cash flows follow a deterministic pattern that is highly predictable from regeneration to rotation age; the profitability of forestry projects are then determined based on these cash flow assumptions (Duku-Kaakyire and Nanang, 2004). Although stochastic price models can be used in the NPV method (e.g., Brazee and Mendelsohn, 1988; Haight, 1990; Reed and Haight, 1996; Brazee; 2000; Lu and Gong, 2003; O'Donnell et al., 2013), a constant price is often used to estimate the future value of an asset in present value terms. Black and Scholes (1973) pioneered the option pricing theory and Merton (1973) later expanded the mathematical understanding of it. Real Options Analysis (ROA) is a capital budgeting technique based on option pricing theory to value real assets similar to financial options. The Black and Scholes (hereafter, Black-Scholes) model is a type of

ROA that can be utilized to value natural resource assets (e.g., forests, coal mine, oil field etc.) in much the same way as valuing financial options by creating a hedged position and adopting arbitrage arguments. The expected present value of a forest stand, including the value generated from risk and uncertainty in terms of price volatility, can be estimated using yield, product class and stumpage information for different ages and inputting variables of the Black-Scholes model. Forest valuation with this model using projected future prices requires estimation of volatility of future log prices (Hughes 2000).

The Black-Scholes model accounts for the value of volatility in timber price that NPV does not. The other advantage of the Black-Scholes model over conventional NPV is that the holder of an option can determine the exercise date, delay, expand, stage, or abandon the option. The model states that for a call option, it should not be exercised if the stock price is lower than the exercise price which means the return will always be positive. For a call option, if the stock price becomes smaller than the exercise price the intrinsic value becomes negative and the intrinsic value is given as zero. The conventional NPV method does not allow such flexibility or consider the value of such flexibility.

There is a need to evaluate economic returns from a diverse array of loblolly pine plantation scenarios using ROA as well as NPV given the possible influence of stumpage price variability. A comparison of these valuation methods has not been reported for loblolly pine plantations for a range of site productivity classes and the important silvicultural approaches including planting densities, cultural intensities, and thinning regimes. ROA is relatively new and little used by forest planners in the U.S. South and an investigation in its potential value is warranted given that future timber price uncertainty is an issue facing forest investors.

Existing field studies on loblolly pine plantation performance for an array of site productivity, plantation density management, and cultural intensities in the Lower Coastal Plain provided an opportunity to evaluate economic returns using NPV and ROA approaches and compare the two methods.

This research reported here uses a case study approach based on three study sites to addresses the following objectives.

1. Quantify loblolly pine stand yield of traditional timber products for silvicultural regimes differing in planting density, cultural intensity and thinning regime for a range of site indices in the Lower Coastal Plain.
2. Evaluate financial return from different plantation regimes for traditional forest products using NPV and ROA approaches.
3. Identify optimum plantation regimes for different site classes using NPV and ROA approaches.
4. Compare NPV and ROA approaches and identify advantages and limitations of the two approaches.

## 3.2 Methods

*Study Population*

The case study examined loblolly pine performance on three installations of the Plantation Management Research Cooperative (PMRC) Coastal Plain Culture Density Study. The three installations were selected among a larger set of installations to represent low, medium, and high site productivity classes, respectively, based on stand performance on plots with 600 trees per acre (TPA) planting density and operation culture through age 18. Location, soil and site productivity attributes of these installations (sites) are presented in Table 3.1.

Each installation represents a unique site and contained 12 plots, each with a distinct combination of six planting densities (300, 600, 900, 1200, 1500, and 1800 TPA) and two cultural intensities (operational and intensive). Tree spacing and plot size by planting density are shown in Table 3.2. Seedling were planted in the 1995/1996 dormant season. All seedlings used at all installations were of the same first generation open pollinated family and grown at the same nursery. To insure greater consistency in stand densities, two seedlings were planted at each planting spot. Seedlings were eliminated after the first growing season to leave one seedling per planting spot.

The operational and intensive culture regimes through age 18 are described in Table 3.3. All plots received mechanical site preparation and bedding. Operational culture stands received banded chemical site preparation, first growing season banded herbaceous weed control, fertilization at planting and three additional fertilizations on a four-year interval starting at age 7. The intensive cultural treatment plots received broadcast chemical site preparation, herbicide treatments to maintain a competing vegetation free condition throughout their rotation, insecticide applications to control tip moth (*Rhyacionia frustrana*) as often as necessary through the first two growing seasons, and fertilization at planting, ages 2 and 3, at on 2-year intervals beginning at age 5.

*Mensurational Evaluation*

Measurements of height, diameter at breast height (DBH) at 4.5 feet above ground, and number of surviving trees were carried out at 2-year intervals from age 2 to 12, at age 15, annually from age 15 to 18 for installations 1 and 11 and at age 18 for installation 16. Height was measured on a subsample of trees. Height of trees not measured for height was estimated from DBH and height relationships using the model form In (H) = $b_0 + b_1$ (1/DBH) for each plot and measurement year. A tree was considered a dominant tree if it was in the upper 50% of DBH on the plot (Zhao et al., 2011).

Basal area per acre (BA/Ac), the cross-sectional area of stems at breast height, was calculated by summing basal areas of the individual trees and multiplying the plot basal area by the reciprocal of the plot acreage. Quadratic mean diameter (QMD) was calculated by dividing BA/Ac by the corresponding TPA and converting the cross-sectional area to diameter. The expressed site index for each installation was calculated from mean dominant height at age 18 on the 600 TPA, operational culture plot following Zhao et al. (2014).

Green Weight Estimation

Because traditional timber products are sold on a green weight basis, green weight was calculated for traditional timber products (i.e., pulpwood, chip-n-saw, and sawtimber). Stem diameter measurements at different heights of a tree indicate different product classes. A Timber Mart South (TMS) diameter specification for timber product classes for southern pine was used for green weight estimation. The product class specification based on DBH and top diameter is given in Table 3.4.

The green weight of traditional timber products was calculated using Pienaar et al. (1987) equations reported for loblolly pine in the Lower Coastal Plain. The equations utilized follow:

$$GW_{TS} = 0.0740959 * DBH^{1.829983} * HT^{1.247669} \quad [1]$$

$$GW_{Pulp} = 0.0740959\, DBH^{1.829983} HT^{1.247669} - 0.123329 \left[\frac{{D_3}^{3.523107}}{DBH^{1.449947}}\right](HT - 4.5) \quad [2]$$

$$GW_{CNS} = 0.0740959\, DBH^{1.829983} HT^{1.247669} - 0.123329 \left[\frac{{D_6}^{3.523107}}{DBH^{1.449947}}\right](HT - 4.5) \quad [3]$$

$$GW_{Saw} = 0.0740959\, DBH^{1.829983} HT^{1.247669} - 0.123329 \left[\frac{{D_8}^{3.523107}}{DBH^{1.449947}}\right](HT - 4.5) \quad [4]$$

Where $GW_{TS}$ is green weight (lbs) of a solid bole of a tree with bark measured from base to the nearest 0.1-inch tip. DBH and HT indicate diameter at breast height (4.5 feet above ground) in inches and total height in feet of a tree, respectively. $GW_{Pulp}$ is the green weight of pulpwood with $D_3$ being the top merchantable diameter limit of 3 inches; $GW_{CNS}$ is the green weight of chip-n-saw with $D_6$ being the top merchantable diameter limit of 6 inches; $GW_{Saw}$ is the green weight of sawtimber with $D_8$ being the top merchantable diameter limit of 8 inches. Per acre values were calculated by summing individual tree values for a plot and adjusting by the expansion factor. The merchantable green weight for traditional timber product was calculated by summing up the individual traditional timber product green weight.

The Mean Annual Increment (MAI) is the cumulative wood weight at a given age divided by the specified age. The weight MAI for merchantable traditional timber product was calculated by dividing the total merchantable green weight per acre by the stand age.

Stand attributes from the low, medium and high sites were averaged by treatment combination for the no-thin scenario through age 18 to represent an average site. The average site was considered more representative of a larger population of sites than the low or high sites and provided reasonable productivity trends across treatments. The medium site, when considered alone, exhibited atypical productivity, especially for the 1200 TPA density, and the averaging for the three installations was considered more representative for this case study.

Growth and Yield Simulation

The growth-and-yield simulator, SiMS 2009, (ForesTech International, 2009) was used to project growth and yield of each of the 36 stands in the study population. SiMS software has been commercially used by many timber management organizations for growth and yield projection for loblolly pine plantations. The growth and yield simulator allows the user to input site index, stand table information (DBH class, height, TPA), treatments (fertilizer, herbicide), tree density, thinning specifications, product class specifications, financial parameters, and many other criteria. For the average site, the averaged stand table was used for growth projection.

Growth projections were performed for three scenarios: 1) No-thin, 2) One-thin and, 3) Two-thin. Measured and calculated age 18 stand attributes were used for projections for the no-thin scenario. The growth and yield projection of one-thin scenario was based on the first thinning occurring when a stand met the following criteria; BA at least 120 $ft^2$/acre, QMD at least 6 inch and average height of the dominant trees at least 40 feet. For the two-thin scenario the second thinning was simulated when the stand reached a BA of at least 120 $ft^2$/acre. Given these criteria, stand age simulated at first thinning varied with site, density, and cultural intensity. Many stands were first thinned well prior to age 18. A fifth row plus thinning from below with a residual BA of 75 $ft^2$/ac was simulated for a first thinning. A thinning from below with a residual BA of 75 $ft^2$/ac was simulated for second thinning. Fertilizations for no-thin scenarios were simulated according to the actual application schedule through age 18. Fertilization simulation for thinned scenario simulations for operational culture plots included the actual fertilization through age 7 and fertilization at ages 12 and 17. For intensive culture, thinned scenarios included the actual fertilization through age 9 and fertilization at ages 14 and 19.

*Financial Evaluation*

A financial evaluation of non-thinned, one-thin, and two-thin scenarios for traditional timber products was done using historical timber prices of each product class and ROA and NPV valuation approaches. The financial evaluations were based on real price, real risk-free interest rate of 5%, and presented as pre-tax dollars. The annual administration cost was assumed to be offset by annual hunting revenue. The cost of different densities, treatments for both operational and intensive culture for no-thin and thinning scenarios are presented in Tables 3.5 and 3.6, respectively.

Price Model

Historical prices from the first quarter of 1986 to the fourth quarter of 2014 for traditional timber products were obtained from Timber Mart-South (Norris Foundation, 2014). Nominal prices were converted to real prices using the consumer price index (CPI) with a base year of 2014 (age 18 in this study). The geometric Brownian motion (GBM) was used to forecast expected prices beyond 2014.

The Augmented Dickey-Fuller (ADF) test was done using SAS 9.4 to determine whether the price series data were stationary. The tests showed all product prices followed a non-stationary random walk with drift, as the null hypothesis of non-stationarity was not rejected for all product price series (see Appendix 3A.1). The null hypothesis of non-stationarity was not rejected for a single mean for all product prices (i.e., pulp, chip-n-saw, and sawtimber). The check on autocorrelation of white noise showed the rejection of the null hypothesis, meaning the data was a non-stationarity time series for all product prices.

Furthermore, the autocorrelation function (ACF) trend decreased gradually for all product prices which is further evidence of non-stationary time series.

A GBM is a special case of the Itô process that can be represented by the following differential equation (Dixit and Pindyck, 1994; Mei et al., 2010).

$$d\,Pt = \alpha\,Pt\,dt + \sigma\,Pt\,dz \quad [5]$$

Where Pt is the timber commodity price at time t, $\alpha$ and $\sigma$ are the constant drift and standard deviation parameters, and dz is the increment of a Wiener process defined as $dz = \varepsilon_t\sqrt{dt}$, where $\varepsilon_t$ has a standard normal distribution. The two unknown parameters $\alpha$ and $\sigma$ was estimated following Tsay (2005). The continuously compounded return is expressed as $r_t = d\ln(P_t) = \ln(P_t) - \ln(P_{t-1})$ in the tth time interval, the $\hat{\alpha} = \bar{r}/\Delta + s_r^2/2\Delta$ and $\hat{\sigma} = S_r/\sqrt{\Delta}$ are consistent estimates of the mean and standard deviation of the series $r_t$. Where the $\bar{r}$ and $S_r$ are the sample mean standard deviation and $\Delta$ is the equally spaced time interval measured in years. The parameters, drift ($\alpha$) and volatility ($\sigma$), are presented in Table 3.7.

A more simplified version of GBM can be achieved through Itô's lemma and it can be shown that $\ln(P_t)$ follows a generalized Wiener process with a drift rate $\alpha$ and variance rate of $\sigma^2$ such that the equation can be written as (Hull, 2012):

$$d\ln Pt = (\alpha - \sigma^2/2)\,dt + \sigma\,dz \quad [6]$$

The GBM is a non-stationary random walk process in which Monte Carlo simulation was utilized using equation 6. The MS Excel based Monte Carlo simulation was used to forecast prices following Hull (2012). A Monte Carlo simulation of a stochastic process is based on the principle of probability theory that utilizes random outcomes. The simulations were performed for each product price data with a thousand iterations and mean price was taken for each period (i.e., year). The next year's price was determined using equation 6 by inserting last year's initial stock price ($P_0$), drift rate, volatility and random amount generated by the Wiener process. After the simulation, a GBM performance test was employed using 80% of the real data to estimate statistical parameters. The forecasted prices were then compared with the remaining 20% of the real data and found to be satisfactorily close to the observed prices (See Appendix 3A.2.) The root mean squared error (RMSE) was used to test the absolute measure of fit. The RMSE values were considered small and ranged between 0.6 for pulpwood to 2.0 for sawtimber (Table 3.7).

Real Options Analysis Technique

The simplest model of ROA can be written in the form of the equations below as suggested by Hull (2012):

$$CALL_{ROA} = Max\ (S_t - ET, 0) \quad [7]$$

$$PUT_{ROA} = Max\ (ET - S_t, 0) \quad [8]$$

Where, $Call_{ROA}$ is the value of a call option and $PUT_{ROA}$ is the value of the put option. $S_t$ is current value of stock and ET is the exercise price. Formula 7 reflects that the option will be exercised if $S_t > ET$ and will not be exercised if the St < ET. In the case of a put option (Formula 8), the option will be exercised when ET > St.

Financial calculation was conducted with the real option valuation technique using the Black-Scholes formula (Black and Scholes, 1973). The Black and Scholes formula can be used to value a forest or stand and it can be regarded as a call option, a contract which gives the holder (the owner) the right to buy an asset (forest stand) at a fixed exercise price at maturity (rotation age T) based on projected harvest volume at current time t (Hughes, 2000). The exercise price entails any expense required to put the asset that will create the future cash flows in place. In this study, exercise price is the costs of stand management. The Black-Scholes model is based on following assumptions (Black and Scholes, 1973):

1) The riskless interest rate is known and constant over time.
2) The asset pays no dividend.

3) The stock price follows a random walk in continuous time with a variance rate proportional to the square of the stock price. Thus, the distribution of underlying asset price is log normal.

4) The variance rate of the return on the stock is constant.

5) There are no transaction costs in buying or selling the asset or the option, and no taxes.

Following the assumption above, Black-Scholes produced their model to value a call option as depicted in equation 9.

$$V_{ROA} = S_t * N(d1) - ET_{pv} * N(d2) \qquad [9]$$

And St = V(T) * Pt [10]

Where,

St = Log value (stock price equivalent of Black-Scholes model)

V(T) = tree biomass in ton/ac harvested at year T

Pt = stumpage price of varying forest products ($/ton)

r = risk-free interest rate

T = time to maturity or rotation age

$ET_{PV}$ = Total cost to implement the project (i.e., planting, site prep, and administration cost). It is commonly known as exercise cost and referred with a letter K or X.

Exp = exponential function

d1 $= \frac{ln\left[\frac{Pt}{ETpv}\right]}{\sigma\sqrt{T}} + \frac{\sigma\sqrt{T}}{2}$

d2 $= d_1 - \sigma\sqrt{T}$

$\sigma^2$ = annualized variance of the continuously compounded returns

$$\sigma = \sqrt{\frac{\sum_{t=1}^{N}\left[ln\left(\frac{P_t}{P_{t-1}}\right) - \ln(\acute{P}t)\right]^2}{n-1}}$$

$V_{ROA}$ = the net expected stand value (call option) at T1, T2, or $T_N$., and

N(d1) and N(d2) are the cumulative standard normal distribution function. It is the probability that a normally distributed variable with a mean of zero and standard deviation of one would have a value of less than d. "In" denotes the natural logarithm.

The cumulative present value of cost to implement the project $ET_{PV}$ was calculated using equation 11. $ET_{PV}$ is the cost of site preparation, planting, fertilization, competition control at various stages.

$$ET_{PV} = \sum_{t=0}^{T} \left(\frac{ET_{(T-t)}}{e^{r(T-t)}}\right) + \frac{Et}{e^{rt}} \qquad [11]$$

Where,

$ET_{PV}$ = cumulative present value of cost

r = risk free interest rate

T = The time horizon in the same unit as t up to rotation age T.

t = A given year (t = 0, 1, 2, …T)

exp = exponential term

Discounted Cash Flow Technique

NPV was calculated for the different regimes using the continuous time version.

$$NPV = \sum_{t=0}^{T} R_t \, exp^{(-rt)} - ET_{PV} \qquad [12]$$

Where, NPV = Net present value

$R_t$ = Revenues for a given year t (including thinning revenue)

$ET_{PV}$ = Cumulative present value of cost from equation 11.

exp = exponential function

r= risk free rate

T = rotation age

Financial Evaluation of Unequal Rotation Age

One of the objectives of this study was to determine the optimal rotation of stands of varying planting density and cultural intensity. The values from ROA and NPV at various ages were used to determine optimal time of harvest. However, the optimal value from ROA and NPV of different rotation length (i.e., mutually exclusive projects with unequal lives) cannot be compared. An equivalent annual annuity (EAA) was used to extrapolate optimal rotation values for ROA and NPV for a valid comparison and ranking of management regimes. The EAA calculates the net expected present value as a series of equal cash flow for the length of the investment and is presented on a per year basis (Equations 13 and 14). The EAA for ROA and NPV was calculated as:

$$EAA_{ROA} = \frac{r * V_{ROA}}{1 - Exp^{(-rT)}} \qquad [13]$$

$$EAA_{NPV} = \frac{r * NPV}{1 - Exp^{(-rT)}} \qquad [14]$$

A sensitivity analysis was performed to determine the effects of price volatility on the ROA results. The annualized standard deviation was increased by 10, 20, and 30 percent and effect of this increment on ROA return was compared with ROA for the base standard deviation. Results were also compared with NPV values.

## 3.3 **Results**

### *Growth and Yield*

Non-Thinned Scenarios

Measured average tree size and stand production attributes at age 18 for site classes, cultural intensities and planting densities are presented in Table 3.8. Simulated merchantable stem green weight projections after age 18 are presented in Figures 3.1 and 3.2 for operational and intensive culture regimes, respectively.

Mean dominant height (47 to 86 feet) and quadratic mean diameter (5.1 to 11.4 inches) generally increased with higher site class, intensive culture and lower planting density. Generally, dominant trees were tallest for the lowest density and shortest for the highest densities in both operational and intensive regimes. The height difference from 600 to 1200 TPA density was minimal. Average dominant height was greater with intensive than operational culture on low and average sites, particularly for 600 and 1200 TPA densities. The effect of intensive culture on average dominant height was greatest on the low site. On the high site, intensive culture had little effect on average dominant height.

The QMD was generally greatest for the lowest density (300 TPA) and gradually decreased as tree density increased to 1800 TPA (Table 8). The decrease in QMD from lower density to higher density occurred on all site classes for both operational and intensive regimes. The QMD was consistently greater for intensive than operational culture for a given site class and density. There was a greater effect of intensive culture on QMD on the low site, particularly at lower densities. On the high site, intensive culture had a smaller effect.

Basal area patterns for operational and intensive culture at age 18 differed greatly among the site classes and within each site class (Table 3.8). The maximum basal area was observed in the 600 to 1500 TPA range depending on site and cultural regime. For the operational regime, age 18 maximum basal area on the low (183 $ft^2$/ac), average (195 $ft^2$/ac), and high (229 $ft^2$/ac) sites were observed on the 1500, 1200, and 900 planting densities, respectively. For the intensive regime, maximum basal area on the low (202 $ft^2$/ac), average (195 $ft^2$/ac), and high (161 $ft^2$/ac) sites occurred on the 1200, 1200, and 600 planting densities, respectively.

Age 18 merchantable green weight MAI tended to be greatest on the high site with operational culture (7.4 to 13.0 tons/ac/yr) and least on the low site with operational culture (3.4 to 5.8 tons/ac/yr) (Table 3.8). Intensive culture increased merchantable green weight MAI on the low site, had a mixed impact on the average site, and resulted in lower MAI on the high site. Lower MAI for intensive than operational culture corresponded with higher mortality on intensive culture stands, especially at higher planting densities (Figure 3.3). The maximum merchantable green weight MAI occurred in the 600 to 1500 TPA range depending on site class and cultural regime. For the operational regime, maximum MAIs on the low (5.8 tons/ac), average (8.7 tons/ac), and high (13.0 tons/ac) sites were observed on the 1500, 900, and 900 planting densities, respectively. For the intensive regime, maximum MAIs on the low (9.7 tons/ac), average (9.8 tons/ac), and high (8.9 tons/ac) sites were observed on the 1200, 1200, and 600 planting densities, respectively. On the low site, intensive culture resulted in especially large MAI increases for the 600, 900, and 1200 TPA planting densities.

Average tree survival across the site classes through age 18 varied markedly by planting density and cultural intensity (Figure 3.1). The lowest rate of mortality occurred in lower planting densities (300 and 600 TPA). The rate of mortality increased markedly from 900 to 1800 planting densities. There was a higher rate of mortality for the intensive regime compared to the operational regime. By age 18, considerable mortality due to overstocking occurred on high planting density, intensive culture plots.

Merchantable green weight measured through age 18 and simulated after age 18 to age 30, for operational culture (Figure 3.2) and intensive culture (Figure 3.3) stands varied markedly by site class and planting density. Several green weight yield trajectories exhibited reductions during the age 15 to age 18 interval associated with mortality due to intraspecific competitions (Figure 3.3). For operational culture stands, observed merchantable green weight yields increased with better site class through age 18 (Figure 3.1). The high site stands across the density range had markedly greater merchantable green weight than the average and low site classes before and after age 18. For the average site class, the 900 TPA followed by 1200 TPA yielded the greatest total merchantable green weight. For the low site class, merchantable green weight yield was greatest for stands with 1200 to 1800 TPA densities, intermediate for the 300 TPA density and lowest for 600 and 900 densities through age 18.

The merchantable green weight trajectories for intensive culture stands (Figure 3.3) differed markedly from those of operational culture stands (Figure 3.2) in low and high site classes. For the low site class, total merchantable green weight increased much more rapidly in intensive culture than operational culture stands for all planting densities. For the high site class, significant mortality for higher planting densities with the intensive regime caused a marked decline in standing green weight by age 18 and lower merchantable green weights compared to operational culture stands. The average site class did not have substantial differences in merchantable green weight between the operational and intensive culture stands although intensive culture stands had slightly greater weight by age 18.

The yield trajectories for intensive culture stands show that the greatest merchantable green weight at or around age 15 on low and high sites occurred with the 900 TPA density, which was closely followed by the 600 and 1200 TPA density. For the average site, the highest merchantable green weight was observed for 1200 TPA density throughout the rotation due to exceptional yield on the medium site. A similar yield trajectory for 1200 TPA was reported as the average performance for a larger set of PMRC Coastal Plain Culture Density Study sites by Zhao et al. (2014).

The simulation of stand growth for each site class, density level, and cultural regime produced satisfactory growth and yield trajectories consistent with growth trajectories observed through age 18.

Thinned Scenarios

A) One -Thin Scenario

Simulated first thinning age ranged from 8 to 22 reflecting the great variability in tree and stand development (Table 3.9). For an average site with the operational culture regime, simulated thinning ages were 12 years for the 600 TPA density and age 13 for the 900 TPA density. The simulated thinning ages for the intensive culture regime were age 8 for 600 TPA density and age 10 for the 900 TPA density. Thinning ages for other density levels varied from 12 to 20 with operational culture and 8 to 16 with intensive culture regime. Generally, intensive culture stands meet thinning criteria 3-4 years prior to the operational regime. For the low site, the earliest simulated thinning with operational culture was at age 17 (300 TPA density) compared to age 12 with intensive culture. The maximum age for the simulated first thinning with the operational culture regime was 22 years (1500 and 1800 TPA densities) as compared to age 16 for the same densities with intensive culture. On the high site, intensive culture stands were generally thinned earlier than operational culture stands. The earliest thinning with intensive culture occurred at age 8 (600 TPA) and the latest at age 12. Operational and intensive culture stands with lower densities (300 - 900 TPA) had similar simulated thinning ages, while at higher densities (1200, 1500, and 1800 TPA), operational culture stands reached thinning criteria several years later than intensive culture stands.

Merchantable green weight by site class and planting densities with the one-thin scenario for the operational and intensive culture regimes are presented in Figure 3.4 and Figure 3.5, respectively. Generally, simulated post thinning growth was greater for the 600 TPA density than other density levels for most sites. The 600 and 900 TPA densities consistently produced relatively high merchantable yield across sites and cultural regimes. The 600 TPA density for the low site operational regime was the exception having the lowest yield throughout the rotation. Projected growth was intermediate for 300 and 1200 TPA densities and lower for the 1500 and 1800 TPA densities.

B) Two-Thin Scenario

There were marked differences in simulated second thinning timing among the various site, density, cultural regime combinations (Table 3.9). Simulated second thinning ages were as low as 12 or 13 years (low, average, high sites - intensive regime, 600 TPA) and as high as 32 years (low site – operational regime, 600 TPA). For the average site with intensive culture, second thinning criteria were met as early as 12 years for the 600 TPA density and 15 years for the 900 TPA density. The operational culture stands took longer to reach the second thinning stage. The low and high site classes showed a marked difference in simulated second thinning age. Second thinning age for the 600 TPA density was as early as 14 years on the high site and as late as 32 years on the low site. In general, second thinning for operational culture occurred much earlier on the high than the low site class and second thinning age differences between cultural regimes were greatest on the low site.

Growth trajectories and projections for two thinned scenarios through age 30 for operational and intensive culture regimes are shown in Figures 3.6 and 3.7, respectively. As with first thinning scenarios, the 600 TPA density had greatest projected total yield in most cases, followed closely by the 900 TPA density. The 300 TPA density had considerably lower projected yield.

*Financial Evaluation*

<u>No Thinning Scenarios</u>

Financial returns and optimum rotation age for the no-thinning scenario are summarized for operational and intensive culture regimes in Table 3.10. The average optimal rotation was not highly influenced by different planting densities for no-thin scenarios; however, slight rotation age differences were observed for the extreme end of densities. Optimum rotation age ranged from 22 to 26 years and averaged 24 years. The operational culture optimum rotation age was slightly greater than that for the intensive regime, particularly for the low site class. The optimal rotation age was 22 years for 300, 600, 900, and 1200 TPA densities and 26 years for the 1500 and 1800 TPA densities for the operational culture stands as compared to 22 years for all densities except the 600 TPA density (24 years) for the intensive culture regime.

Financial returns expressed as EAA followed similar trends as rotation length ROA and NPV. The high site class had higher ROA and NPV compared to the low site class.

For the low site class, financial return strongly differed between cultural regimes and among planting densities. The highest returns ($409 ROA and $387 NPV) for operational culture regime were observed for the 300 TPA density. The modest positive return ($135 ROA, $1 NPV) for the 1500 TPA density was unusual as none of the other planting densities above 300 TPA had positive returns. In contrast, the intensive culture regime produced positive returns for densities from 300 through 1200 TPA with maximum return ($568 ROA and $471 NPV) for the 600 TPA density.

The highest returns ($509 ROA and $491 NPV) for the average site for the operational culture regime were observed for the 300 TPA density followed by intermediate returns for the 900 and 600 TPA densities respectively. The intensive culture regime had a similar result with the 300 TPA density producing the highest returns ($486 ROA and $380 NPV), followed by the 600, 1200, and 900 TPA densities, respectively.

For the high site, the optimal rotation age was 24 years with the exception of the 22-year optimum for the 1200, 1500, and 1800 TPA densities for operational culture. There were considerable differences in financial returns between cultural regimes and among densities. The operational regime yielded greater financial return compared to the intensive culture regime. The greatest financial return for the operational culture regime ($1031 ROA and $1024 NPV) occurred for the 900 TPA density while that for the intensive regime, ($627 ROA and 546 NPV) occurred with the 300 TPA density. There was a trend of decreasing return for the intensive culture regime with increasing density. For the operational regime, economic return increased from 300 to 900 TPA and then decreased with greater density.

The two extremes of low and high site showed marked differences in financial return with cultural regime. On the low site, the operational culture regime did not produce positive returns for most densities while the intensive culture regime produced considerable financial return. In contrast, on the high site the operational regime produced greater financial return than the intensive regime.

Thinning Scenarios

Financial returns for one-thin and two-thin scenarios are summarized for operational and intensive culture regimes in Tables 3.11 and 3.12 respectively. EAA values showed similar trends as ROA and NPV values. The high site class generally had higher ROA and NPV compared to the low site class. Optimal rotation ages for the one-thin scenario were generally shorter than for the two-thin scenario, except in a few cases with the intensive culture regime where rotation ages were the same. The optimal rotation age generally increased from low to high planting density, a trend more evident for operational than intensive culture.

For the low site case, optimum rotation age ranged from 22 years for the 600 and 900 TPA, intensive culture, one-thin scenario to 38 years for the 1200 to 1800 TPA, operational culture, two-thin scenario. With operational culture, rotation age generally increased with increasing planting density for both thinning scenarios. For intensive culture, optimum rotation was shortest for the 600 and 900 TPA densities, intermediate for the 300 TPA density and longest for the higher densities.

Low site financial returns were greater for the two-thin than one-thin scenario for each planting density and cultural regime combination and were generally greater with intensive than operational culture. The ROA and NPV values for the two-thin scenario are greater than those for the one-thin scenario for the 300 TPA density; however, equal EAA values (\$34 $EAA_{ROA}$ and \$31 $EAA_{NPV}$) indicated similar returns from one- or two-thin scenarios. Financial returns were greater with intensive than operational culture with the exception of the 1500 TPA density. The financial returns indicated that higher densities favor operational culture and lower density favor intensive culture. The highest returns (\$1,267 ROA and \$997 NPV equivalent of \$91 $EAA_{ROA}$ and \$71 $EAA_{NPV}$) resulted from the 600 TPA density, intensive culture, two-thin scenario. The greatest one-thin scenario returns (\$956 ROA and \$927 NPV equivalent of \$72 $EAA_{ROA}$ and \$69 $EAA_{NPV)}$ also resulted from the 600 TPA density, intensive culture combination. The financial return trend (highest to lowest) for the low site intensive culture regime was

600, 900, 300, 1200, 1800 and 1500 TPA densities. The general financial return trend (highest to lowest) for the low site operational culture regime was 300, 1500, 1800, 1200, 900, and 600 TPA densities respectively. In general, the low site yielded higher financial return at low to moderate densities with intensive culture.

The rotation ages for average site stands for the one-thin scenario with operational culture ranged from 24 years with the 300 TPA density to 29 years with 1200 to 1800 TPA density. The optimal rotation age for the two-thin scenario with operational culture ranged from 29 years for the 300 and 600 TPA densities to 39 years for the 1800 TPA density. The optimal rotation age for the average site were generally shorter for intensive than operational culture for both one-thin and two-thin scenarios. The shorter optimum rotation ages with intensive culture were particularly large and consistent for two thinning scenarios. For example, optimum rotation age for the 600 TPA density were reduced due to intensive culture from 26 to 24 years with the one-thin scenario and from 29 to 24 years with the two-thin scenario.

For stands on an average site, there were clear trends in financial returns by thinning frequencies, cultural regimes, and planting densities. Financial returns were greater for the two-thin than the one-thin scenario for all densities. The highest financial return ($1,009 ROA and $977 NPV) occurred for the 600 TPA density, intensive culture, two-thin scenario. Financial returns for a given planting density were greater for intensive than operational culture with the exception of the 1500 and 1800 TPA densities with the two-thin scenario. Financial returns for the one-thin and two-thin scenarios generally show a decreasing trend with density beyond 900 TPA for the operational culture and 600 TPA for intensive culture.

For the high site, optimum rotation ages range from 24 to 30 years. Optimum rotation age was similar to slightly less for intensive culture than operational regimes. The range in optimum rotation age among densities was less for the intensive than operational culture regime. The financial returns for high site stands for both operational and intensive culture regimes were generally higher than those for the average or the low sites. Returns for the operational culture regime were consistently higher than for the intensive regime. Two-thin returns were often greater than the one-thin returns. The highest EAA returns ($98 for both $EAA_{ROA}$ and $EAA_{NPV;}$ $1,375 ROA and $1,372 NPV) occurred with the 900 TPA density, operational regime, and one-thin scenario. The 900 TPA density, operational regime, and two-thin scenario had higher return ($1,405 ROA and $1,402 NPV); however, the optimal rotation age was increased by two years and EAA return ($97 $EAA_{ROA}$ and $96 $EAA_{NPV}$) was lower than for the one-thin scenario. The general trends of financial return (highest to lowest) for the one- and two-thin scenarios were 900, 600, 300 followed by 1200 through 1800 TPA densities for the operational regime; and 600, 900, 300, 1500, 1200, and 1800 TPA densities for the intensive regime.

*No Thinning and Thinning Financial Return Comparison*

Financial returns expressed as $EAA_{ROA}$ for no-thin, one-thin, and two-thin scenarios for site classes, cultural regimes, and planting densities are presented in Table 3.13. Financial returns were greater with thinning than without thinning for all site class, cultural regime and planting density combinations. The two-thin scenarios often resulted in greater economic return than the one-thin scenario. However, the one-thin scenario had greater return for the 300 TPA density, intensive regime combination on average and high site classes. The highest returns (> $80 $EAA_{ROA}$) were observed in thinned stands with one of the following conditions:  high site with 300, 600, and 900 TPA densities and operational culture; high site with 600 TPA density and intensive culture; and low site with 600 TPA density and intensive culture. The lowest returns ($0 $EAA_{ROA}$) tended to be with no thinning regimes either on the low site with operational culture or with 1500 or 1800 planting densities and intensive culture.

*ROA vs NPV and Sensitivity Analysis*

Returns from the ROA method were consistently higher than from the traditional NPV method (Tables 3.10, 3.11., 3.12, and 3.13). Unlike the NPV method, which had negative values for many site, culture and density combinations, the lowest ROA value were zero and never negative because of the assumption with ROA that a rational investor would choose to buy underlying stock at market price with a lower cost rather than exercise an out-of-the money call option.

The ROA values for the non-thinned planting density and cultural regime combinations increased with increasing price volatility assumed in the sensitivity analysis (Figure 3.8). The NPV value remained constant as it was not affected by price volatility. Difference between NPV and ROA tended to be greater for intensive than operational culture especially with increasing planting density because higher density normally had smaller DBH trees (i.e., more pulp wood) which had slightly higher standard deviation (volatility) and this increased the difference between ROA and NPV.

**3.4 Discussion**

This study provided a unique opportunity to examine effects of site index, cultural intensity and planting density, and simulated stand development with and without thinning, on economic returns using ROA and NPV methods for loblolly pine plantations in the Lower Coastal Plains of Florida and Georgia assuming traditional timber products. This case study approach using three sites was intended to illustrate general trends that may broadly describe yield and economic return patterns in the larger population. Results on a particular site or across a large number of sites may differ from those reported here.

*Growth and Yield Response*

There was greater tree mortality due to self -thinning with increasing planting density, particularly from 900 to 1800 trees per acre, regardless of cultural regime; however, the rate of mortality was especially high for the intensive culture regime on the high site. Similar mortality trends were reported for a larger set of installations of the same PMRC study (Zhao et al. 2011, Zhao and Kane, 2012). Greater mortality with higher planting density (1200 TPA) was also reported for non-thinned loblolly pine stands on in Louisiana (Sword-Sayer et al., 2004).

Average dominant height through age 18 was greater in intensive than operational culture stands and for lower densities, especially 300 and 600 TPA, compared to 1500 and 1800 TPA. The difference in tree height among densities was greater on low and average than on the high site. A similar result of average dominant height being greater at lower densities than higher densities was found by Harms et al. (2000). It has been reported that planting density has little effect on dominant height for many commercially valuable species (Clutter et al., 1983) and experimental results support that claim (Pienaar and Shiver (1984), Harms et al. (1994). However, other studies examined a wider range of planting densities and found that density impacts average dominant height (Pienaar and Shiver, 1993; Lee and Lenhart, 1998; MacFarlane et al., 2000; Sharma et al., 2002; Zhao et al., 2011; Zhao and Kane, 2012).

The QMD increased with higher site class, lower planting density, and intensive culture. Sharma et al. (2002) found the greatest effect of density on QMD and the least effect on the average dominant height in a 16-year old loblolly pine from Coastal Plain and Piedmont sites of Virginia and North Carolina.

Generally, both BA and merchantable stemwood weight increased with increasing planting density up to a certain density (e.g., 900 TPA for average and high sites; 1500 TPA for low site for operational culture regime) and then decreased gradually. The impact of intensive culture varied with site class with the largest growth gains observed on the low site and smallest on the high site. This inverse relationship between site quality and magnitude of response to silvicultural treatments for loblolly pine was also reported by Zhao et al. (2016). On the high site, operational culture yielded greater total stem weight than the intensive culture at each density level. The greatest weight MAI (13.0 tons/ac at age 18) occurred with the 900 TPA density and operational culture, indicating the potential for plantation management for fiber production with relatively higher density than currently used. However, the very high BA (229 $ft^2$/ac) for these stands suggests a high risk of losses due to self-thinning as evidenced by the mortality curve (Figure 3.1). Maximum BAs of 200 and 209 $ft^2$/ac were reported for a 23-year old loblolly pine plantation in southeastern Oklahoma (Hennessey et al., 2004) and an age 15 intensively managed plantations in Georgia (Jokela et al., 2004), respectively. The BA of up to 243 $ft^2$/ac was found through simulation at age 25 for the high site, 900 TPA planting density, operational culture regime. The lower planting densities resulted in less BA and total yield but greater QMD than higher densities, similar to trends reported by Lee and Lenhart (1998).

With the exception of the 300 TPA density, the low site stands with operational culture did not meet thinning criteria by age 18 while intensive culture stands met thinning criteria as early as age 8 (300 and 600 TPA) and as late as age 16 (1500 and 1800 TPA). Stands on the average and high sites with either cultural regime generally took less time to meet thinning criteria, particularly in lower densities (300, 600, and 900 TPA). Lower planting densities generally met the thinning criteria sooner than higher densities. The QMD on higher densities were smaller and it took longer for these densities to surpass the 6-inch QMD minimum criteria even though average dominant height and BA thinning criteria were met much earlier. Ideally, higher density stands (1200, 1500, and 1800 TPA), especially those with intensive culture or on average or high sites should be thinned as early as age 12 when BA reaches 140 $ft^2$/ac. This would capture productivity otherwise lost to mortality and provide ample space for future tree growth. This earlier thinning would require a relatively low minimum DBH (4.5 inch) for commercial pulpwood or markets for smaller DBH trees (e.g. bioenergy feedstock). Early thinning may also reduce the risk of fire and disease.

Thinning ages are similar to those reported by Huang and Kronard (2002) who suggested thinning as early as age 11 for a site index 90 stand, which corresponds to the high site in this study. Similar to the current study, first and second thinning ages of 7 and 14 were reported for a stand planted at 1200 TPA (Sword-Sayer et al., 2004) and of 9 and 12 reported for a stand planted at about 1000 TPA (Hennessey et al., 2004).

The simulated thinnings markedly increased QMD and merchantable yield especially with intensive culture. Similar to Sword-Sayer et al. (2004), this study found the increase in QMD with thinned scenarios especially significant for economic return as it increases product value by shifting the product class from pulpwood to chip-n-saw and from chip-n-saw to sawtimber. The 600 and 900 TPA density benefited the most from thinning as the QMD improved over 3 inches for all sites. The average increase in QMD due to thinning was not substantial with operational culture except on the high site or for lower planting densities. However, average increase in QMD due to intensive culture and thinning combination as substantial.

The simulated growth rates for thinned scenarios are consistent for those reported by (Zhao et al., 2014) through age 18 which demonstrated excellent potential for high growth rates in thinned stands provided sufficient quality sites, management regimes that provide needed competition control and nutrients, and appropriate stocking levels. A similar growth trajectory for loblolly pine was reported by Sword-Sayer et al. (2004) for 1200 TPA density.

*Regime Current Practice*

The operational culture regime in this study contains significant silvicultural input and investment cost in seedlings, fertilization and competition control. It included more fertilization than used by most forest landowners in the southern U.S. Total rotation cost per acre for the operational culture, and 600 TPA density with no-thinning was $512. The management intensity for the operational regime in this study is comparable to Munsell and Fox’s (2010) intensive regime used to evaluate growth and yield and economic return loblolly pine plantations managed for multiple products including energy feedstocks.

The operational regime appears comparable to that used in Brazil, Australia, China, New Zealand, and South Africa for pine plantations where practices include site preparation similar to that used for agricultural fields, followed by fertilization, and mechanical or chemical weed control during the rotation (Evans, 1992).

The intensive culture regime included many silviculture inputs that cost $1,149 per acre over the rotation. Borders and Bailey (2001) reported cost per acre for intensively managed plantations (which they believed somewhat higher than for conventional regimes at that time) for 680 TPA planting density equivalent to $840 in 2014 real dollars which is considerably less than intensive culture regime costs in the current study. The Borders and Bailey (2001) regime included three fertilizations on a 4-year interval and two herbaceous weed control treatments. The current study operational culture included four fertilizations one of which occurred during the first growing season. Costs of individual treatments were similar for Borders and Bailey (2001) and the current study. The Borders and Bailey (2001) intensive regime was intermediate between the operational and intensive culture regimes in the current study.

Researchers have recommended various planting densities ranging from 300 to 400 trees per acre (Bowling, 1987; Vardaman, 1989; Caulfield et al., 1992) and up to 1300 trees per acre (Bailey, 1986; Borders et al., 1991). Timberland practices for non-industrial and industrial landowners owning about 17 million timberland acres in the US South were reported by Lang et al. (2016). According to their study, planting density averaged 571 TPA and survival averaged 88%. Most landowners reported regimes with one or two thinnings with first thinning average age of 14 years and second thinning average age of 21 years. Many landowners used regimes including chemical site preparation, single or double bedding, burning, and vegetation control. Fertilization has been widely used in southern pine plantations both at planting on phosphorus deficient soils, and more generally in mid-rotation plantations, especially following thinning (Albaugh et al., 2012; Fox et al., 2004).

*Financial Response*

In non-thinned scenarios, operational culture provided better economic return for average and high sites than the low site. The low site had greater economic return with intensive culture, particularly at the lower densities (300, 600, and 900 TPA) because these densities strongly responded to intensive culture, so much so that the merchantable green weight MAI at age 18 or simulated growth after age 18 showed about the same level of productivity as that of the high site with intensive culture. For the low site, the 600 TPA density produced the greatest return followed by the 300 and 900 TPA densities.

For the average site, no-thin scenario case, the returns from operational culture were slightly greater than from intensive culture because the higher intensive culture costs were not compensated by sufficient value associated with greater yield and yield of high value products. Lower densities proved advantageous for both operational and intensive culture

For the high site and no-thinning scenario, mortality and high cost reduced financial return from intensive culture, and operational culture produced much greater return for all planting densities. Financial returns were especially high for operational culture and planting density between 300 and 900 TPA.

The financial returns for non-thinned stands from various cases in this study demonstrate that lower density (i.e., 300, 600, and 900 TPA) are advantageous on average and high site classes. Even though the 300 TPA is the lowest density examined, it produced the highest return for an average site due to greater tree QMD and height (Table 3.8) and lower planting costs. The 900 TPA density on the high site operational regime was a unique case as it produced the greatest return followed by 600 and 300 TPA. These results indicate that growth and economic return responses to intensive treatment are site specific. Fox et al. (2004) emphasize that the effect of fertilization depends on particular site and stand conditions.

Financial returns were much greater with a thinning scenario, either one-thin or two-thin, than for the no-thin scenario. Intensive culture resulted in greater financial returns than operational culture under the thinned scenarios with the exception of the high site. The 600 TPA density consistently produced greater financial return among the densities for both one-thin and two-thin scenarios combined with intensive culture. Financial returns were particularly high across the range of planting densities for the high site operational culture combination with thinning.

The two-thin scenario generally accrued greater financial return than the one-thin scenario for most densities. The financial advantage of the two-thin scenario was not as large or consistent for the 300 TPA density relative to other densities. Huang and Kronard (2002) recommended up to three thinnings for 600 TPA density to maximize profits on site indices above 80 under relatively low interest rates (2.5, 5.0, and 7.5%). The site indices for average and high sites were greater than 80 and the real risk-free rate of interest applied was 5% for this study. Although a three-thinning regime was out of the scope of this study, conducting a third thinning was possible at or before age 24 for 600, 900, and 1200 TPA densities with the intensive culture regime and 600 and 900 TPA densities with the operational regime on the high site.

The greater financial returns from thinning than non-thinning scenarios resulted from multiple factors including receiving early revenue from thinning, reducing intraspecific competition causing mortality and reducing individual tree growth, and favoring greater size and higher proportions of yield in higher valued products. Significant less individual tree DBH growth at higher densities prior to commercial thinning had negative effects on financial returns by delaying commercial thinning age and by reducing proportions of yield in higher value product classes at thinning and final harvest. The high relative costs of the intensive regime did not provide enough additional revenue to be economically attractive except for the low site with planting densities in the 300 to 900 TPA range.

*Optimum Economic Regimes*

Based on this case study evaluation, the following regimes provide the greatest economic return for low, average, and high site classes.

<u>Low site</u>

Plant 600 TPA. Apply intensive culture. Thin twice.

<u>Average Site</u>

Plant 600 TPA. Apply intensive culture. Thin twice.

<u>High Site</u>

Plant 900 TPA. Apply operational culture. Thin twice.

*NPV and ROA Comparison*

ROA values were consistently greater than NPV values whether expressed over a full rotation or as an equivalent annual annuity term. The main reason ROA was greater is that the ROA method captured the value of uncertainty from price volatility while the NPV method did not. Both approaches indicate when not to invest in a project (ROA value of zero or negative NPV value) (Luehrman, 1998). However, the ROA approach is more advantageous than the NPV valuation because forestry comes with embedded optionality. In cases when the value of a stand becomes zero (no pay off), the option holder can either delay or abandon the options to recoup at least minimal value. A zero value for ROA indicates the call value is “out of the money”. In forestry, it occurs when the present value of the underlying asset is lower than the cost of managing a stand (the exercise price). In the current study, the option to delay or option to abandon was not calculated when the ROA value became zero, but as mentioned above the project inherently has embedded value and can be easily calculated from the Black-Scholes model. In fact, when NPV goes to negative, the put option equals the abandonment option value. The calculated ROA value increases when the price volatility increases and can be tested by sensitivity analysis. In essence, ROA and NPV gave the same conclusion on determining optimal regimes and rotation ages. The results from the ROA method compared to NPV would not have changed the decision of a landowner; however, the ROA method provides a wide range of flexibility options and gives appropriate value to the project if the project has already begun.

The corresponding EAA values for ROA and NPV show results in equivalent annual annuity terms. The EAA approach is helpful in determining returns from different regimes that had considerably different rotation ages. Klemperer (1996) suggests an EAA approach to value two mutually exclusive management regimes that have considerably larger rotation age differences and management regimes that can be altered or modified in the next rotation. The EAA was particularly useful in ranking of optimal management combination for integrated timber products and bioenergy in the next chapter.

The ROA approach is an extension of financial option pricing models to value non-financial real assets. It is not an alternative but an extension of the static NPV method. The Black-Scholes model of ROA was used to identify optimal rotation age of stands in a similar manner as reported by Hughes (2000) and Susaeta et al. (2009). The Black-Scholes method was used in the current study for optimal rotation age determination but this method can also be used for valuation of other kinds of options, such as options to delay, stage, or abandon. The Black-Scholes model nonetheless provides an easy way to estimate future stand values in present dollars that is comparable with conventional NPV.

Both approaches are good and have advantages and limitations. Advantages of static NPV include that it is straightforward and easy to follow compared to Black-Scholes model of ROA. Although the static NPV method is superior compared to other methods of valuation such as accounting rate of return and internal rate of return (Trigeorgis, 1996), it only provides decision guidance a year in advance of project initiation and assumes no project changes regardless of what may happen (Guthrie, 2009). It does not take uncertainty into account unless decision tree analysis, the simplest form of ROA, is employed. It does not provide flexibility to account for future learning. Big companies often run a pilot project to learn whether the investment is worth the risk. It neither recognizes nor explicitly accounts for the managerial alternative of waiting, delaying the start of, or abandoning the investment project (Luehrman 1998).

ROA recognizes the opportunity to invest at pilot scale with low startup cost and apply the knowledge learned to future investment. A major criticism, particularly of the Black-Scholes model, is that it cannot be applied to optimal rotation determination because the parameters used in Black-Scholes are not necessarily equivalent to forestry terms and the forestry version of the Black-Scholes model does not meet the requisite of a financial model (Thomson, 1991). The assumption of constant volatility in the Black-Scholes model is flawed and has been proven false (Hull, 2012). The assumption of risk-free and constant interest rate is easily violated in today's market as no investment is risk free and only available in treasury bonds for short periods. The ROA returns are overly optimistic especially when you increase the price volatility. The last and important point is that Black-Scholes model is difficult to understand compared to static NPV method.

**3.5 Conclusion**

The conclusions below are based on a case study of loblolly pine plantations on three sites selected to be relatively illustrative of low, average, and high quality sites in the Lower Coastal Plain of Florida and Georgia.  The general trends reported follow most expectations but due to the case study nature of this evaluation, results for other sites or forests may differ from those reported.

Merchantable yields were strongly influenced by site index, planting density, cultural intensity, thinning regime and stand harvest age. High merchantable yields occurred with combinations of high resource availability, good stocking for individual tree and stand level growth, and sufficient age for trees to grow into larger, higher valued products. High resource availability occurred either with high site index or intensive culture. Good stocking occurred with moderate planting densities (600 to 900 trees per acre) and timely thinning.

Financial returns were generally greater for thinned than non-thinned scenarios and with moderate planting densities. Greatest returns were on the high-quality site with operational culture and the lowest returns were on the low site index site with operational culture. Intensive culture provided greater returns than operational culture on the low and average sites.

Recommended regimes for economic returns are 600 tree per acre planting density, intensive culture and thin twice on low and average sites and 900 trees per acre planting density, operational culture and thin twice on the high site index site.

The ROA values were consistently greater than NPV values because ROA valued volatility in stumpage prices. The ROA and NPV valuation methods resulted in identical conclusions regarding optimum rotation length and optimum silvicultural regime for economic return.

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Table 3. 1. Location, soil attributes, site index, and productivity classes for three installations (sites) in the Lower Coastal Plain[1].

| Installation (Site) | State | County | NRCS Soil Series | Soil Taxonomy | Site Index[2] | Productivity Class[3] |
|---|---|---|---|---|---|---|
| 11 | FL | Nassau | Ocilla | loamy, siliceous, semiactive, thermic aquic arenic paleudult | 61 | low |
| 16 | GA | Clinch | Albany | loamy, siliceous, subactive, thermic aquic arenic paleudult | 83 | medium |
| 1 | FL | Baker | Sapelo | sandy, siliceous, thermic ultic alaquod | 97 | high |

1. From Zhao et al. (2014).
2. Estimated height of dominant trees on 600 trees per acre, operational plot at age 25 following Zhao et al. (2014).
3. Based on site index.

Table 3. 2. Planting density, spacing, and plot sizes for varying planting densities.

| Planting density (TPA) | Spacing (ft. X ft.) | Measurement plot size (ac) | Gross plot size (ac) |
|---|---|---|---|
| 300 | 12 X 12 | 0.26 | 0.56 |
| 600 | 8 X 9 | 0.13 | 0.37 |
| 900 | 8 X 6 | 0.11 | 0.31 |
| 1200 | 6 X 6 | 0.10 | 0.30 |
| 1500 | 6 X 4.8 | 0.11 | 0.32 |
| 1800 | 6 X 4 | 0.10 | 0.31 |

Table 3. 3. Silvicultural treatments through age 18 for the operational and intensive culture regimes for the loblolly pine culture/density study in the Lower Coastal Plain of Florida and Georgia.

| Operational Regime | Intensive Regime |
|---|---|
| Bedding | Bedding |
| Fall banded chemical site preparation | Fall broadcast chemical site preparation |
| | Tip Moth Control |
| Herbaceous weed control: 1st year banded | Repeated herbicide application to achieve sustained complete vegetation control |
| Fertilization: at planting, 500 lbs/ac of 10-10-10; before 8th, 12th and 16th growing season, 200 lbs/ac N + 25 lbs/ac P | Fertilization: at planting 500 lbs/ac of 10-10-10; spring 3rd growing season, 600 lbs/ac 10-10-10 + micronutrients + 117 lbs./ac of $NH_4NO_3$; spring 4th growing season 117 lbs/ac $NH_4NO_3$; spring 6th growing season 300 lbs/ac $NH_4NO_3$; spring 8th, 10th, 12th, 14th, 16th, and 18th growing season 200 lbs./ac N +25 lbs/ac P |

Table 3. 4. Southern pine product class specifications*

| Product | DBH Limit | Top Dia. Limit |
|---|---|---|
| Pulpwood | 4.5 inch – 8.5 inch | 3 inch |
| Chip-n-saw | 8.5 inch – 11.5 inch | 6 inch |
| Sawtimber | >11.5 inch | 8 inch |
| Bioenergy | < 4.5 inch | 0.1 inch |

* The product class specifications follow Timber Mart South (TMS) specifications.

Table 3. 5. Cost information of silvicultural activities through age 18 for operational and intensive culture regimes for the no-thin scenario.

| Year | Operational Culture Activities | Cost Per Acre |
|---|---|---|
| 0 | Mechanical site prep (bedding) | $80 |
| 0 | Chemical site prep (12 oz Aresenal + (1 qt Garlon or Accord) | $80 |
| 0 | Machine Planting | $62 |
| 0 | Fertilizer (500 lbs of 10-10-10) | $61 |
| 7 | Fertilizer (300 lbs of $NH_4NO_3$) | $36 |
| 11 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $65 |
| 15 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $128 |
| | Total cost for operational culture | $512 |
| | Intensive Culture Activities | |
| 0 | Mechanical site prep (bedding) | $80 |
| 0 | Chemical site prep | $80 |
| 0 | Machine Planting(seedling+planting) | $62 |
| 0 | Fertilizer (500 lbs of 10-10-10) (10% of each N-P-K) | $61 |
| 1 | Herbicide (4 oz Ounce + glyphosate) | $50 |
| 2 | Fertilizer (600 lbs of 10-10-10 + 117 lbs of $NH_4NO_3$) +117 lbs of $NH_4NO_3$ | $79 |
| 3 | Fertilizer (300 lbs of $NH_4NO_3$) 40% of reported cost | $40 |
| 5 | Fertilizer (300 lbs of $NH_4NO_3$) 40% of reported cost | $37 |
| 7 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $73 |
| 8 | Chemical release | $60 |
| 9 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $69 |
| 11 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $69 |
| 13 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $129 |
| 15 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $128 |
| 17 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $132 |
| | Total Cost for intensive culture | $1,149 |

Table 3. 6. Cost information of silvicultural activities for intensive and operational culture regimes for thinning scenarios.

| Year | Operational Culture Activities | Cost per Acre |
|---|---|---|
| 0 | Mechanical site prep (bedding) | $80 |
| 0 | Chemical site prep | $80 |
| 0 | Machine Planting | $62 |
| 0 | Fertilizer (500 lbs of 10-10-10) | $61 |
| 7 | Fertilizer (300 lbs of $NH_4NO_3$) | $36 |
| 12* | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $63 |
| 17* | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $132 |
| | Total cost for operational culture | $514 |
| | Intensive Culture Activities | |
| 0 | Mechanical site prep (bedding) | $80 |
| 0 | Chemical site prep | $80 |
| 0 | Machine Planting | $62 |
| 0 | Fertilizer (500 lbs of 10-10-10) (10% of each N-P-K) | $61 |
| 1 | Herbicide (12 oz Arsenal) | $50 |
| 2 | Fertilizer (600 lbs of 10-10-10 + 117 lbs of $NH_4NO_3$) +117 lbs of $NH_4NO_3$ | $79 |
| 3 | Fertilizer (300 lbs of $NH_4NO_3$) 40% of reported cost | $40 |
| 5 | Fertilizer (300 lbs of $NH_4NO_3$) 40% of reported cost | $37 |
| 7 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $73 |
| 8 | Chemical release | $60 |
| 9 | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $69 |
| 14* | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $132 |
| 19* | Fertilizer (200 lbs elemental N and 25 lbs of elemental P/acre) | $121 |
| | Total cost for intensive culture | $944 |

*Fertilizations simulated with SiMS

Table 3. 7. RMSE, volatility (standard deviation) and drift values for pulpwood, chip-n-saw and sawtimber.

| Parameter | Pulpwood | Chip-n-saw | Sawtimber |
|---|---|---|---|
| RMSE | 0.633 | 1.279 | 2.006 |
| Volatility | 0.156 | 0.123 | 0.1206 |
| Drift | 0.0115 | -0.007 | -0.011 |

Note: Statistical values presented in the table are based on historical real price (2014 dollars) series from the first quarter of 1986 to fourth quarter of 2014.The units are reported as $/ton

Table 3. 8. Tree and stand attributes for 18-year non-thinned loblolly pine plantations located in the Lower Coastal Plain of Georgia and Florida on different sites for operational and intensive culture and varying planting densities.

| | Operational Regime | | | | | Intensive Regime | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Planting Density (TPA)[1] | TPA at Age 18 | Mean Dominant Height (ft) | QMD[2] (in) | BA[3] ($ft^2$/ac) | Merchantable Green Weight MAI[4] (ton/ac) | TPA at age 18 | Mean Dominant height (ft) | QMD (in) | BA ($ft^2$/ac) | Merchantable Green Weight MAI (ton/ac) |
| Low Site | | | | | | | | | | |
| 300 | 246 | 66 | 9.8 | 125 | 5.4 | 246 | 74 | 10.8 | 158 | 6.7 |
| 600 | 492 | 47 | 6.6 | 117 | 3.4 | 386 | 80 | 9.5 | 190 | 9.0 |
| 900 | 652 | 52 | 6.1 | 127 | 4.1 | 577 | 73 | 7.8 | 190 | 9.5 |
| 1200 | 978 | 56 | 5.5 | 157 | 5.3 | 867 | 68 | 6.7 | 202 | 9.7 |
| 1500 | 1238 | 56 | 5.3 | 183 | 5.8 | 926 | 60 | 6.1 | 188 | 7.3 |
| 1800 | 1134 | 56 | 5.1 | 163 | 5.0 | 1006 | 66 | 6.0 | 199 | 8.3 |
| Average Site | | | | | | | | | | |
| 300 | 254 | 71 | 9.7 | 133 | 5.8 | 224 | 77 | 10.9 | 147 | 6.7 |
| 600 | 492 | 66 | 7.6 | 159 | 7.2 | 363 | 78 | 9.1 | 166 | 8.0 |
| 900 | 700 | 68 | 6.9 | 185 | 8.7 | 517 | 75 | 7.9 | 171 | 8.4 |
| 1200 | 932 | 65 | 6.2 | 195 | 8.4 | 666 | 74 | 7.4 | 195 | 9.8 |
| 1500 | 1082 | 65 | 5.8 | 192 | 7.9 | 692 | 69 | 7.0 | 174 | 7.7 |
| 1800 | 1100 | 64 | 5.6 | 183 | 7.3 | 820 | 67 | 6.4 | 180 | 7.6 |
| High Site | | | | | | | | | | |
| 300 | 253 | 82 | 10.6 | 154 | 7.4 | 200 | 84 | 11.4 | 142 | 7.2 |
| 600 | 461 | 83 | 8.8 | 197 | 10.7 | 340 | 85 | 9.3 | 161 | 8.9 |
| 900 | 624 | 86 | 8.2 | 229 | 13.0 | 397 | 82 | 8.5 | 157 | 8.4 |
| 1200 | 817 | 75 | 7.1 | 223 | 11.6 | 464 | 77 | 7.9 | 159 | 8.6 |
| 1500 | 870 | 77 | 6.6 | 208 | 10.9 | 444 | 78 | 8.1 | 159 | 8.3 |
| 1800 | 858 | 77 | 6.7 | 208 | 11.1 | 503 | 77 | 7.2 | 141 | 7.2 |

1. TPA = trees per acre
2. QMD = quadratic mean diameter is the dbh of the tree of average basal area
3. BA = basal area is the average amount of area occupied by tree stems at breast height of trees
4. MAI = mean annual increment is total green tons/acre/year

Table 3. 9. Simulated thinning ages (years) used in one-thin and two-thin scenarios for different sites, operational or intensive culture, and various planting densities for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| Operational Regime | | | Intensive Regime | | |
|---|---|---|---|---|---|
| Planting Density | 1st Thin (Age) | 2nd Thin (Age) | Planting Density | 1st Thin (Age) | 2nd Thin (Age) |
| Low Site | | | | | |
| 300 | 17 | 26 | 300 | 12 | 19 |
| 600 | 19 | 32 | 600 | 8 | 13 |
| 900 | 18 | 28 | 900 | 8 | 13 |
| 1200 | 20 | 29 | 1200 | 12 | 18 |
| 1500 | 22 | 31 | 1500 | 16 | 22 |
| 1800 | 22 | 31 | 1800 | 16 | 22 |
| Average Site | | | | | |
| 300 | 16 | 25 | 300 | 12 | 19 |
| 600 | 12 | 18 | 600 | 8 | 12 |
| 900 | 13 | 19 | 900 | 10 | 15 |
| 1200 | 18 | 25 | 1200 | 12 | 17 |
| 1500 | 19 | 26 | 1500 | 15 | 21 |
| 1800 | 20 | 28 | 1800 | 16 | 22 |
| High Site | | | | | |
| 300 | 12 | 18 | 300 | 12 | 18 |
| 600 | 9 | 14 | 600 | 8 | 12 |
| 900 | 10 | 15 | 900 | 10 | 14 |
| 1200 | 14 | 20 | 1200 | 12 | 17 |
| 1500 | 15 | 21 | 1500 | 12 | 17 |
| 1800 | 16 | 22 | 1800 | 12 | 17 |

Table 3. 10. Economic returns and optimal rotation ages for the no-thin scenario for low, average, and high site classes and various planting densities for the operational and intensive culture regime for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| | Operational Regime | | | | | Intensive Regime | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Planting Density (TPA) | Optimal Rotation Age (Years) | ROA | NPV | $EAA_{ROA}$[1] | $EAA_{NPV}$[1] | Optimal Rotation Age (Years) | ROA | NPV | $EAA_{ROA}$[1] | $EAA_{NPV}$[1] |
| | | | | | Low site | | | | | |
| 300 | 22 | $409 | $387 | $31 | $29 | $22 | $436 | $329 | $33 | $25 |
| 600 | 22 | $0[2] | ($105)[3] | $0 | ($8) | $24 | $568 | $471 | $41 | $34 |
| 900 | 22 | $0 | ($69) | $0 | ($5) | $22 | $318 | $156 | $24 | $12 |
| 1200 | 22 | $0 | ($4) | $0 | ($0) | $22 | $222 | $2 | $17 | $0 |
| 1500 | 26 | $135 | $1 | $9 | $0 | $22 | $0 | ($262) | $0 | ($20) |
| 1800 | 26 | $0 | ($66) | $0 | ($5) | $22 | $0 | ($196) | $0 | ($15) |
| | | | | | Average Site | | | | | |
| 300 | 24 | $509 | $491 | $36 | $35 | $24 | $486 | $380 | $35 | $27 |
| 600 | 24 | $433 | $405 | $31 | $29 | $24 | $434 | $306 | $31 | $22 |
| 900 | 24 | $465 | $434 | $33 | $31 | $24 | $284 | $95 | $20 | $7 |
| 1200 | 22 | $338 | $291 | $25 | $22 | $22 | $298 | $118 | $22 | $9 |
| 1500 | 22 | $290 | $226 | $22 | $17 | $22 | $0 | ($121) | $0 | ($9) |
| 1800 | 26 | $239 | $138 | $16 | $9 | $26 | $0 | ($191) | $0 | ($13) |
| | | | | | High site | | | | | |
| 300 | 24 | $858 | $852 | $61 | $61 | $24 | $627 | $546 | $45 | $39 |
| 600 | 24 | $944 | $938 | $68 | $67 | $24 | $586 | $492 | $42 | $35 |
| 900 | 24 | $1,031 | $1,024 | $74 | $73 | $24 | $380 | $228 | $27 | $16 |
| 1200 | 22 | $647 | $628 | $48 | $47 | $24 | $272 | $64 | $19 | $5 |
| 1500 | 22 | $578 | $552 | $43 | $41 | $24 | $279 | $63 | $20 | $5 |
| 1800 | 22 | $519 | $483 | $39 | $36 | $24 | $0 | ($111) | $0 | ($8) |

1. ROA and NPV values are presented in terms of equivalent annual annuity (EAA) to compare PV in the same time horizon.
2. Zero ($0) ROA value indicates call options should not be exercised at that moment.
3. Values in parentheses indicates negative values.

Table 3. 11. Economic returns and optimal rotation ages for one-thin and two-thin scenarios for low, average, and high site classes and varying planting density for the operational culture regime for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| Planting Density (TPA) | Optimal rotation (ages) | One Thin ROA | One Thin NPV | One Thin $EAA_{ROA}$[1] | One Thin $EAA_{NPV}$[1] | Optimal Rotation (Ages) | Two Thin ROA | Two Thin NPV | Two Thin $EAA_{ROA}$ | Two Thin $EAA_{NPV}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Low Site | | | | | | | | | | |
| 300 | 26 | $491 | $470 | $34 | $32 | 34 | $560 | $533 | $34 | $33 |
| 600 | 29 | $0[2] | ($3)[3] | $0 | ($0) | 36 | $351 | $100 | $21 | $6 |
| 900 | 29 | $154 | $48 | $10 | $3 | 36 | $217 | $114 | $13 | $7 |
| 1200 | 33 | $275 | $185 | $17 | $11 | 38 | $337 | $249 | $20 | $15 |
| 1500 | 33 | $319 | $230 | $20 | $14 | 38 | $377 | $288 | $22 | $17 |
| 1800 | 33 | $242 | $120 | $15 | $7 | 38 | $375 | $319 | $22 | $19 |
| Average Site | | | | | | | | | | |
| 300 | 24 | $559 | $545 | $40 | $39 | 29 | $630 | $612 | $41 | $40 |
| 600 | 26 | $539 | $517 | $37 | $36 | 29 | $650 | $630 | $42 | $41 |
| 900 | 26 | $572 | $547 | $39 | $38 | 32 | $674 | $646 | $42 | $40 |
| 1200 | 29 | $526 | $486 | $34 | $32 | 33 | $623 | $584 | $39 | $36 |
| 1500 | 29 | $463 | $411 | $30 | $27 | 35 | $551 | $495 | $33 | $30 |
| 1800 | 29 | $388 | $316 | $25 | $21 | 39 | $500 | $416 | $29 | $24 |
| High Site | | | | | | | | | | |
| 300 | 24 | $1,108 | $1,105 | $79 | $79 | 26 | $1,185 | $1,182 | $81 | $81 |
| 600 | 24 | $1,153 | $1,149 | $82 | $82 | 26 | $1,193 | $1,189 | $82 | $82 |
| 900 | 24 | $1,375 | $1,372 | $98 | $98 | 26 | $1,405 | $1,402 | $97 | $96 |
| 1200 | 26 | $932 | $920 | $64 | $63 | 29 | $1,074 | $1,062 | $70 | $69 |
| 1500 | 29 | $948 | $929 | $62 | $61 | 29 | $1,088 | $1,074 | $71 | $70 |
| 1800 | 29 | $851 | $825 | $56 | $54 | 30 | $968 | $945 | $62 | $61 |

1. ROA and NPV values are presented in terms of equal equivalent annuity (EAA) to compare PV in the same time horizon. Fixed rotation ROA and NPV values are presented to compare values for same time horizon for ease.
2. Zero ($0) ROA value indicates call options should not be exercised at that moment.
3. Values in parentheses indicates negative values.

Table 3. 12. Economic returns and optimal rotation ages for one thin and two thin scenarios for low, average, and high site classes and varying planting density for the intensive culture regime for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| Planting Density (TPA) | Optimal Rotation (ages) | One Thin | | | | Optimal Rotation (Ages) | Two Thin | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ROA | NPV | $EAA_{ROA}$ | $EAA_{NPV}$ | | ROA | NPV | $EAA_{ROA}$ | $EAA_{NPV}$ |
| Low Site | | | | | | | | | | |
| 300 | 24 | $629 | $572 | $45 | $41 | 26 | $718 | $664 | $49 | $46 |
| 600 | 22 | $956 | $927 | $72 | $69 | 24 | $1,267 | $997 | $91 | $71 |
| 900 | 22 | $714 | $662 | $53 | $50 | 24 | $843 | $796 | $60 | $57 |
| 1200 | 26 | $457 | $339 | $31 | $23 | 29 | $581 | $475 | $38 | $31 |
| 1500 | 29 | $257 | $43 | $17 | $3 | 29 | $336 | $156 | $22 | $10 |
| 1800 | 29 | $308 | $104 | $20 | $7 | 33 | $415 | $229 | $26 | $14 |
| Average Site | | | | | | | | | | |
| 300 | 24 | $594 | $532 | $42 | $38 | 25 | $646 | $587 | $45 | $41 |
| 600 | 24 | $928 | $892 | $66 | $64 | 24 | $1,009 | $977 | $72 | $70 |
| 900 | 24 | $703 | $642 | $50 | $46 | 26 | $780 | $720 | $54 | $49 |
| 1200 | 26 | $553 | $455 | $38 | $31 | 26 | $646 | $564 | $44 | $39 |
| 1500 | 29 | $363 | $193 | $24 | $13 | 30 | $461 | $314 | $30 | $20 |
| 1800 | 29 | $340 | $149 | $22 | $10 | 30 | $413 | $242 | $27 | $16 |
| High Site | | | | | | | | | | |
| 300 | 24 | $962 | $932 | $69 | $67 | 26 | $892 | $852 | $61 | $59 |
| 600 | 24 | $1,124 | $1,098 | $80 | $79 | 24 | $1,148 | $1,123 | $82 | $80 |
| 900 | 24 | $997 | $961 | $71 | $69 | 26 | $1,122 | $1,087 | $77 | $75 |
| 1200 | 26 | $678 | $600 | $47 | $41 | 26 | $756 | $688 | $52 | $47 |
| 1500 | 24 | $741 | $673 | $53 | $48 | 29 | $849 | $773 | $55 | $50 |
| 1800 | 26 | $445 | $306 | $31 | $21 | 26 | $561 | $433 | $39 | $30 |

1. ROA and NPV values are presented in terms of equivalent annual annuity (EAA) to compare PV in the same time horizon. Fixed rotation ROA and NPV values are presented to compare values for same time horizon for ease.
2. Zero ($0) ROA value indicates call options should not be exercised at that moment.

Table 3. 13. ROA returns in EAA terms for no-thin, one-thin, and two-thin scenarios for low, average, and high site classes and varying planting density for the operational and intensive culture regimes for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| Operational regime | | | | Intensive Regime | | | |
|---|---|---|---|---|---|---|---|
| Planting Density | No Thin $EAA_{ROA}$ | One-Thin $EAA_{ROA}$ | Two-Thin $EAA_{ROA}$ | Planting Density | No Thinning $EAA_{ROA}$ | One-Thin $EAA_{ROA}$ | Two-Thin $EAA_{ROA}$ |
| Low Site | | | | | | | |
| 300 | $31 | $34 | $34 | 300 | $33 | $45 | $49 |
| 600 | $0 | $0 | $21 | 600 | $41 | $72 | $91 |
| 900 | $0 | $10 | $13 | 900 | $24 | $53 | $60 |
| 1200 | $0 | $17 | $20 | 1200 | $17 | $31 | $38 |
| 1500 | $9 | $20 | $22 | 1500 | $0 | $17 | $22 |
| 1800 | $0 | $15 | $22 | 1800 | $0 | $20 | $26 |
| Average Site | | | | | | | |
| 300 | $36 | $40 | $41 | 300 | $35 | $42 | $45 |
| 600 | $31 | $37 | $42 | 600 | $31 | $66 | $72 |
| 900 | $33 | $39 | $42 | 900 | $20 | $50 | $54 |
| 1200 | $25 | $34 | $39 | 1200 | $22 | $38 | $44 |
| 1500 | $22 | $30 | $33 | 1500 | $0 | $24 | $30 |
| 1800 | $16 | $25 | $29 | 1800 | $0 | $22 | $27 |
| High Site | | | | | | | |
| 300 | $61 | $79 | $81 | 300 | $45 | $69 | $61 |
| 600 | $68 | $82 | $82 | 600 | $42 | $80 | $82 |
| 900 | $74 | $98 | $97 | 900 | $27 | $71 | $75 |
| 1200 | $48 | $64 | $70 | 1200 | $19 | $47 | $52 |
| 1500 | $43 | $62 | $71 | 1500 | $20 | $53 | $55 |
| 1800 | $39 | $56 | $62 | 1800 | $0 | $31 | $39 |

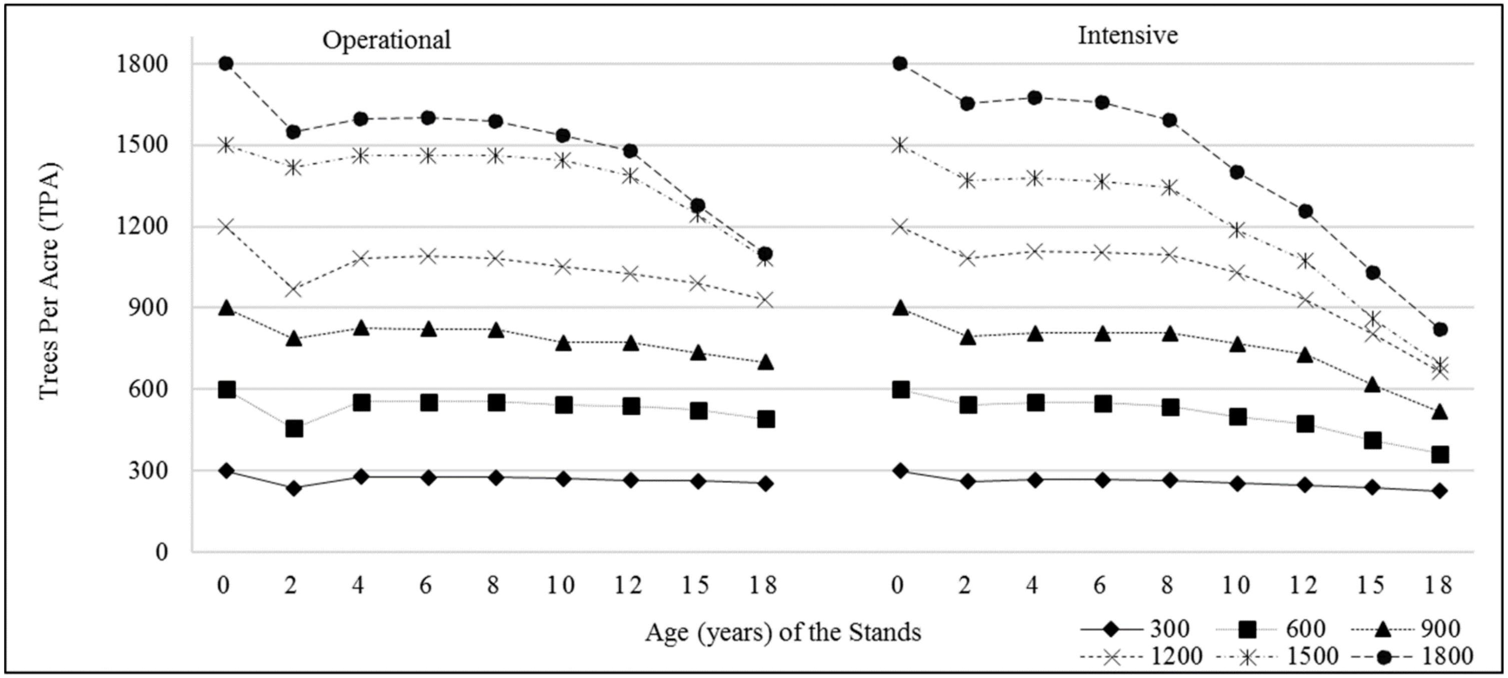


Figure 3. 1. Average loblolly pine survival trends through age 18 by planting density for operational and intensive regimes.
Note: the increase on tpa from age 2 to 4 results from recording multiple stems of trees forking below 4.5 feet height beginning in these age intervals.

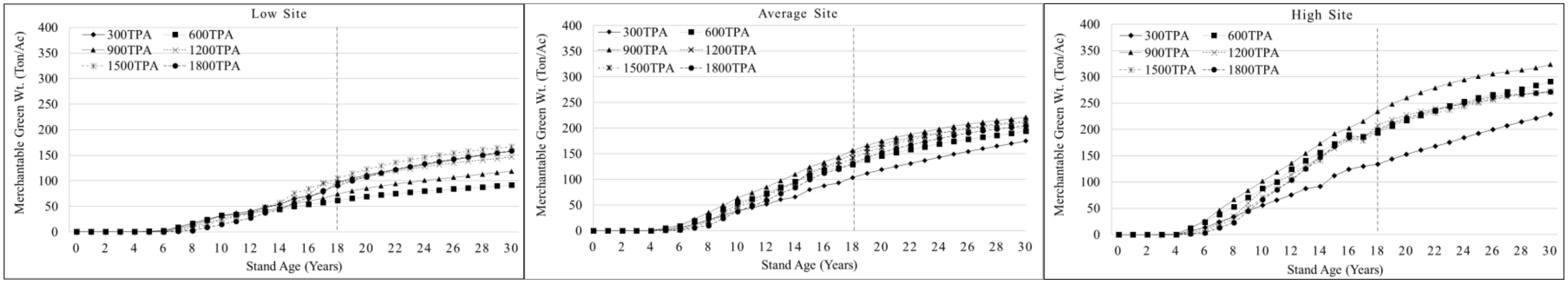


Figure 3. 2. Merchantable green weight of traditional timber product for non-thinned loblolly pine plantations on low, average, and high sites for operational culture and various planting densities.
Note: The vertical bar separates the measured data through age 18 and simulated data using SiMS after age 18.

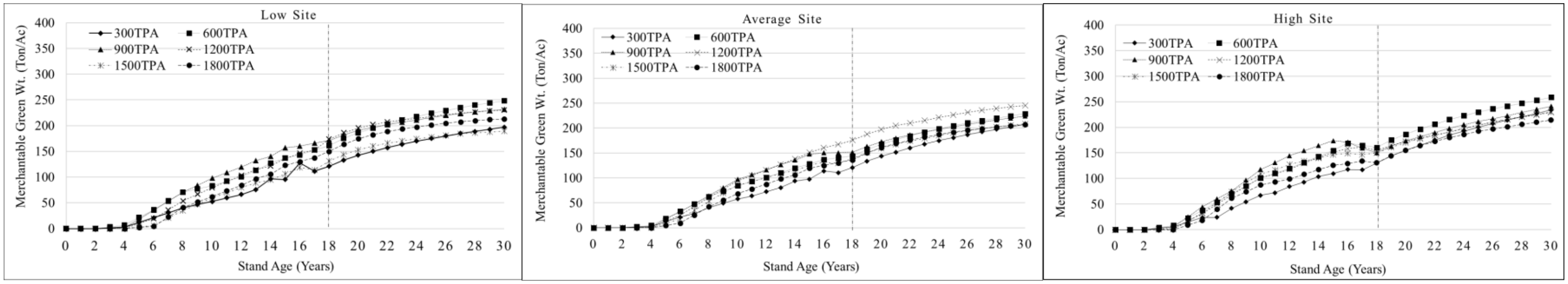

Figure 3. 3. Merchantable green weight of traditional timber products for non-thinned loblolly pine plantations on low, average, and high sites for intensive culture and various planting densities.
Note: The vertical bar separates the measured data through age 18 and simulated data using SiMS after age 18.

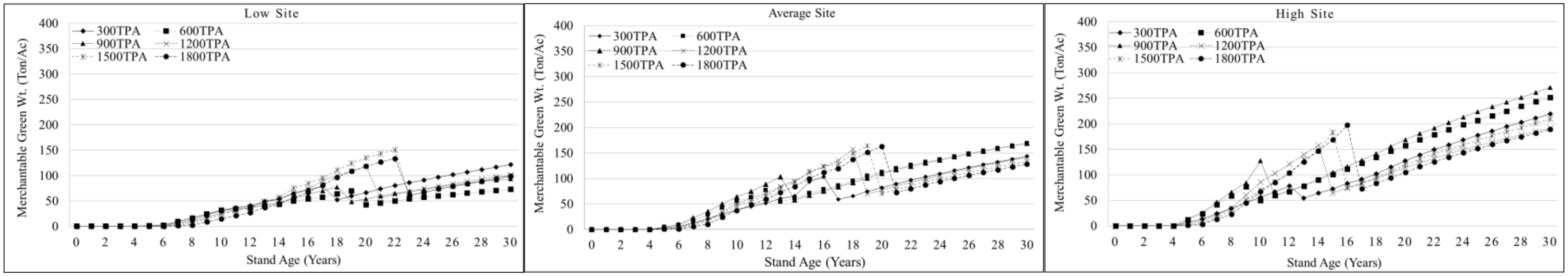


Figure 3. 4. Merchantable green weight of traditional timber product for low, average, and high site one-thin scenario for operational culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

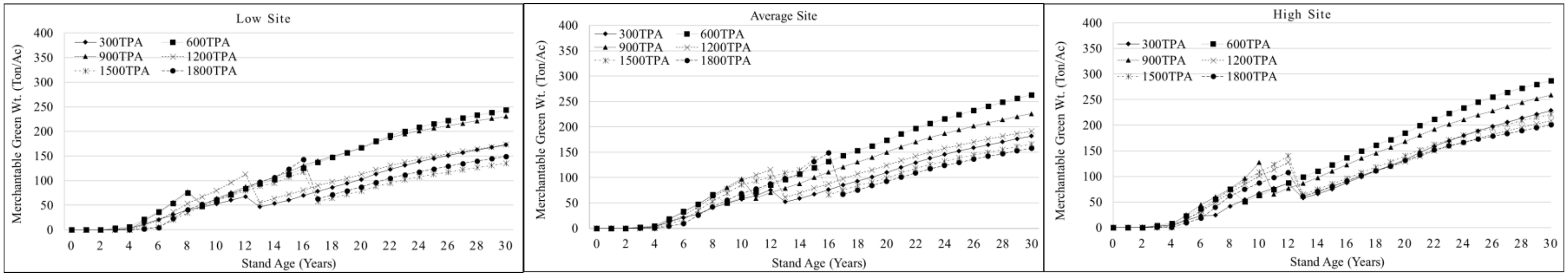


Figure 3. 5. Merchantable green weight of traditional timber product for low, average, and high site one-thin scenario for intensive culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

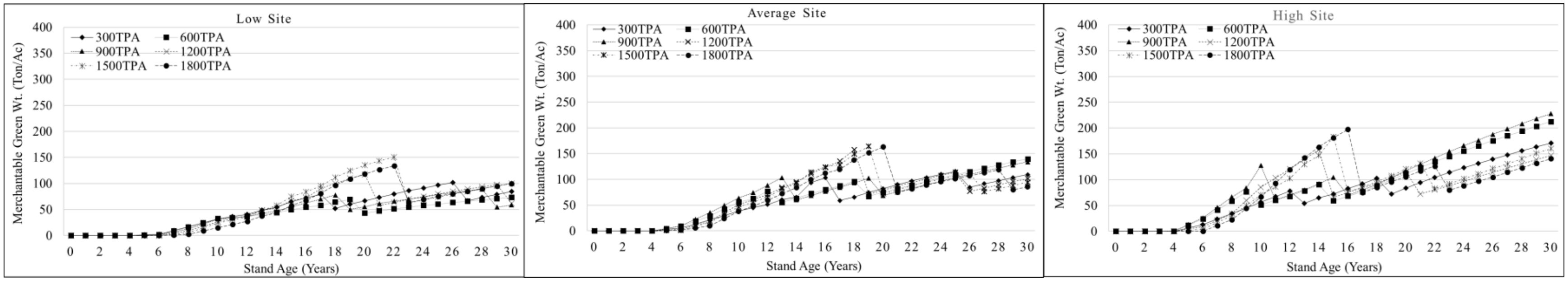


Figure 3. 6. Merchantable green weight of traditional timber product for low, average, and high site two-thin scenario for operational culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

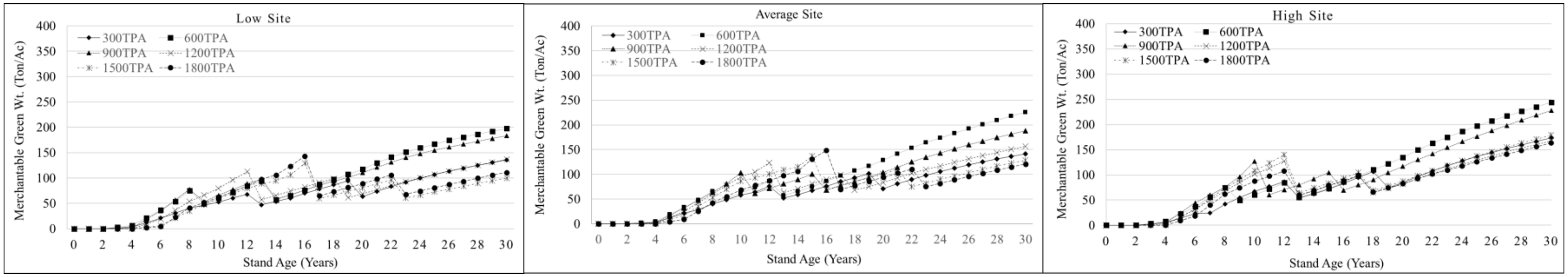

Figure 3. 7. Merchantable green weight of traditional timber product for low, average, and high site two-thin scenario for intensive culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

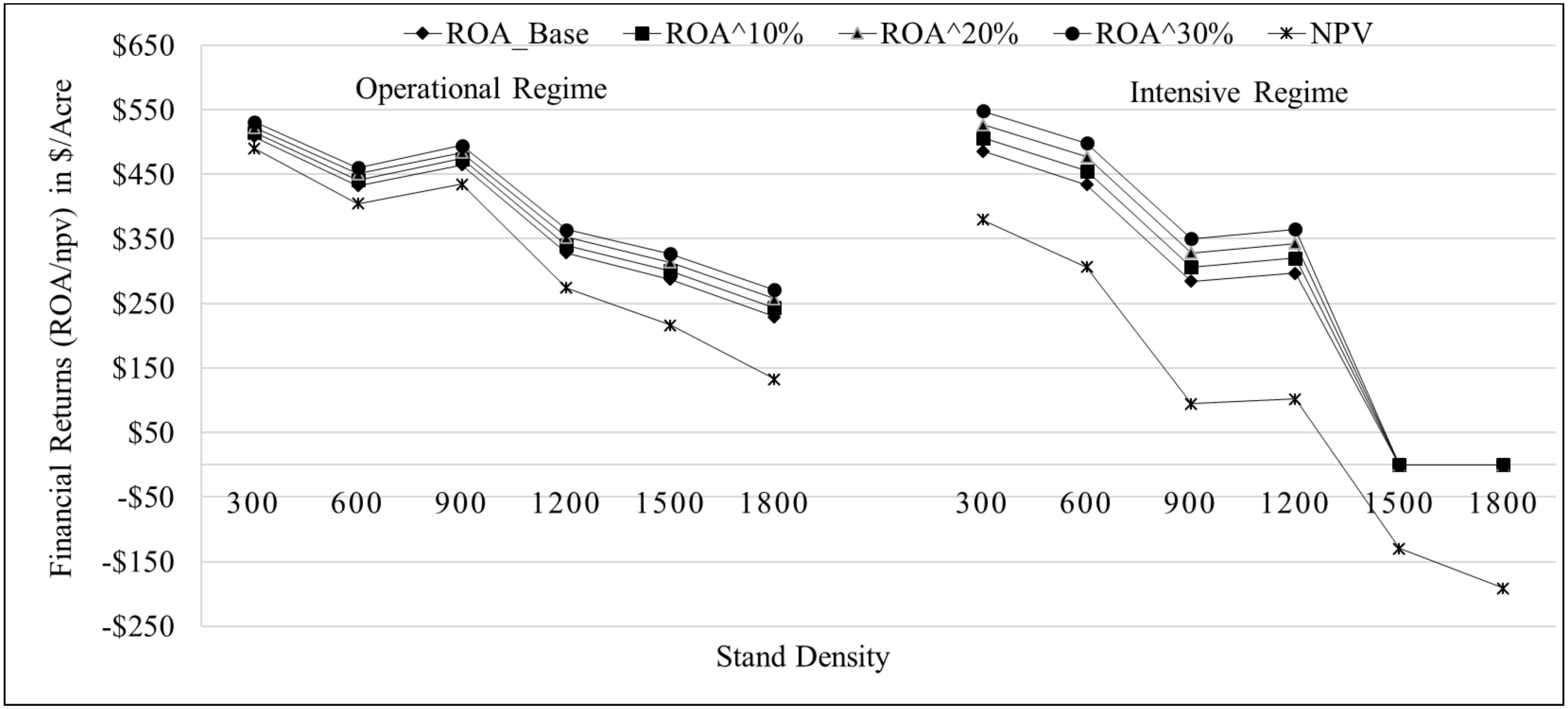


Figure 3. 8. The effect of price volatility on financial return for average stands at fixed optimal rotation age 24.
Note that ROA values of zero indicate that the call options should not be exercised.

APPENDIX 3A.1. AUGMENTED DICKEY-FULLER TEST OF TRADITIONAL TIMBER PRODUCT PRICES.
Note: Price series are quarterly from the first quarter of 1986 to fourth quarter of 2014 as reported by Timber Mart South.

1. Augmented Dickey-Fuller Test and Autocorrelation Check for White Noise of Pulp Price Time Series for the period of 1986 to 2014.

| Augmented Dickey-Fuller Unit Root Tests | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type | Lags | Rho | Pr < Rho | Tau | Pr < Tau | F | Pr > F |
| Single Mean | 0 | -2.0806 | 0.7662 | -0.82 | 0.8109 | 1.50 | 0.6878 |
| | 1 | -2.2987 | 0.7395 | -0.87 | 0.7940 | 1.55 | 0.6753 |
| | 2 | -1.0683 | 0.8780 | -0.51 | 0.8836 | 2.13 | 0.5276 |
| Trend | 0 | -12.4808 | 0.2707 | -2.43 | 0.3630 | 3.03 | 0.5722 |
| | 1 | -14.0206 | 0.2017 | -2.49 | 0.3321 | 3.16 | 0.5451 |
| | 2 | -8.4510 | 0.5344 | -1.83 | 0.6837 | 1.76 | 0.8265 |

| Autocorrelation Check for White Noise | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| To Lag | Chi-Square | DF | Pr > ChiSq | Autocorrelations | | | | | |
| 6 | 490.79 | 6 | <.0001 | 0.940 | 0.882 | 0.831 | 0.795 | 0.750 | 0.706 |
| 12 | 740.83 | 12 | <.0001 | 0.664 | 0.628 | 0.583 | 0.542 | 0.508 | 0.475 |
| 18 | 848.29 | 18 | <.0001 | 0.432 | 0.400 | 0.374 | 0.349 | 0.319 | 0.289 |
| 24 | 873.76 | 24 | <.0001 | 0.256 | 0.210 | 0.168 | 0.138 | 0.114 | 0.087 |

2. Augmented Dickey-Fuller Test and Autocorrelation Check for White Noise of CNS Price Time Series for the period of 1986 to 2014.

| Augmented Dickey-Fuller Unit Root Tests | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type | Lags | Rho | Pr < Rho | Tau | Pr < Tau | F | Pr > F |
| Single Mean | 0 | -4.0815 | 0.5237 | -1.95 | 0.3090 | 2.67 | 0.3894 |
| | 1 | -5.0309 | 0.4245 | -2.23 | 0.1959 | 3.31 | 0.2286 |
| | 2 | -4.3388 | 0.4953 | -2.18 | 0.2135 | 3.37 | 0.2117 |
| Trend | 0 | -4.0144 | 0.8822 | -1.55 | 0.8061 | 1.88 | 0.8018 |
| | 1 | -4.9628 | 0.8178 | -1.79 | 0.7019 | 2.47 | 0.6842 |
| | 2 | -3.9003 | 0.8889 | -1.62 | 0.7768 | 2.41 | 0.6970 |

| Autocorrelation Check for White Noise | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| To Lag | Chi-Square | DF | Pr > ChiSq | Autocorrelations | | | | | |
| 6 | 493.00 | 6 | <.0001 | 0.958 | 0.911 | 0.869 | 0.827 | 0.781 | 0.741 |
| 12 | 758.58 | 12 | <.0001 | 0.708 | 0.669 | 0.626 | 0.586 | 0.540 | 0.485 |
| 18 | 842.26 | 18 | <.0001 | 0.431 | 0.382 | 0.338 | 0.297 | 0.264 | 0.228 |
| 24 | 853.62 | 24 | <.0001 | 0.192 | 0.153 | 0.117 | 0.086 | 0.050 | 0.014 |

3. Augmented Dickey-Fuller Test and Autocorrelation Check for White Noise of Sawtimber Price Time Series for the period of 1986 to 2014

| Augmented Dickey-Fuller Unit Root Tests | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type | Lags | Rho | Pr < Rho | Tau | Pr < Tau | F | Pr > F |
| Single Mean | 0 | -2.5960 | 0.7027 | -1.63 | 0.4659 | 2.29 | 0.4871 |
| | 1 | -3.3084 | 0.6146 | -1.69 | 0.4326 | 2.10 | 0.5346 |
| | 2 | -3.0775 | 0.6428 | -1.78 | 0.3877 | 2.51 | 0.4315 |
| Trend | 0 | -2.4415 | 0.9561 | -0.99 | 0.9401 | 1.31 | 0.9144 |
| | 1 | -3.9885 | 0.8840 | -1.32 | 0.8779 | 1.46 | 0.8858 |
| | 2 | -2.9912 | 0.9354 | -1.13 | 0.9193 | 1.57 | 0.8632 |

| Autocorrelation Check for White Noise | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| To Lag | Chi-Square | DF | Pr > ChiSq | Autocorrelations | | | | | |
| 6 | 592.66 | 6 | <.0001 | 0.975 | 0.946 | 0.917 | 0.887 | 0.853 | 0.824 |
| 12 | 1010.77 | 12 | <.0001 | 0.801 | 0.779 | 0.754 | 0.725 | 0.695 | 0.658 |
| 18 | 1243.96 | 18 | <.0001 | 0.619 | 0.581 | 0.546 | 0.513 | 0.481 | 0.452 |
| 24 | 1344.27 | 24 | <.0001 | 0.423 | 0.391 | 0.354 | 0.317 | 0.281 | 0.248 |

Appendix 3A.2. The Geometric Brownian Motion (GBM) Performance Test.

Table 1. Pulp Actual vs Predicted Price Comparison

| S.N. | Year | Actual | Predicted from GBM simulation | Absolute Difference | | | |
|---|---|---|---|---|---|---|---|
| 1 | 2009 | 8.96 | 9.45 | 0.49 | 0.054 | | 0.237 |
| 2 | 2010 | 10.34 | 9.88 | 0.46 | 0.045 | | 0.213 |
| 3 | 2011 | 8.57 | 9.71 | 1.14 | 0.133 | | 1.295 |
| 4 | 2012 | 9.02 | 9.79 | 0.77 | 0.086 | | 0.598 |
| 5 | 2013 | 9.81 | 10.06 | 0.25 | 0.025 | | 0.061 |
| 6 | 2014 | 10.32 | 10.28 | 0.04 | 0.004 | | 0.002 |
| | | | | MAPE | 0.058 | MSE | 0.401 |
| | | | | | | RMSE | 0.633 |

Table 2. Chip-n-saw Actual vs Predicted Price Comparison

| S.N. | Year | Actual | Predicted from GBM simulation | Absolute Difference | | | |
|---|---|---|---|---|---|---|---|
| 1 | 2009 | 15.92 | 17.19 | 1.27 | 0.080 | | 1.605 |
| 2 | 2010 | 16.89 | 17.03 | 0.14 | 0.008 | | 0.020 |
| 3 | 2011 | 14.68 | 16.96 | 2.28 | 0.155 | | 5.198 |
| 4 | 2012 | 15.24 | 16.85 | 1.61 | 0.105 | | 2.581 |
| 5 | 2013 | 16.29 | 16.92 | 0.63 | 0.039 | | 0.401 |
| 6 | 2014 | 17.13 | 17.05 | 0.08 | 0.005 | | 0.006 |
| | | | | MAPE | 0.065 | MSE | 1.635 |
| | | | | | | RMSE | 1.279 |

Table 3. Sawtimber Actual vs Predicted Price Comparison

| S.N. | Year | Actual | Predicted from GBM simulation | Absolute Difference | | | |
|---|---|---|---|---|---|---|---|
| 1 | 2009 | 29.64 | 29.55 | 0.09 | 0.003 | | 0.007 |
| 2 | 2010 | 30.39 | 29.63 | 0.76 | 0.025 | | 0.576 |
| 3 | 2011 | 25.17 | 28.32 | 3.15 | 0.125 | | 9.901 |
| 4 | 2012 | 24.04 | 27.05 | 3.01 | 0.125 | | 9.068 |
| 5 | 2013 | 24.92 | 26.66 | 1.74 | 0.070 | | 3.025 |
| 6 | 2014 | 25.53 | 26.78 | 1.25 | 0.049 | | 1.564 |
| | | | | MAPE | 0.066 | MSE | 4.024 |
| | | | | | | RMSE | 2.006 |

# CHAPTER 4

# THE EFFECT OF VARYING SITE QUALITIES, PLANTING DENSITIES, CULTURAL INTENSITIES, AND THINNING ON TIMBER YIELD AND ECONOMIC RETURN FROM AN INTEGRATED PRODUCTS MIX AND BIOENERGY FEEDSTOCK USING TRADITIONAL DISCOUNTED CASH FLOW AND REAL OPTIONS APPROACHES[3]

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ABSTRACT

This research examined timber yields and financial returns from loblolly pine plantations managed for an integrated product mix or bioenergy feedstock only for combinations of site class, cultural regime, and density management (planting density and thinning) for three sites (case studies) in the Lower Coastal Plain of Florida and Georgia. Financial returns were determined using Black-Scholes model under the real options analysis approach (ROA) and the traditional discounted cash flow approach of net present value (NPV). Conclusions regarding best management regimes for the integrated product mix were the same using ROA and NPV; however, ROA returns were greater than NPV returns because ROA captured the value associated with price volatility for the different products. The price volatility was especially high for bioenergy feedstock. Planting densities of 600 or 900 TPA generally resulted in greatest financial returns. Financial returns were greater with thinning, either one-thin or two-thin, than without thinning. With thinning, intensive culture increased returns on the low and average but not the high site class. For low and average sites, the optimum regime was 600 to 900 TPA planting density, intensive culture and two thinnings. The optimum plantation regime on the high sites was planting 600 to 900 TPA under operational culture with two thinnings. Financial returns for integrated forest products were greater than those previously reported for traditional timber product due to the addition of bioenergy feedstock income. This increase in financial returns was greater for ROA than NPV due to the relatively high volatility in bioenergy feedstock prices. Financial returns for the integrated products mix regimes were generally less than for bioenergy feedstock dedicated regimes but the feedstock dedicated regime returns reflected unusually high historical prices.

## 4.1 Introduction

Historically, the major driving force of loblolly pine management in the U.S. South has been attractive sawtimber and pulpwood markets. Management regimes have varied over time due to factors such as timber product prices, regeneration costs (Henderson and Munn, 2012), and government policies. Concerns related to global climate change are driving limits on carbon emissions globally and this concern has led governments to consider policies on carbon emissions, biofuels, and energy supplies. The fossil fuel price volatility in recent years has had a considerable effect on energy security. As a result, legislative and executive actions have occurred at the federal and state levels in support and promotion of the use of biomass energy in the U.S. and in the European Union (Perlack and Stokes 2011). The use of forest biomass and carbon sequestration from forests and feedstock supply from forests and agricultural products are potential mitigation options addressing climate change and energy security. The mandate of replacing 30% of current U.S. petroleum consumption with biofuels by 2030 requires the forestry sector to supply approximately 1 billion dry tons of biomass feedstock per year (Perlack and Stokes, 2011). Lower value stems and residuals from thinning and final harvest from loblolly pine plantations can supply bioenergy markets and provide income opportunities to growers.

Past studies (Hagler, 1996; Binkley, 1997) show relatively low production of average total biomass productivity from natural and planted pine in the southern U.S. Many recent studies (Borders and Bailey, 2001; Yin and Sedjo, 2001; Allen et al., 2005, Fox et al. 2007) demonstrate with intensive cultural practices plantation loblolly pine can grow at high rates within its native range as well as in exotic locations. Intensive cultural practices such as chemical site preparation, periodic fertilization and herbicide applications have helped to double mean annual increment and reduce rotation length by more than 50 percent (Fox et al., 2004). Intensively cultured and genetically improved loblolly pine established in the 1990s produced greater than 400 cubic feet per acre per year which is 4.5 times greater wood volume than from plantations established in the 1960s (Borders and Bailey, 2001; Fox et al., 2004). These productivity gains increase the potential for economic returns from traditional timber products such as pulpwood, chip-n-saw, and sawtimber. The biomass gain in trees in relatively shorter periods is not only financially beneficial when considering traditional timber commodities, but also has implications for the developing markets in bioenergy feedstock.

Biological growth and yield effects of site, planting density, and cultural intensity have been the subject of various reports (Sharma et al., 2002; Carlson et al., 2009; Zhao et al., 2011). The effects of these factors on financial returns have been reported but to a lesser degree. Effects on financial returns have been reported for planting density (Bailey, 1986; Hotvedt and Straka, 1987; Borders et al., 1991; Caulfield, et al., 1992), site index increment or genetic improvement (Huang and Kronard, 2002; McKeand et al., 2006), intensive fertilization application (Borders and Bailey, 2001; Allen et al., 2005; Fox et al., 2007), and thinning (Hotvedt and Straka, 1987; Baldwin and Busby, 1993; Huang and Kronard, 2002). There are few reports (Munsell and Fox, 2010) on the economics for integrated cultural regimes including combinations with varying planting densities, culture levels, and thinning regimes across a range of site productivity classes.

The traditional discounted cash flow approach such as net present value (NPV) has been criticized for being too simple or failing to capture values from managerial flexibility and price uncertainties (Zinkhan, 1995; Thorsen, 1999). Real options analysis (ROA) is an augmentation of static NPV that provides a reliable approximation of future values considering price uncertainties and managerial flexibility (Olafsson, 2003; Chaudhari et al., 2016). There is a need to evaluate economic returns from a diverse array of loblolly pine plantation scenarios using ROA as well as NPV given the possible influence of stumpage price variability due to new market opportunities. ROA is relatively new and little used by forest planners in the US South and an investigation of its potential value is warranted given that future timber price uncertainty is an issue facing forest investors. Given that forest stand decisions are affected by timber price uncertainty, new market opportunities (e.g. bioenergy feedstocks), and managerial decisions, an examination of alternative financial tools that value these factors is warranted.

A comparison of these valuation methods was reported in Chapter 3 for loblolly pine plantations for an array of site classes and management regimes and a traditional timber product mix. A similar evaluation is needed for plantation regimes for integrated product mixes that include traditional products and bioenergy feedstock or a single product of bioenergy feedstock.

The case studies reported in Chapter 3 on loblolly pine plantation performance for an array of site productivity, plantation density management, and cultural intensities in the Lower Coastal Plain, provides an opportunity to evaluate financial returns from an integrated product mix and a single product of bioenergy feedstock using NPV and ROA approaches. This research reported here addresses the following objectives:

1. Quantify loblolly pine stand yield for integrated forest products (traditional products and bioenergy feedstock) and bioenergy feedstock alone for silvicultural regimes differing in planting density, cultural intensity and thinning for a range of site indices in the Lower Coastal Plain.
2. Determine financial return for different plantation regimes for integrated timber products and for a dedicated bioenergy feedstock regime using NPV and ROA valuation approaches.
3. Identify optimum silvicultural regimes for different product regimes and site classes using NPV and ROA approaches.
4. Evaluate relative advantages of NPV and ROA approaches.

### 4.2 Methods

Methods generally followed those detailed by Chaudhari in Chapter 3. Methods specific to this chapter are described below. The methods specific to this chapter are related to the addition of bioenergy feedstock to the product mix and the evaluation of regimes for plantations dedicated to producing bioenergy feedstock.

The treatments for operational and intensive culture regimes through age 18 are presented in Table 3.3 of Chapter 3. Fertilizer application frequency and rate were major differences between operational and intensive culture regimes. Fertilization for the integrated timber products mix was the same as for the traditional timber products mix as reported in Table 3.3. The fertilization schedules for the dedicated bioenergy feedstock regime were similar to those for the traditional timber product mix with the exception that the last fertilization occurred at age seven for operational culture and at age nine for intensive culture.

*Mensurational Evaluation*

Green Weight Estimation

The stem green weight with bark was calculated for the entire stem and by product class (Table 4.1) using equations by Pienaar et al. (1987). The integrated timber product mix included stem weight of traditional timber products plus the remaining part of the stem as bioenergy feedstock to a 0.1-inch diameter tip. Total stem weight to a 0.1-inch diameter tip was calculated for the bioenergy feedstock dedicated plantation case. Equations 1 through 4 are same as reported by Chaudhari in Chapter 3.

$$GW_{TS} = 0.0740959 * DBH^{1.829983} * HT^{1.247669} \quad [1]$$

$$GW_{Pulp} = 0.0740959\, DBH^{1.829983} HT^{1.247669} - 0.123329 \left[\frac{D_3{}^{3.523107}}{DBH^{1.449947}}\right](HT - 4.5) \quad [2]$$

$$GW_{CNS} = 0.0740959\, DBH^{1.829983} HT^{1.247669} - 0.123329 \left[\frac{D_6{}^{3.523107}}{DBH^{1.449947}}\right](HT - 4.5) \quad [3]$$

$$GW_{Saw} = 0.0740959\, DBH^{1.829983} HT^{1.247669} - 0.123329 \left[\frac{D_8{}^{3.523107}}{DBH^{1.449947}}\right](HT - 4.5) \quad [4]$$

$GW_{Bioenergy} =$ $GW_{TS}$ - $GW_{Pulp}$ or $GW_{TS}$ - $GW_{CNS}$ or $GW_{TS}$ - $GW_{Saw}$ [5]

Where, $GW_{TS}$ is green weight (lbs) of a solid bole with bark measured from base to the nearest 0.1-inch tip. $GW_{Pulp}$ is the green weight of pulpwood with $D_3$ being the top merchantable diameter limit of 3 inch; $GW_{CNS}$ is the green weight of chip-n-saw with $D_6$ being the top merchantable diameter limit of 6 inch; $GW_{Saw}$ is the green weight of sawtimber with $D_8$ being the top merchantable diameter limit of 8 inch. $GW_{Bioenergy}$ is the green weight of the upper stems not used for pulpwood, chip-n-saw and sawtimber in integrated product regimes. Total stem green weight ($GW_{TS}$) is the green weight available for a bioenergy regime. Per acre values were calculated by summing individual tree values for a plot and adjusting by the expansion factor.

Mean Annual Increment (MAI) was calculated at the standing total stem green weight divided by the stand age.

Growth and Yield Simulation

Growth and yield simulations were conducted using Simulator for Managed Stands (SiMS) 2009, (ForesTech International, 2009) as described by Chaudhari in Chapter 3. Four scenarios were analyzed including 1) no-thin bioenergy feedstock with no growth projections and three scenarios using growth projections, namely, 2) No-thin integrated, 3) one-thin integrated, and 4) two-thin integrated.

*Financial Evaluation*

Financial evaluations of the four scenarios were conducted using historical timber prices of each product class and ROA and NPV valuation approaches. Financial evaluations were based on real price, real risk-free interest rate of 5%, and presented as pre-tax dollars. Annual administration cost was assumed to be offset by annual hunting revenue. Costs and timing of planting densities and treatment components for operational and intensive culture regimes with no-thin and thinning scenarios are presented in Chapter 3.

Price Model

Historical prices of traditional timber products (first quarter 1986 to the fourth quarter 2014) and bioenergy feedstock (first quarter of 1996 to the fourth quarter 2014) prices were obtained from Timber Mart-South (TMS) (Norris Foundation, 2014). The TMS definition of "in-woods whole tree chips pine" that includes fuel quality chips generally from tops, limbs, and smaller bole was considered equivalent to bioenergy feedstock for the purpose of this study. The bioenergy feedstock price was reported as freight on board (FOB) mill price. Bioenergy feedstock stumpage price was calculated by deducting the average cost of felling, loading, and hauling from the TMS in-woods whole tree chips price using the Auburn Harvest Analyzer (Tufts et al. 1985). Nominal prices were converted to real prices using the consumer price index (CPI) with a base year of 2014 (age 18 in this study). The geometric Brownian motion (GBM) was used to forecast expected prices beyond 2014.

The unit-root tests of stationarity (or non-stationarity) were performed on historical price series of traditional timber products as well as bioenergy feedstock prices in SAS 9.4 using the Augmented Dickey-Fuller (ADF) test. The tests showed all product prices followed a non-stationary random walk with drift as the null hypothesis of non-stationarity were accepted for all product price series. The ADF test results for traditional timber products and bioenergy feedstocks are reported by Chaudhari in Chapter 3 and Appendix 4A.1, respectively. The p-values at 5% significance level were not rejected for a single mean (i.e., null hypothesis of non-stationarity being accepted) for all product prices (i.e., pulp, chip-n-saw, sawtimber, and bioenergy feedstock). The check on autocorrelation of white noise showed the rejection of the null hypothesis, meaning the data was a non-stationarity time series for all product prices. Furthermore, the autocorrelation function (ACF) trend for all product prices decreased slowly and gradually which is further evidence of the time series being non-stationary. That is the case for all product prices.

The forecast of future prices using the GBM price model was done following procedures described by Chaudhari in in Chapter 3. The parameter estimation for the bioenergy feedstock price series was conducted in the same fashion as for the traditional timber products. The parameters, drift (α) and volatility (σ), are presented in Table 4.2. The root mean squared error (RMSE) was used to test absolute measure of fit and is given in Table 4.2.

Real Options Analysis Technique

The Black-Scholes model (Black and Scholes, 1973) was employed as described by Chaudhari in Chapter 3 to calculate the net expected present value of a stand for integrated timber product and dedicated bioenergy regimes using the real options analysis technique. A forest land owner's perspective was used to calculate such values. The value of the stand was regarded as a value of a call option where the owner of the stand has the right to buy an asset by paying the cost of site preparation, planting, fertilization, competition control and some administrative cost.

*Discounted Cash Flow Technique*

The NPV for a stand for integrated timber products and bioenergy regimes was calculated as described by Chaudhari in Chapter 3.

Financial Evaluation of Unequal Rotation Age

One of the objectives of this study was to determine the optimal rotation age of stands of varying planting density, intensity and thinning regimes. Optimum rotation age was determined as the age of maximum ROA and NPV stand value for both the integrated timber product mix and the dedicated bioenergy only regimes. However, ROA or NPV values for different rotation length (i.e., mutually exclusive projects with unequal lives), particularly for the integrated timber product regime and the dedicated bioenergy regime only, cannot be compared. An equivalent annual annuity (EAA) was calculated to standardize optimal rotation ROA or NPV values for comparison purposes. The EAA produces the net present value as a series of equal cash flow for the length of the investment and is presented on a per year basis (Klemperer, 1996) (Equations 6 and 7). The EAA for ROA and NPV was calculated as below:

$$EAA_{ROA} = \frac{r * V_{ROA}}{1 - Exp^{(-rT)}} \quad [6]$$

$$EAA_{NPV} = \frac{r * NPV}{1 - Exp^{(-rT)}} \quad [7]$$

A break-even price analysis or the minimum bioenergy price for a positive return was performed using the NPV approach. The break-even price analysis was carried out using the same financial criteria used for the NPV approach described above.

## 4.3 Results

*Growth and Yield*

Non-Thinned Scenarios (Integrated Product and Bioenergy Dedicated)

Tree size and stand attributes at age 18 by site class, cultural intensity and planting density are presented in Table 4.3. Result detail for these attributes with the exception of total stem MAI were reported by Chaudhari in Chapter 3.

Age 18 weight MAI tended to be greatest on the high site with operational culture (9.3 to 14.7 tons/ac/yr) and least on the low site with operational culture (3.8 to 7.5 tons/ac/yr) (Table 4.3). The impact of intensive culture varied with site; it increased MAI on the low site, had a mixed impact on the average site, and resulted in lower MAI on the high site. The maximum weight MAI occurred in the 600 to 1500 TPA range depending on site class and cultural regime. For the operational regime, maximum MAIs on the low (7.5 tons/ac), average (9.8 tons/ac), and high (14.7 tons/ac) sites were observed on the 1500, 900, and 900 planting densities, respectively. For the intensive regime, maximum MAIs on the low (10.9 tons/ac), average (10.8 tons/ac), and high (10.2 tons/ac) sites were observed on the 600, 1200, and 600 planting densities, respectively. On the low site, intensive culture resulted in especially large MAI increases for the 600, 900, and 1200 TPA planting densities.

Total stem green weight per acre measured through age 18 and simulated after age 18 to age 30, varied markedly by site class and planting density for operational culture (Figure 4.1) and intensive culture (Figure 4.2) stands. The simulation of stand growth for each site class, density level, and cultural regime produced satisfactory growth and yield trajectories consistent with growth trajectories of each density level observed through age 18. Several yield trajectories exhibited reductions during the age 15 to age 18 interval associated with natural mortality due to intraspecific competition (Figure 4.2).

For operational culture stands, observed green weight yields increased with better site classes through age 18 (Figure 4.1). The high site stands had markedly greater total stem green weight than the average and low site classes before and after age 18 across the density range. For the average site class, the 900 TPA followed by 1200 TPA densities yielded the greatest total stem green weight. For the low site class, green weight yield was greatest for stands with 1200 to 1800 TPA densities.

The total stem green weight trajectories for intensive culture stands (Figure 4.2) were similar to those for operational stands (Figure 4.1) for the average site but differed markedly from those of operational culture stands for low and high site classes. The yield trajectories on the low site increased much more rapidly with intensive than operational culture across planting densities. The high site stands were impacted negatively by intensive culture at high planting densities due to greater mortality due to fast growth and overstocking.

The yield trajectories for intensive culture stands show that greatest total stem green weight at age 18 on low and high sites occurred with the 600 TPA density, which was closely followed by the 900 TPA density. For the average site, the highest yield was observed for 1200 TPA due to exceptional yield on the medium site. A similar yield trajectory for 1200 TPA was reported as the average performance for a larger set of PMRC Coastal Plain Culture Density Study sites by Zhao et al. (2014).

Thinned Scenarios

### One -Thin Scenario

Simulated first thinning ages for the integrated timber products regime were the same as reported for the traditional products regime (Chapter 3 Table 3.9). General trends are reported here. First thinning ages ranged from 8 to 22 years. Stands on the high site or with intensive culture in combination with 600 to 900 TPA planting densities tended to have suitable attributes for first thinning at younger ages. In contrast, stands on the low or average sites without intensive culture or with planting densities >1200 tended the meet thinning criteria at later ages.

Total stem green weight yields by site class and planting densities with the one-thin scenario for the operational and intensive culture regimes are presented in Figure 4.3 and Figure 4.4, respectively. In general, the post-thinning projections showed the 600 and 900 TPA densities consistently producing the greatest total stemwood weight. Projected yields were intermediate for 300 and 1200 TPA densities and lower for 1500 and 1800 TPA densities. The low site, operational culture, 600 TPA density combination produced low total green stemwood yield before and after thinning.

### Two-Thin Scenario

Second thinning ages for the integrated product regime were the same as those reported for the traditional timber product regime (Table 3.9 Chapter 3). General trends are reported here. The second thinning ages differed markedly among the sites, planting densities, and cultural regime combinations. Stands that received intensive culture met the second thinning criteria as early as 12 or 13 (low, average, high sites - intensive regime, 600 TPA) and as late as age 21 or 22 (1500 and 1800 TPA density - low and average sites). Stands that received operational culture met second thinning criteria later than the intensive culture counterpart. The earliest simulated second thinning for operational culture occurred at age 14 or 15 (600 and 900 TPA density – high site) and the latest occurred at age 32 (600 TPA density -low site). Second thinning age differences between operational and intensive culture were greatest on the low site and smallest on the high site.

Growth trajectories and projections of yield for two-thin scenarios through age 30 for operational and intensive culture regimes are shown in Figure 4.5 and 4.6, respectively. Generally, the 600 TPA density had the greatest projected total stem green weight, followed closely by the 900 TPA density. The 300 TPA density had lower projected total stem green weight yield.

*Financial Evaluation*

No Thinning Scenarios -Integrated Timber Products

Financial returns for the no-thinning scenarios are summarized for operational and intensive culture regimes in Tables 4.4 and Table 4.5, respectively. Trends in results for the integrated timber products regime are very similar to those reported for traditional timber products without bioenergy (Chapter 3). The addition of the feedstock product resulted in increased financial returns compared with the traditional product regime. The feedstock addition affected the optimal rotation ages in several cases.

Optimum rotation age ranged from 22 to 26 years and averaged 24 years. Optimum rotation age varied slightly with planting densities, site classes and cultural regimes. For the specified planting densities, optimum rotation ages were slightly greater for the operational than for the intensive regime, particularly on the low site.

For the low site, financial return differed among planting densities and cultural regimes. Returns were modest or negative for operational culture with the exception of the 300 TPA density ($556 ROA and $402 NPV). The intensive culture regime produced positive returns for densities from 300 through

1200 TPA with maximum return ($899 ROA and $517 NPV) for the 600 TPA density. Financial returns expressed as EAA followed a similar trend.

For the average site, the highest returns ($652 ROA and $508 NPV) for the operational culture regime were observed for the 300 TPA density followed by intermediate returns for the 900 and 600 TPA densities respectively, and lower returns for the 1200 to 1800 TPA densities. The EAA values followed similar trends. The intensive culture regime had a similar result with the 300 TPA density producing the highest returns ($782 ROA and $401 NPV), followed by the 600, 1200, and 900 TPA densities, respectively. The 1500 and 1800 TPA densities did not produced positive returns ($0 ROA and -$104 NPV for 1500 TPA; $0 ROA and -$176 NPV for 1800 TPA).

On the high site, there were differences in financial returns between cultural regimes and among densities. The operational regime yielded greater financial return than the intensive culture regime. The greatest financial return with operational culture ($1,186 ROA and $1052 NPV) occurred for the 900 TPA density while that for intensive culture ($955 ROA and $601 NPV) occurred with the 300 TPA density. There was a trend of decreasing return from 300 through 1800 TPA density for intensive culture. For the operational regime, economic return increased from 300 to 900 TPA and then decreased with greater density.

The two extreme cases of low and high site showed marked differences in financial return with cultural regime. On the low site, the operational culture regime did not produce substantial positive returns for most densities while the intensive culture regime produced positive financial return across densities. In contrast, the operational regime produced greater financial return than the intensive regime on the high site.

No Thinning Scenarios -Dedicated Bioenergy

Age 11 was the optimal rotation age for the dedicated bioenergy feedstock case (Table 4.4 and Table 4.5). The optimum rotation age determination was strongly influenced by the very high real prices observed during the 2007 to 2009 period.

The ROA and NPV for bioenergy were positive for all site classes, densities, and cultural regimes (Table 4.4 and Table 4.5). There were considerable differences in ROA and NPV values among site, culture, and density combinations. The higher returns tended to be with higher densities, better sites, and intensive culture. The 300 TPA density produced the lowest returns for all site and culture combinations except on the low site with operational culture.

For the low site class, the highest return ($960 ROA and $536 NPV equivalent of $113 $EAA_{ROA}$ and $63 $EAA_{NPV}$) was observed for the intensive culture and 900 TPA density combination while the highest return ($508 ROA and $229 NPV equivalent of $60 $EAA_{ROA}$ and $27 $EAA_{NPV}$) for the operational culture occurred at the1500 TPA density. The highest to lowest return trends with planting density were 1500>1200>1800>900>300>600 for the operational regime and 900>1800>1200>600>1500>300 for the intensive regime.

For the average site, the highest return ($971 ROA and $523 NPV equivalent of $115 $EAA_{ROA}$ and 62 $EAA_{NPV}$) was observed for the intensive culture and 1200 TPA combination. The highest return ($755 ROA and $497 NPV equivalent of $89 $EAA_{ROA}$ and $59 $EAA_{NPV}$) from the operational culture was observed at 1500 TPA density. The highest to lowest return trends for planting density was 1500>900>1800>1200>600>300 for the operational regime and 1200>900>1500>1800>600>300 for the intensive regime.

For the high site, the ROA return tended to be higher for intensive than operational culture while the NPV return was consistently less for intensive than operational culture.  Highest return for operational culture ($1,101 ROA and $909 NPV equivalent of $130 $EAA_{ROA}$ and $107 $EAA_{NPV}$) and intensive regime

(\$1,154 ROA and \$745 NPV equivalent of \$136 $EAA_{ROA}$ and \$88 $EAA_{NPV}$) occurred with the 900 TPA density. The highest to lowest NPV return trends for planting density were 900>1500>1800>1200>600>300 for the operational regime and 900>1500>1200>600>1800>300 for the intensive regime.

Thinning Scenarios

Financial returns for one-thin and two-thin scenarios for the integrated timber product mix are summarized for operational and intensive culture regimes in Tables 4.6 and 4.7, respectively. Financial returns for the integrated timber products followed similar trends as reported for traditional timber products (Chapter 3). Returns for the integrated products regime are greater than for the traditional products regime because of additional revenues from bioenergy feedstock and, in the case of the ROA metric, value generated through increased price volatility.

The high site class generally had higher ROA and NPV compared to the low site class. Optimal rotation ages for the one-thin scenario were generally shorter than for the two-thin scenario, except in a few cases with the intensive culture regime where rotation ages were the same. The optimal rotation age generally increased from low to high planting density, a trend more evident for operational than intensive culture.

For the low site, optimum rotation age ranged from 22 years for the 600 and 900 TPA, intensive culture, one-thin scenario to 38 years for the 1200 to 1800 TPA, operational culture, two-thin scenario.

Low site financial returns were greater for the two-thin than one-thin scenario for each planting density and cultural regime combination and were generally greater with intensive than operational culture. Greater returns with operational culture occurred at higher densities and the 300 TPA density, while returns with intensive culture were greater at lower densities. The highest return (\$1,336 ROA and \$834 NPV equivalent of \$96 $EAA_{ROA}$ and \$60 $EAA_{NPV}$) resulted from the 900 TPA density, intensive culture, two-thin scenario. The greatest one-thin scenario returns ($1208 ROA and $953 NPV equivalent of $91 $EAA_{ROA}$ and $71 $EAA_{NPV}$) resulted from the 600 TPA density, intensive culture combination. The financial return trends (highest to lowest) for the intensive culture regime were 900> 600> 300> 1200> 1800>1500 TPA densities, for the two-thin scenario and 600>900>300>1200>1800>1500 TPA densities for the one-thin scenario. The general financial return trend (highest to lowest) for the low site with operational culture was 300>1500>1800>1200>900>600 TPA densities.

The rotation ages for the average site for the one-thin scenario ranged from 24 to 29 years with lower density favoring shorter rotation and higher density favoring longer rotation. For the two-thin scenario, the optimal rotation age with operational culture ranged from 29 years for the 300 and 600 TPA densities to 39 years for the 1800 TPA density. The optimal rotation ages of stands with intensive culture regime were much shorter ranging from 24 to 30 years. The shorter optimum rotation ages with intensive as compared with operational culture were particularly large and consistent for two thinning scenarios.

For the average site, financial returns were greater for the two-thin than the one-thin scenario for all density levels. The highest financial return ($1,295 ROA and $1,028 NPV an equivalent of $93 $EAA_{ROA}$ and $74 $EAA_{NPV}$) occurred with the 600 TPA density, intensive culture, two-thin scenario. Financial returns for a given planting density were greater for intensive than operational culture. Returns for the one-thin and two-thin scenarios generally show a decreasing trend with density beyond 900 TPA for the operational culture and 600 TPA for intensive culture. With intensive culture, the density levels of 1500 and 1800 TPA had markedly lower financial returns and longer rotation ages than lower densities. EAA values showed similar trends as ROA and NPV values.

High site returns were greater for the two-thin than one-thin scenario for all planting density levels but the 300 and 900 TPA density on both operational and intensive culture regime. The optimum rotation ages ranged from 24 to 33 years. Optimum rotation ages were slightly shorter for intensive culture regime, particularly at higher densities. The range in optimum rotation age among densities was less for the intensive than operational culture regime. The financial returns for high site stands for both operational and intensive culture regimes were generally higher than those for the average or the low sites. Returns for the operational culture regime were consistently higher than for the intensive regime. The general trends of financial return (highest to lowest) for the one- and two-thin scenarios were 900, 600, 300 followed by 1200 through 1800 TPA densities for the operational regime and 600, 900, 300, 1500, 1200, and 1800 TPA densities for the intensive regime.

No Thinning and Thinning Financial Return Comparison

Financial returns expressed as $EAA_{ROA}$ for no-thin, one-thin, two-thin, and bioenergy scenarios for site classes, cultural regimes, and planting densities are presented in Table 4.8. The bioenergy regime consistently produced greatest return for all density levels except the 300 TPA density.

When considering regimes for the integrated products mix, financial returns were generally greater with thinning than without thinning for all site classes, cultural regimes and planting densities combinations. The two-thin scenarios often resulted in greater economic return than the one-thin scenario. However, the one-thin scenario had greater return for the 300 TPA density, intensive regime combination on average and high site classes. The highest returns (> \$90 $EAA_{ROA}$) were observed in thinned stands with one of the following conditions: high site with 300, 600, and 900 TPA densities and operational culture; high site with 600 and 900 TPA density and intensive culture; and low site with 600 TPA density and intensive culture. The lowest returns (\$0 $EAA_{ROA}$) tended to be no thinning regimes either on the low site with operational culture or with 1500 or 1800 planting densities and intensive culture.

Bioenergy Feedstock Break-Even Price

The break-even price for bioenergy feedstock needed so that bioenergy dedicated stands provide a 5% return ranged from \$5 to \$16 depending on site class, planting density and cultural intensity (Table 4.9).

The break-even price tended to be lowest for the high site with operational culture and highest for the low site with operational culture. Break-even price generally decreased as site class improved and was generally less for operational than intensive culture. There were no clear trends in break-even price with planting density.

**4.4 Discussion**

This study provides a unique opportunity to quantify timber yields, determine financial returns, identify optimum silvicultural regimes, and evaluate relative advantages of NPV and ROA approaches for loblolly pine plantations managed for integrated timber products or bioenergy feedstock. The results reported here complemented those for loblolly pine stands managed for traditional timber products reported in Chapter 3. Three sites were used as case studies to illustrate general trends that may broadly describe biological yields and economic return patterns in the larger population of loblolly pine plantations in the Lower Coastal Plain. Results on a particular site or across a large number of sites may vary from those from the current study.

*Growth and Yield*

Total stem green weight yields and yield trends with site, cultural regime, planting density, and thinning scenario were reasonable and consistent with reports based on the full set of installations of this study (Zhao et al. 2011, Zhao et al. 2014). The total stem green weight yields and age 18 MAI were, as expected, slightly greater than those for merchantable stem green weight yield reported in Chapter 3. This is because total stem green weight included weight of the upper portion of the stem (bioenergy feedstock) not included for the merchantable stem green weight. The age 18 total stem weight MAI values were not necessarily maximum MAI values. Higher densities had greater MAI around age 14 and lower densities had greater MAI around age 18 to 20.

Planting density had a strong influence on yield across site classes while intensive culture impacts varied with site class. The 600, 900, and 1200 trees per acre were the optimal densities from total yield perspective, except for the low site operational regime where higher densities had greater MAI.

The positive impact of intensive culture was apparent on low and average sites, but not on the high site. The largest yield gains due to intensive culture occurred on the low site and the smallest occurred on the high site. This inverse relationship between site quality and magnitude of response to silvicultural treatments was also reported for loblolly pine by Zhao et al. (2016). On the high site, operational culture yielded greater total stem weight than intensive culture at each density level at age 18. This resulted in part from greater density dependent mortality in intensive culture stands.

Recent studies (Borders and Bailey, 2001; Allen et al., 2005; 2007; Munsell and Fox, 2010) show that a growth rate higher than 10 tons/ac/yr in loblolly pine plantations is biologically possible and may be financially attractive. The present study found a growth rate exceeding 12 ton/ac/yr at age 18 on the high site with operational culture on all but the 300 TPA density. The average site with intensive or operational culture produced greater than 9 ton/ac/yr on average for 900 and 1200 TPA densities. Intensive culture on the low site resulted in MAI greater than 10 ton/ac/yr for the 600, 900, and 1200 TPA densities.

Lower planting densities generally met the thinning criteria sooner than higher densities. The QMD on higher densities were smaller and it took longer for these densities to surpass the 6-inch QMD minimum criteria even though average dominant height and BA thinning criteria were met. Thinning ages were similar to those reported by Huang and Kronard (2002), (Sword-Sayer et al., 2004), and (Hennessey et al., 2004).

The simulated thinnings resulted in increased QMD especially with intensive culture. Average increases in QMD due to the intensive culture and thinning combination were substantial. This study found the increase in QMD with thinned scenarios especially significant for economic return as it increased product value by shifting the product class from pulpwood to chip-n-saw and from chip-n-saw to sawtimber, similar to findings by Sword-Sayer et al. (2004).

*Financial Return*

Financial returns were slightly higher from integrated timber products than values from traditional timber products reported in Chapter 3 due to additional revenue from bioenergy feedstock for the integrated timber product regime. Improvements in return due to the additional bioenergy feedstock revenue were greater for the ROA than NPV valuation because ROA captured the considerable value from the volatility in bioenergy feedstock price. The greater return for ROA was also realized in higher densities which is mostly occupied by pulpwood and chip-n-saw sized trees that had greater volatility. The addition of bioenergy feedstock to the product mix did not change the optimal rotation ages drastically but resulted in an increase in rotation age in several cases.

The financial returns indicate optimal rotation ages were sensitive to site quality, planting density, and cultural regime. The importance of planting density on rotation age has been reported previously (Bailey, 1986).

For the non-thinned scenario with integrated timber products, economic returns were generally greater for the lower planting densities, up to 900 TPA density, particularly for the low site with intensive culture. Similar results were reported by Bowling (1987), Conrad et al. (1982), and Caulfield et al. (1992). Intensive culture increased return on the low site at these lower densities and on the average site at densities of 300 and 600 TPA. Operational culture yielded better financial returns than intensive culture on the average site for most densities above 600 TPA and high sites for all densities because these site and density combinations were productive with operational inputs and the additional competition control and fertilization with intensive culture resulted in greater overstocking and mortality. Operational culture provided better economic return for average and high sites than the low site, particularly on the lower densities (i.e., 300, 600, and 900 TPA). These results indicate that growth and economic return responses are site specific and are consistent with observations that effects of cultural treatment depend on particular site and stand conditions (Fox et al. 2004).

Financial returns were greater with thinning, either one-thin or two-thin, than without thinning and the two-thin scenario generally resulted in greater financial return than the one-thin scenario. These results and specific trends in economic returns for the integrated product mix are similar to those reported for a traditional product mix (Chapter 3). Thinning favored positive returns due to factors such as early revenue, lower losses to mortality, and greater growth of larger, higher value trees.

The inclusion of bioenergy feedstock in the integrated timber products mix resulted in increased returns due to greater revenue, and in the case of the ROA valuation, greater price volatility. Historic price volatility was substantially greater for bioenergy feedstock than that for pulpwood, chip-n-saw, or sawtimber. This relatively higher volatility generated greater ROA return. A sensitivity analysis on increased price volatility and its effect on ROA return was demonstrated on Chapter 3 for traditional products.

The current results indicating that bioenergy feedstock dedicated plantations provide greater returns than plantations managed for integrated timber products are based on historical biomass prices and must be viewed in the context of abnormally high bioenergy feedstock prices ($16.9 to $7.8 per ton) for the period corresponding to ages 11 through 13 of the study plantations. These historical bioenergy feedstock prices are not realistic for the current market. Recent bioenergy feedstock prices are in the $1 to $5 per ton range (Nesbit et al. 2011; Dwivedi et al., 2012; Personal communication (Dr. Dale Greene, Dr. Shawn Baker). The 2014 fourth quarter price was $1.51 per ton (TMS, 2014). At the current price range, the bioenergy only regime produces negative NPV and $0 ROA values. The bioenergy price is also highly dependent on location, distance to the mill, conversion technologies, and individual landowners (Nesbit et al., 2011; Dwivedi et al., 2012; Shrestha et al., 2015).

The concept of bioenergy from woody biomass is not new. It dates back to the oil embargo of 1973-1974. The U.S. government has invested in research to advance bioenergy feedstock production and processing technologies. However, bioenergy plantations have not become operational due to complexity in conversion technologies, government policies, market conditions, and local factors (Nesbit et al., 2011).

Bioenergy markets are driven by public policy and government support. In the absence of such support, research, pilot projects, and incentives for production, woody bioenergy markets are unlikely to grow sustainably (Alavalapati et al., 2013). The forest management regime supplying bioenergy feedstock will depend on bioenergy feedstock price. If the price is sufficiently high, an integrated forest management regime with intensive culture and a higher planting density (>= 900 TPA) may be implemented to provide significant yields of small diameter trees at first thinning and stand conditions allowing subsequent returns from either traditional timber products or integrated timber products. The analysis reported here using historical prices demonstrates that a bioenergy only regime can be more lucrative than management for a mix of products on moderate to highly productive sites or with intensive culture on poorer sites. However, bioenergy feedstock price is the key for successful bioenergy dedicated loblolly pine plantations. While an integrated timber product regime or a plantation dedicated to bioenergy may provide attractive returns under high price scenarios, the resulting intensity of woody biomass harvests could have deleterious effects on stand productivity, biodiversity, soil fertility, and water quality (Alavalapati et al., 2013).

*Optimum Economic Regimes*

Based on this case study evaluation, the following regimes are identified as providing greatest economic return based on assumptions used for this study.

Integrated Product Mix - Low site

Plant 600 and 900 TPA. Apply intensive culture. Thin twice.

Integrated Product Mix - Average Site

Plant 600 to 900 TPA. Apply intensive culture. Thin twice.

Integrated Product Mix - High Site

Plant 600 to 900 TPA. Apply operational culture. Thin twice.

Dedicated Bioenergy – All Sites

Given the high historical price on this analysis: Plant 900 to 1500 TPA. Apply intensive culture. No thinning.

*NPV and ROA Comparison*

Advantages and limitation of NPV and ROA valuation approaches in the context of evaluating plantation management regime returns with a traditional timber product mix were discussed in Chapter 3. The present study added bioenergy feedstock to the product mix and plantation regimes dedicated to bioenergy feedstock production. The relatively high volatility in historic bioenergy feedstock price compared with the price volatility of traditional products provided a different case for comparing NPV and ROA than reported in Chapter 3.

The high price volatility for bioenergy feedstock contributed to a consistently much higher value for ROA than NPV. The increase in ROA value due to feedstock price volatility resulted in different rankings for ROA and NPV measures for at least one scenario. For the bioenergy feedstock scenario, ROA values tended to be higher for intensive than operational culture while the reverse occurred for NPV values. The ROA values were only greater because of the higher volatility. When and the impact of price volatility, especially at higher levels, when using ROA (Black-Scholes model).

The Black-Scholes model was useful for valuation of integrated timber product and bioenergy. This model allows the option to exercise at the end of the maturity date (rotation age) only; therefore, a growth and yield projection was necessary to estimate the underlying asset value (i.e., expected present value of a stand) for a future date. Since the ROA value or the NPV cannot be used to compare stand values of different rotation ages, EAA values for ROA and NPV were compared in determining returns from different site, planting density, cultural intensity, and thinning regime combinations with considerably different rotation ages.

Financial return from both ROA and NPV came to the same conclusion in most cases; however, the differences in return between approaches increased when price volatility increased. The price uncertainty factor (i.e., volatility or the standard deviation) creates value which ROA captures and NPV fails to capture. When the volatility approaches zero, ROA and NPV methods produce equal values (Amram and Kulatilaka, 1999). Although ROA captures the value of price volatility, care should be taken in using ROA when price volatilities are exceptionally high and it is recommended that the NPV method be tested in such cases. It is recommended that a sensitivity analysis be conducted on both approaches considering high, medium and low prices and price volatility in cases of marked price volatility.

## 4.5 Conclusion

The conclusions reported for the integrated timber product and dedicated bioenergy regime are based on a case study of loblolly pine plantations on three sites selected to be relatively illustrative of low, average, and high quality sites in Lower Coastal Plain of Florida and Georgia. Generally, the reported trends in this study follow expectations but due to the case study nature of this evaluation, results for other sites or forests may differ from those reported.

Total green stem weight for an integrated timber products mix was influenced by site quality, planting density, cultural intensity, thinning regimes, and harvest age. Intensive culture resulted in higher yield on low and average sites but not on the non-thinned high site class with high resource availability due to overstocking and greater mortality. Moderate planting densities (600 to 900 trees per acre) and timely thinning were essential for desirable growth and yield for integrated timber products.

Financial returns were generally greater for the dedicated bioenergy feedstock regime than the integrated timber products regimes due to high historical feedstock prices. However, under current markets the dedicated bioenergy feedstock regime would have financial returns significantly less than those for integrated timber product regimes with or without thinning scenarios. For a dedicated bioenergy feedstock regime to provide a 5% return, a stumpage price of at least $5 to $16 per ton is needed depending on the site, density, and cultural regime.

The integrated products mix which included feedstock resulted in small increases in financial return compared to the traditional product mix without feedstock. Generally, thinning scenarios (one-thin or two-thin) yielded greater financial return and these returns were greatest on the high site class with operational culture and lowest on the low site class with operational culture. Intensive culture provided greater financial returns than operational culture on both low and average sites.

The best regimes for integrated timber products based on economic returns are plant to 600 to 900 trees per acre, thin twice, and apply intensive culture on low and average sites and operational culture on high site. Given the high historical feedstock price used for this analysis, planting 900 to 1500 trees per acre with intensive culture and no thinning was the best regime for dedicated bioenergy feedstock plantations.

The ROA approach captured the value of price volatility and thus the returns were consistently greater than for the NPV approach. Both ROA and NPV valuation methods resulted in identical conclusions regarding optimum rotation length and optimum silvicultural regime for economic return in all but one case with unusually high price volatility for feedstock.

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Table 4. 1. Southern pine product class specifications for integrated product mix.

| **Product** | DBH Limit | Top Dia. Limit |
|---|---|---|
| Pulpwood | 4.5 inch – 8.5 inch | 3 inch |
| Chip-n-saw | 8.5 inch – 11.5 inch | 6 inch |
| Sawtimber | >11.5 inch | 8 inch |
| Bioenergy | < 4.5 inch | 0.1 inch |

Table 4. 2. RMSE, volatility, and drift values for pulpwood, chip-n-saw, sawtimber, and bioenergy.

| Parameter | Pulp | Chip-n-saw | Sawtimber | Bioenergy |
|---|---|---|---|---|
| RMSE | 0.633 | 1.279 | 2.006 | 8.339 |
| Volatility | 0.156 | 0.123 | 0.1206 | 0.697 |
| Drift | 0.012 | -0.007 | -0.011 | 0.243 |

Note: Statistical values presented in the table are based on historical real price (2014 dollars) series from the first quarter of 1986 to fourth quarter of 2014.The units are reported as $/ton

Table 4. 3. Tree and stand attributes for 18-year non-thinned loblolly pine plantations located in the Lower Coastal Plain of Florida and Georgia on different sites for operational and intensive culture and varying planting densities.

| | Operational Regime | | | | | Intensive Regime | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Planting Density (TPA) | TPA[1] at Age 18 | Mean Dominant Height (ft) | QMD[2] (in) | BA[3] ($ft^2/ac$) | MAI[4] (ton/ac) | TPA at age 18 | Mean Dominant height (ft) | QMD (in) | BA ($ft^2/ac$) | MAI (ton/ac) |
| | | | | | Low Site | | | | | |
| 300 | 246 | 66 | 9.8 | 125 | 5.8 | 246 | 74 | 10.8 | 158 | 7.9 |
| 600 | 492 | 47 | 6.6 | 117 | 3.8 | 386 | 80 | 9.5 | 190 | 10.9 |
| 900 | 652 | 52 | 6.1 | 127 | 4.6 | 577 | 73 | 7.8 | 190 | 10.4 |
| 1200 | 978 | 56 | 5.5 | 157 | 6.2 | 867 | 68 | 6.7 | 202 | 10.4 |
| 1500 | 1238 | 56 | 5.3 | 183 | 7.5 | 926 | 60 | 6.1 | 188 | 8.1 |
| 1800 | 1134 | 56 | 5.1 | 163 | 6.7 | 1006 | 66 | 6.0 | 199 | 9.4 |
| | | | | | Average Site | | | | | |
| 300 | 254 | 71 | 9.7 | 133 | 6.8 | 224 | 77 | 10.9 | 147 | 8.0 |
| 600 | 492 | 66 | 7.6 | 159 | 8.2 | 363 | 78 | 9.1 | 166 | 9.6 |
| 900 | 700 | 68 | 6.9 | 185 | 9.8 | 517 | 75 | 7.9 | 171 | 9.4 |
| 1200 | 932 | 65 | 6.2 | 195 | 9.5 | 666 | 74 | 7.4 | 195 | 10.8 |
| 1500 | 1082 | 65 | 5.8 | 192 | 9.4 | 692 | 69 | 7.0 | 174 | 8.7 |
| 1800 | 1100 | 64 | 5.6 | 183 | 8.9 | 820 | 67 | 6.4 | 180 | 8.7 |
| | | | | | High Site | | | | | |
| 300 | 253 | 82 | 10.6 | 154 | 9.3 | 200 | 84 | 11.4 | 142 | 8.6 |
| 600 | 461 | 83 | 8.8 | 197 | 12.4 | 340 | 85 | 9.3 | 161 | 10.2 |
| 900 | 624 | 86 | 8.2 | 229 | 14.7 | 397 | 82 | 8.5 | 157 | 9.8 |
| 1200 | 817 | 75 | 7.1 | 223 | 12.6 | 464 | 77 | 7.9 | 159 | 9.4 |
| 1500 | 870 | 77 | 6.6 | 208 | 12.3 | 444 | 78 | 8.1 | 159 | 9.4 |
| 1800 | 858 | 77 | 6.7 | 208 | 12.3 | 503 | 77 | 7.2 | 141 | 8.1 |

1. TPA = trees per acre
2. QMD = quadratic mean diameter is the dbh of the tree of average basal area
3. BA = basal area is the average amount of area occupied by tree stems at breast height of trees
4. MAI = mean annual increment is total stem green tons/acre/year.

Table 4. 4. Economic returns for optimal rotation ages for no-thin integrated timber products and bioenergy scenarios for low, average, and high site classes and various planting densities for the operational culture regime for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| | Integrated Products | | | | | Bioenergy | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Planting Density (TPA) | Optimal Rotation Age (Years) | ROA | NPV | $EAA_{ROA}$[1] | $EAA_{NPV}$[1] | Optimal Rotation Age (Years) | ROA | NPV | $EAA_{ROA}$ | $EAA_{NPV}$ |
| Low Site | | | | | | | | | | |
| 300 | 24 | $556 | $402 | $40 | $29 | 11 | $313 | $117 | $37 | $14 |
| 600 | 22 | $0[2] | ($100)[3] | $0 | ($7) | 11 | $308 | $85 | $36 | $10 |
| 900 | 22 | $0 | ($60) | $0 | ($5) | 11 | $343 | $98 | $40 | $12 |
| 1200 | 22 | $259 | $1 | $19 | $0 | 11 | $418 | $156 | $49 | $18 |
| 1500 | 26 | $304 | $12 | $21 | $1 | 11 | $508 | $229 | $60 | $27 |
| 1800 | 24 | $0 | ($55) | $0 | ($4) | 11 | $383 | $64 | $45 | $8 |
| Average Site | | | | | | | | | | |
| 300 | 24 | $652 | $508 | $47 | $36 | 11 | $406 | $219 | $48 | $26 |
| 600 | 24 | $589 | $421 | $42 | $30 | 11 | $564 | $364 | $67 | $43 |
| 900 | 26 | $643 | $452 | $44 | $31 | 11 | $715 | $502 | $85 | $59 |
| 1200 | 24 | $512 | $308 | $37 | $22 | 11 | $666 | $425 | $79 | $50 |
| 1500 | 22 | $474 | $244 | $35 | $18 | 11 | $755 | $497 | $89 | $59 |
| 1800 | 26 | $437 | $153 | $30 | $11 | 11 | $712 | $426 | $84 | $50 |
| High Site | | | | | | | | | | |
| 300 | 24 | $1,017 | $902 | $73 | $65 | 11 | $647 | $476 | $76 | $56 |
| 600 | 24 | $1,091 | $966 | $78 | $69 | 11 | $907 | $728 | $107 | $86 |
| 900 | 24 | $1,186 | $1,052 | $85 | $75 | 11 | $1,101 | $909 | $130 | $107 |
| 1200 | 22 | $803 | $666 | $60 | $50 | 11 | $1,006 | $786 | $119 | $93 |
| 1500 | 22 | $763 | $575 | $57 | $43 | 11 | $1,049 | $808 | $124 | $96 |
| 1800 | 22 | $714 | $502 | $53 | $38 | 11 | $1,068 | $805 | $126 | $95 |

1. ROA and NPV values are presented in terms of equivalent annual annuity (EAA) to compare PV in the same time horizon 2. Zero ($0) ROA value indicates call options should not be exercised. 3. Values in parentheses indicates negative values.

Table 4. 5. Economic returns for optimal rotation ages for no-thin integrated timber products and bioenergy scenarios for low, average, and high site classes and various planting densities for the intensive culture regime for loblolly pine plantations in the Lower Coastal Plain of Georgia.

| | Integrated Products | | | | | | Bioenergy | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Planting Density (TPA) | Optimal Rotation Age (Years) | ROA | NPV | $EAA_{ROA}$[1] | $EAA_{NPV}$[1] | Optimal Rotation Age (Years) | ROA | NPV | $EAA_{ROA}$ | $EAA_{NPV}$ |
| Low site | | | | | | | | | | |
| 300 | 24 | $749 | $362 | $54 | $26 | 11 | $541 | $127 | $64 | $15 |
| 600 | 24 | $899 | $517 | $64 | $37 | 11 | $812 | $400 | $96 | $47 |
| 900 | 24 | $617 | $162 | $44 | $12 | 11 | $960 | $536 | $113 | $63 |
| 1200 | 22 | $503 | $20 | $38 | $1 | 11 | $865 | $408 | $102 | $48 |
| 1500 | 22 | $0[2] | ($250)[3] | $0 | ($19) | 11 | $728 | $230 | $86 | $27 |
| 1800 | 22 | $0 | ($182) | $0 | ($14) | 11 | $898 | $393 | $106 | $46 |
| Average Site | | | | | | | | | | |
| 300 | 24 | $782 | $401 | $56 | $29 | 11 | $581 | $171 | $69 | $20 |
| 600 | 24 | $739 | $330 | $53 | $24 | 11 | $797 | $383 | $94 | $45 |
| 900 | 24 | $580 | $116 | $42 | $8 | 11 | $929 | $502 | $110 | $59 |
| 1200 | 22 | $598 | $140 | $45 | $10 | 11 | $971 | $523 | $115 | $62 |
| 1500 | 22 | $0 | ($104) | $0 | ($8) | 11 | $907 | $428 | $107 | $51 |
| 1800 | 22 | $0 | ($176) | $0 | ($13) | 11 | $874 | $367 | $103 | $43 |
| High site | | | | | | | | | | |
| 300 | 24 | $955 | $601 | $68 | $43 | 11 | $666 | $265 | $79 | $31 |
| 600 | 24 | $900 | $518 | $64 | $37 | 11 | $949 | $549 | $112 | $65 |
| 900 | 24 | $691 | $252 | $49 | $18 | 11 | $1,154 | $745 | $136 | $88 |
| 1200 | 24 | $620 | $144 | $44 | $10 | 11 | $1,009 | $565 | $119 | $67 |
| 1500 | 24 | $638 | $144 | $46 | $10 | 11 | $1,121 | $660 | $132 | $78 |
| 1800 | 24 | $0 | ($95) | $0 | ($7) | 11 | $888 | $382 | $105 | $45 |

1. ROA and NPV values are presented in terms of equivalent annual annuity (EAA) to compare PV in the same time horizon 2. Zero ($0) ROA value indicates call options should not be exercised. 3. Values in parentheses indicates negative values.

Table 4. 6. Economic returns for optimal rotation ages for one-thin and two-thin scenarios for integrated timber products for low, average, and high site classes and varying planting density for the operational culture regime for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| Planting Density (TPA) | Optimal Rotation (Age) | One Thin | | | | Optimal Rotation (Age) | Two Thin | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ROA | NPV | $EAA_{ROA}$[1] | $EAA_{NPV}$[1] | | ROA | NPV | $EAA_{ROA}$ | $EAA_{NPV}$ |
| Low site | | | | | | | | | | |
| 300 | 26 | $639 | $489 | $44 | $34 | 33 | $925 | $766 | $57 | $47 |
| 600 | 29 | $249 | $4 | $16 | $0.3 | 38 | $489 | $251 | $29 | $15 |
| 900 | 29 | $310 | $56 | $20 | $4 | 36 | $394 | $126 | $24 | $8 |
| 1200 | 33 | $464 | $196 | $29 | $12 | 38 | $541 | $262 | $32 | $15 |
| 1500 | 34 | $528 | $242 | $32 | $15 | 35 | $575 | $291 | $35 | $18 |
| 1800 | 35 | $456 | $129 | $28 | $8 | 38 | $550 | $325 | $32 | $19 |
| Average site | | | | | | | | | | |
| 300 | 26 | $702 | $558 | $48 | $38 | 29 | $777 | $625 | $51 | $41 |
| 600 | 26 | $699 | $537 | $48 | $37 | 29 | $812 | $645 | $53 | $42 |
| 900 | 26 | $742 | $565 | $51 | $39 | 32 | $858 | $660 | $54 | $41 |
| 1200 | 29 | $726 | $512 | $47 | $33 | 33 | $838 | $613 | $52 | $38 |
| 1500 | 29 | $673 | $433 | $44 | $28 | 35 | $772 | $510 | $47 | $31 |
| 1800 | 29 | $607 | $337 | $40 | $22 | 39 | $743 | $432 | $43 | $25 |
| High site | | | | | | | | | | |
| 300 | 24 | $1,255 | $1,157 | $90 | $83 | 26 | $1,137 | $1,233 | $78 | $85 |
| 600 | 24 | $1,284 | $1,174 | $92 | $84 | 26 | $1,529 | $1,419 | $105 | $98 |
| 900 | 24 | $1,512 | $1,399 | $108 | $100 | 26 | $1,548 | $1,426 | $106 | $98 |
| 1200 | 26 | $1,105 | $942 | $76 | $65 | 29 | $1,249 | $1,076 | $82 | $70 |
| 1500 | 29 | $1,144 | $948 | $75 | $62 | 29 | $1,279 | $1,093 | $84 | $71 |
| 1800 | 30 | $1,050 | $822 | $68 | $53 | 33 | $1,202 | $968 | $74 | $60 |

1. ROA and NPV values are presented in terms of equivalent annual annuity (EAA) to compare PV in the same time horizon 2. Zero ($0) ROA value indicates call options should not be exercised. 3. Values in red parentheses indicates negative values.

Table 4. 7. Economic returns for optimal rotation ages for one thin and two thin scenarios for integrated timber products for low, typical, and high site classes and varying planting density for the intensive culture regime of integrated timber products for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| Planting Density (TPA) | Optimal Rotation (Age) | One Thin | | | | Optimal Rotation (Age) | Two Thin | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | ROA | NPV | $EAA_{ROA}$[1] | $EAA_{NPV}$[1] | | ROA | NPV | $EAA_{ROA}$ | $EAA_{NPV}$ |
| Low site | | | | | | | | | | |
| 300 | 24 | $911 | $619 | $65 | $44 | 26 | $1,008 | $710 | $69 | $49 |
| 600 | 22 | $1,208 | $953 | $91 | $71 | 24 | $1,303 | $1,034 | $93 | $74 |
| 900 | 22 | $986 | $688 | $74 | $52 | 24 | $1,336 | $834 | $96 | $60 |
| 1200 | 26 | $753 | $359 | $52 | $25 | 29 | $891 | $490 | $58 | $32 |
| 1500 | 29 | $540 | $55 | $35 | $4 | 33 | $655 | $161 | $41 | $10 |
| 1800 | 29 | $610 | $117 | $40 | $8 | 33 | $746 | $244 | $46 | $15 |
| Average Site | | | | | | | | | | |
| 300 | 24 | $847 | $546 | $61 | $39 | 25 | $909 | $608 | $64 | $43 |
| 600 | 24 | $1,195 | $918 | $85 | $66 | 24 | $1,295 | $1,028 | $93 | $74 |
| 900 | 24 | $990 | $671 | $71 | $48 | 26 | $1,072 | $744 | $74 | $51 |
| 1200 | 26 | $907 | $537 | $62 | $37 | 26 | $1,002 | $646 | $69 | $44 |
| 1500 | 29 | $675 | $217 | $44 | $14 | 30 | $777 | $328 | $50 | $21 |
| 1800 | 29 | $661 | $178 | $43 | $12 | 30 | $748 | $272 | $48 | $17 |
| High site | | | | | | | | | | |
| 300 | 24 | $1,235 | $976 | $88 | $70 | 26 | $1,287 | $1,016 | $88 | $70 |
| 600 | 24 | $1,384 | $1,125 | $99 | $81 | 24 | $1,428 | $1,174 | $102 | $84 |
| 900 | 24 | $1,355 | $1,077 | $97 | $77 | 26 | $1,388 | $1,093 | $95 | $75 |
| 1200 | 26 | $984 | $625 | $68 | $43 | 26 | $1,061 | $712 | $73 | $49 |
| 1500 | 24 | $1,045 | $695 | $75 | $50 | 29 | $1,179 | $795 | $77 | $52 |
| 1800 | 26 | $763 | $328 | $52 | $23 | 29 | $892 | $449 | $58 | $29 |

1. ROA and NPV values are presented in terms of equivalent annual annuity (EAA) to compare PV in the same time horizon 2. Zero ($0) ROA value indicates call options should not be exercised. 3. Values in red parentheses indicates negative values.

Table 4. 8. ROA returns in EAA terms for no-thin, one-thin, two-thin, and bioenergy scenarios for low, typical, and high site classes and varying planting density for the operational and intensive culture regimes for loblolly pine plantations in the Lower Coastal Plain of Georgia and Florida.

| | Operational regime | | | | Intensive Regime | | | |
|---|---|---|---|---|---|---|---|---|
| Planting Density (TPA) | No thinning $EAA_{ROA}$ | One-Thin $EAA_{ROA}$ | Two-Thin $EAA_{ROA}$ | Bioenergy $EAA_{ROA}$ | No Thinning $EAA_{ROA}$ | One-Thin $EAA_{ROA}$ | Two-Thin $EAA_{ROA}$ | Bioenergy $EAA_{ROA}$ |
| Low site | | | | | | | | |
| 300 | $40 | $44 | $57 | $37 | $54 | $65 | $69 | $64 |
| 600 | $0 | $16 | $29 | $36 | $64 | $91 | $93 | $96 |
| 900 | $0 | $20 | $24 | $40 | $44 | $74 | $96 | $113 |
| 1200 | $19 | $29 | $32 | $49 | $38 | $52 | $58 | $102 |
| 1500 | $21 | $32 | $35 | $60 | $0 | $35 | $41 | $86 |
| 1800 | $0 | $28 | $32 | $45 | $0 | $40 | $46 | $106 |
| Average Site | | | | | | | | |
| 300 | $47 | $48 | $51 | $48 | $56 | $61 | $64 | $69 |
| 600 | $42 | $48 | $53 | $67 | $53 | $85 | $93 | $94 |
| 900 | $44 | $51 | $54 | $85 | $42 | $71 | $74 | $110 |
| 1200 | $37 | $47 | $52 | $79 | $45 | $62 | $69 | $115 |
| 1500 | $35 | $44 | $47 | $89 | $0 | $44 | $50 | $107 |
| 1800 | $30 | $40 | $43 | $84 | $0 | $43 | $48 | $103 |
| High site | | | | | | | | |
| 300 | $73 | $90 | $78 | $76 | $68 | $88 | $88 | $79 |
| 600 | $78 | $92 | $105 | $107 | $64 | $99 | $102 | $112 |
| 900 | $85 | $108 | $106 | $130 | $49 | $97 | $95 | $136 |
| 1200 | $60 | $76 | $82 | $119 | $44 | $68 | $73 | $119 |
| 1500 | $57 | $75 | $84 | $124 | $46 | $75 | $77 | $132 |
| 1800 | $53 | $68 | $74 | $126 | $0 | $52 | $58 | $105 |

Table 4. 9. Break-even price ($/ton) for loblolly pine plantations dedicated to bioenergy regime only at age 11.

| Planting Density (TPA) | Operational Regime | Intensive Regime |
|---|---|---|
| | Low Site | |
| 300 | $14 | $14 |
| 600 | $15 | $11 |
| 900 | $15 | $10 |
| 1200 | $13 | $11 |
| 1500 | $12 | $13 |
| 1800 | $16 | $11 |
| | Average Site | |
| 300 | $10 | $13 |
| 600 | $8 | $11 |
| 900 | $8 | $10 |
| 1200 | $9 | $10 |
| 1500 | $9 | $11 |
| 1800 | $9 | $12 |
| | High Site | |
| 300 | $7 | $12 |
| 600 | $5 | $9 |
| 900 | $5 | $8 |
| 1200 | $6 | $9 |
| 1500 | $6 | $9 |
| 1800 | $6 | $11 |

Note: The reported values presented in the table are rounded to the nearest integer.

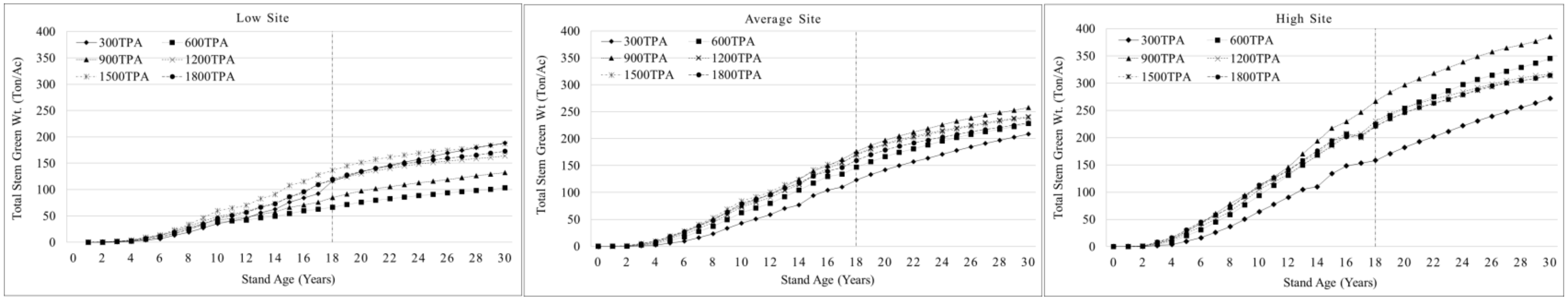


Figure 4. 1. Total stem green weight (integrated timber product) for non-thinned loblolly pine plantations on low, average, and high sites for operational culture and various planting densities.
Note: The vertical bar separates the measured data through age 18 and simulated data using SiMS after age 18.

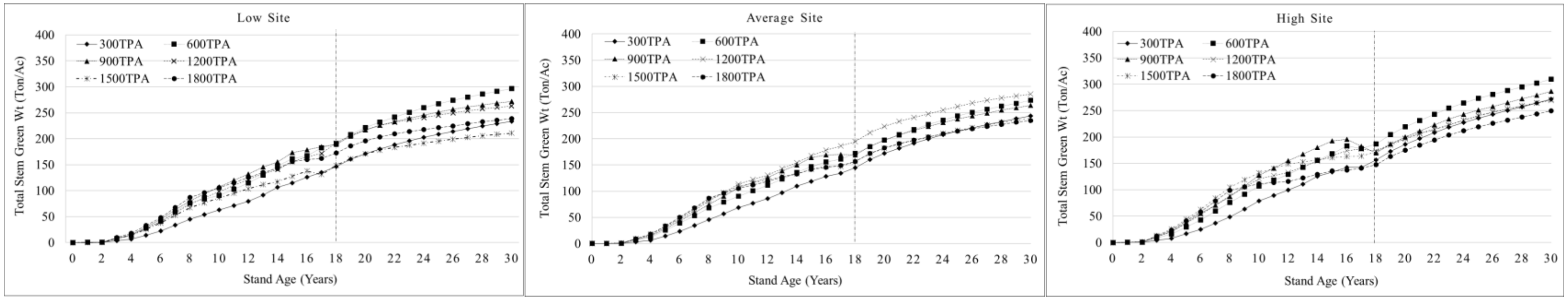


Figure 4. 2. Total stem green weight (integrated timber product) for non-thinned loblolly pine plantations on low, average, and high sites for intensive culture and various planting densities.

Note: The vertical bar separates the measured data through age 18 and simulated data using SiMS after age 18.

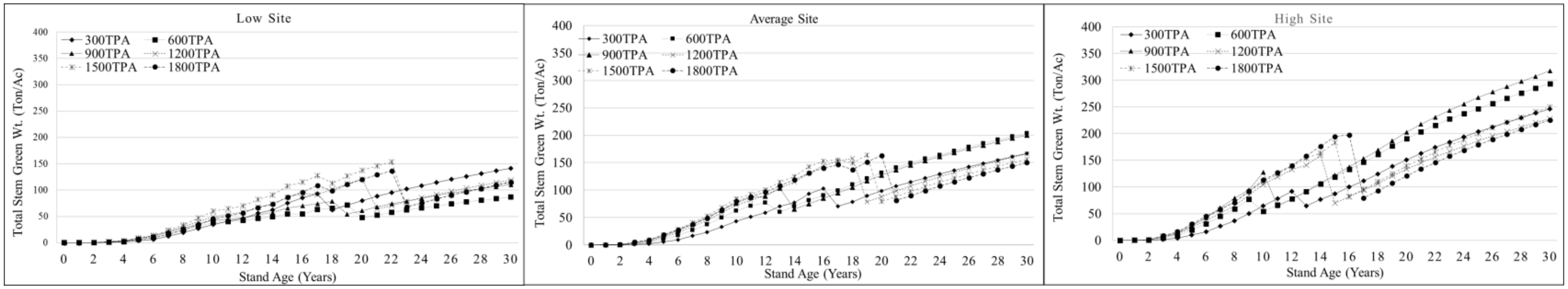


Figure 4. 3. Loblolly pine total stem green weight (integrated timber product) for low, average, and high site one-thin scenario for operational culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

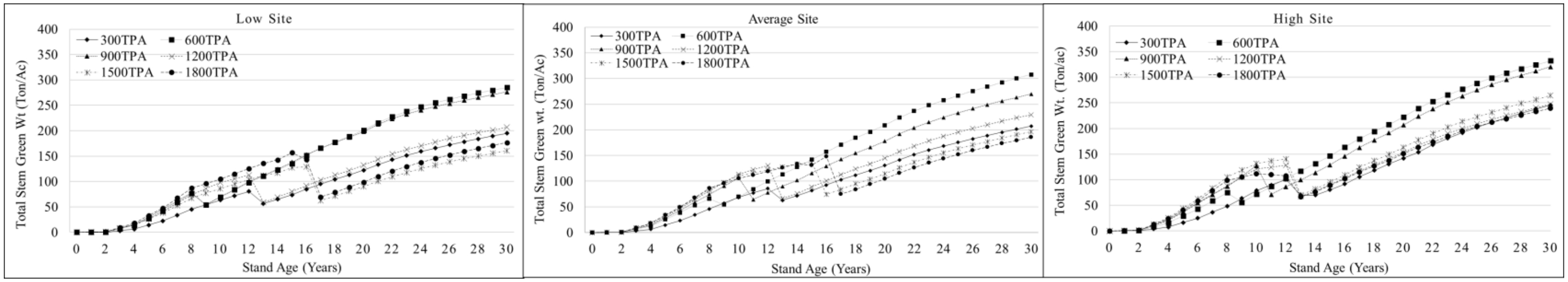


Figure 4. 4. Loblolly pine total stem green weight (integrated timber product) for low, typical, and high site one-thin scenario for intensive culture and various planting densities.
Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

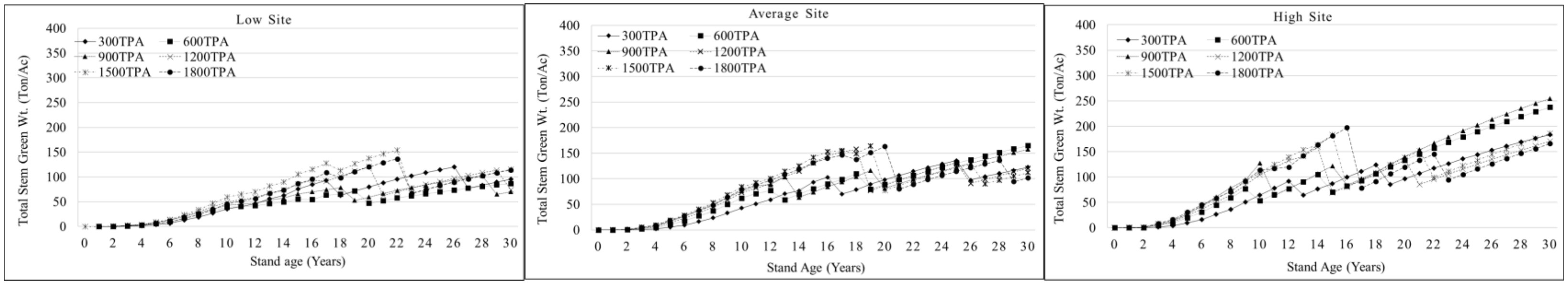


Figure 4. 5. Loblolly pine total stem green weight (integrated timber product) for low, average, and high site two-thin scenario for operational culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter.

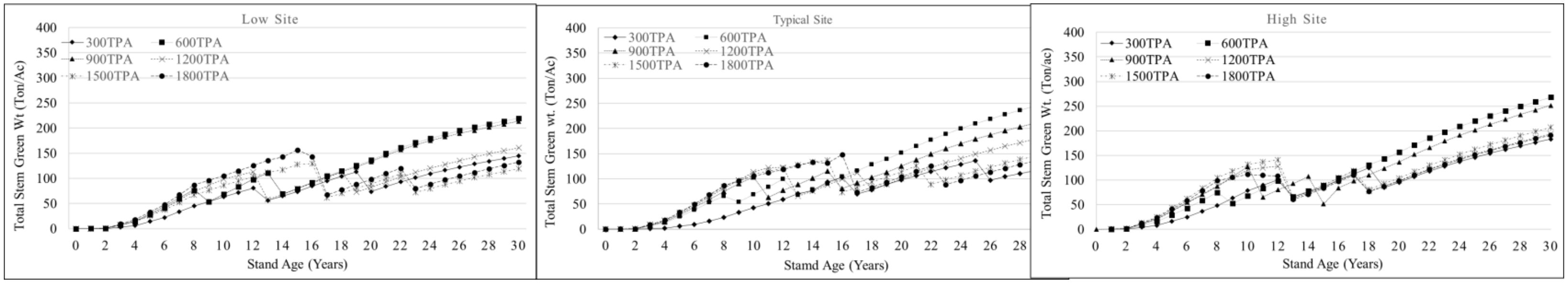


Figure 4. 6. Loblolly pine total stem green weight (integrated timber product) for low, average, and high site two-thin scenario for intensive culture and various planting densities.

Note: For stands with simulated thinning after age 18, yields were measured through age 18 and projected thereafter. For stands with simulated first thinning prior to age 18, yields were measured through thinning age and projected thereafter

APPENDIX 4A.1 AUGMENTED DICKEY-FULLER TEST OF BIOENERGY FEEDSTOCK PRICES. Note: Price series are quarterly from first quarter of 1996 to fourth quarter of 2014 as reported by Timber Mart South.

| Augmented Dickey-Fuller Unit Root Tests | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type | Lags | Rho | Pr < Rho | Tau | Pr < Tau | F | Pr > F |
| Single Mean | 0 | -11.2470 | 0.0880 | -2.48 | 0.1233 | 3.09 | 0.2927 |
| | 1 | -9.2504 | 0.1479 | -2.17 | 0.2189 | 2.36 | 0.4758 |
| | 2 | -8.9353 | 0.1602 | -2.06 | 0.2594 | 2.14 | 0.5314 |
| Trend | 0 | -11.3927 | 0.3190 | -2.39 | 0.3826 | 3.05 | 0.5736 |
| | 1 | -9.1417 | 0.4716 | -2.03 | 0.5765 | 2.32 | 0.7157 |
| | 2 | -8.7032 | 0.5054 | -1.90 | 0.6426 | 2.11 | 0.7574 |

| Autocorrelation Check for White Noise | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| To Lag | Chi-Square | DF | Pr > ChiSq | Autocorrelations | | | | | |
| 6 | 190.84 | 6 | <.0001 | 0.847 | 0.743 | 0.652 | 0.553 | 0.462 | 0.384 |
| 12 | 216.45 | 12 | <.0001 | 0.331 | 0.299 | 0.224 | 0.172 | 0.114 | 0.035 |
| 18 | 228.08 | 18 | <.0001 | -0.066 | -0.106 | -0.115 | -0.138 | -0.180 | -0.190 |

Appendix 4A.2. The Geometric Brownian Motion (GBM) performance test on Bioenergy Feedstock Prices.

table 1. Bioenergy feedstock actual vs predicted price comparison

| S.N. | Year | Actual | Predicted from GBM simulation | Abs Difference | | | |
|---|---|---|---|---|---|---|---|
| 1 | 2009 | 7.25 | 7.96 | 0.71 | 0.098 | | 0.504 |
| 2 | 2010 | 5.65 | 8.9 | 3.25 | 0.576 | | 10.582 |
| 3 | 2011 | 1.96 | 10.23 | 8.27 | 4.227 | | 68.443 |
| 4 | 2012 | 2.86 | 12.02 | 9.16 | 3.202 | | 83.898 |
| 5 | 2013 | 3.63 | 13.19 | 9.56 | 2.631 | | 91.352 |
| 6 | 2014 | 2.06 | 14.8 | 12.74 | 6.199 | | 162.413 |
| | | | | MAPE | 2.822 | MSE | 69.532 |
| | | | | | | RMSE | 8.339 |

# CHAPTER 5

# CONCLUSIONS

This research was conducted to examine the effects of varying site qualities, planting densities, cultural intensities, and thinning scenarios on loblolly pine plantation yields of different products and how economic variables such as timber price volatility and valuation approach affect the optimal forest management regime. A case study approach based on three research sites representing different productivity classes was used. These sites provided the opportunity to examine effects of three site qualities (low, average, and high), six planting densities (300, 600, 900, 1200, 1500, and 1800 trees per acre (TPA), two cultural intensities (operational and intensive) and three thinning scenarios (no-thin, one-thin, and two-thin) on timber yields and financial returns from loblolly pine plantations in the Lower Coastal Plain of Florida and Georgia. The traditional discounted cash flow technique of net present value (NPV) and Black-Scholes' real options analysis (ROA) were used for stand valuation considering a traditional product mix, an integrated product mix including feedstock, and dedicated bioenergy feedstock regime. Optimal rotation ages were determined and optimal management regimes were ranked using the equivalent annual annuity (EAA) approach. The main objectives were to: 1) Quantify loblolly pine stand yield for silvicultural regimes differing in planting density, cultural intensity and thinning for a range of site indices in the Lower Coastal Plain; 2) Evaluate financial return from different plantation regimes from a traditional product mix (pulpwood, chip-n-saw, sawtimber), an integrated product mix (traditional plus bioenergy feedstock), and bioenergy feedstock only using NPV and ROA approaches; 3) Identify optimum plantation regimes for different site classes and product mixes; and 4) Identify advantages and limitations of NPV and ROA approaches.

The traditional discounted cash flow techniques, such as NPV, have been commonly used for forest valuation for more than 100 years while the, ROA approach is relatively new, particularly in forestry applications. Detailed information on the key ROA literature, trends and development, major publication outlets, major ROA methods, ROA application in forestry, and application of stochastic price models in ROA were presented in Chapter 2.

There were clear effects of site quality, cultural intensity, planting density, and simulated stand development with and without thinning, on loblolly pine stand attributes, yields of traditional and integrated timber products, and economic returns using NPV and ROA. For non-thinned stands through age 18, average dominant height was greater in intensive than operational culture stands and at lower densities, especially 300 and 600 trees per acre (TPA) as compared to 1500 and 1800 TPA. Quadratic mean diameter (QMD) increased with higher site class, lower planting density, intensive culture, and thinning. Intensive culture increased basal area and stem green weight MAI measures in stands until they reached overstocked conditions. Growth gains from intensive culture were especially large and persistent on the low site class. Intensive culture on the high site class without thinning resulted in lower basal area and weight MAI measures by age 18 because of significant mortality caused by overstocking for most planting densities. The green weight MAI at age 18 was 0.4 to 1.9 tons/per acre/yr greater for the integrated than the traditional product mix. The total stem green weight MAI at age 18 for the 600 TPA density with operational culture was 3.8, 8.2, and 12.4 tons/acre/yr for the low, average, and high site class, respectively. Similar values with intensive culture were 10.9, 9.6, and 10.2 for low, average, and high site classes, respectively.

Financial analysis using ROA and NPV resulted in the same conclusions regarding optimal rotation ages and silvicultural regimes for the traditional product mix. ROA returns were always higher than NPV returns as the ROA approach captured the value from price volatilities. In a sensitivity analysis, the increase in price volatilities increased ROA return, and the ROA value approached the NPV value when price volatilities approached zero

The regime providing greatest returns, ROA and NPV values expressed as an EAA, for the low and average site classes was the 600 TPA planting density with intensive culture and two thinnings. The regime providing greatest return on the high site was the 900 TPA planting density with operational culture and either one or two thinnings. The two-thinning scenario showed the greatest returns and the no thinning scenario the least returns for most site, density, and culture combinations. Financial returns followed a general planting density trend (greatest to least) of 600, 900, 300, 1200, 1500, and 1800 TPA. Intensive culture general increased financial return on the low site class and decreased financial return on the high site class.

Financial returns for integrated forest products were greater than reported for traditional timber products due to the addition of bioenergy feedstock revenues. This increase in financial returns was greater for ROA than NPV due to the relatively high volatility in bioenergy feedstock price. The optimum plantation regime for integrated forest products on the high site was planting 600 to 900 TPA, operational culture, and two thinnings. For low and average sites, the optimum regime was 600 to 900 TPA planting density, intensive culture and two thinnings.

Financial returns for the integrated products mix regimes were less than for bioenergy feedstock dedicated regimes but the feedstock dedicated regime returns reflected unusually high historical prices. The ROA values were further increased by the high price volatility of bioenergy feedstock. Under the current market price, the bioenergy dedicated regimes will not produce such returns, in fact they will not produce positive return. ROA and NPV values for integrated forest products were greater at lower densities whereas bioenergy dedicated regime had greater values at higher densities.

The NPV and ROA approaches have their own advantages and limitations. The NPV approach was easier to calculate compared to ROA because it does not require estimation of several variables required for ROA. However, ROA has a distinct advantage over NPV in that it captures value associated with price volatility and managerial flexibility. Although both approaches resulted in the same conclusions regarding optimal rotation determination, ROA values were always greater than NPV due to the inclusion of price volatility in the Black-Scholes model. The trends in results and conclusions regarding timber yields and economic returns from this case study are generally consistent with expectations. Actual timber yields and economic returns for an individual plantation or forest may vary from those reported here.