The Economics of management effort in planted forests: an empirical analysis of fertilization and thinning prescriptions of Pinus taeda in the US South.

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(ABSTRACT)

If a landowner‘s main objective is to maximize his/her profits from planted forest investments, questions such as when and where exactly they should fertilize, thin and clearcut must be answered. We take advantage of an experiment established in 5 different states in the US South. Forest inventory data was collected for different combinations of thinning densities where some of them received fertilization. We use the Land Expectation Value methodology where our assumptions are the infinite amount of Pine rotations while costs and stumpage prices are known and constant, and markets are perfect. One of the main results we found is that fertilization has a decreasing marginal benefit on site index quality.

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(GENERAL AUDIENCE ABSTRACT)

If the landowner‘s main objective is to maximize profit from forest investments, questions such as when and where they should fertilize, thin and clearcut must be answered. Fertilization‘s main objective is to provide essential nutrients for tree growth. Thinnings have two main ojectives: a source of revenue in the middle of the forest rotation by selling the thinned trees and secondly to open space to the residual trees so they grown in diameter and gain value. We analyze how thinning and fertilization impact forest management from an economic perspective by checking their benefits and costs to landowners. We found that for low site index, fertilization has a positive impact in the sense its benefit is greater than the fertilization application cost. For better site indices, the opposite is true. For those who want to maximize economic benefits from planted forests. we end up with recommendations of which type of thinning and fertilization should be done according to the landowner site quality.

Dedication

I dedicate this thesis to my family which gave me the necessary conditions to realize my dream of getting a graduate degree in the USA.

Acknowledgments

I would like to give special thanks to Dr. Stella Schons, who guided me through the Master‘s process and shared valuable knowledge I will take with me forever. Special thanks also to the Forest Productivity Cooperative, which provided the data for this thesis work. I also appreciate the support from Dr. Jay Sullivan and Dr. Scott Barrett, who supported my studies during these two years. I am really thankful for my girlfriend‘s support, who at distance is capable of helping me. To my family that always supported my decisions.

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IRR = Internal Rate of return (%)

LEV = Land Expectation Value (U$/acre/year)

NPV = Net Present Value

Chapter 1

Introduction

In the quest to meet the ever-growing demand for wood products since the 1970s, foresters around the world have looked for various silvicultural prescriptions in order to increase the productivity of planted forests, making the forests of the southern US one of the most intensively managed in the world [39]. For example, fertilization and thinning are two common silvicultural techniques that are widely used, by themselves or combined, as their implementation result in significant tree diameter response [33]. Since the 1980s, forest economists have attempted to include the group of silvicultural prescriptions or investments as a variable in models of forest management decisions. Although these theoretical decision models have widely evolved, the empirical verification has been restricted due to the limited availability of data on the response of the forest to different combinations of fertilization and thinning [3].

If the manager‘s main objective is to maximize Net Present Value (NPV) for different site indices, fertilization, and price conditions, it is necessary to understand tree growth under different conditions and to model it [3]. The objective of this thesis is to analyze and indicate from an economic perspective the optimal combination of different thinning rates and fertilization applied at different ranges of site index quality. By doing that, we aim to highlight the importance of optimal decision making in forest management to maximize returns of forest landowners‘ investments. Thus, the main questions we will answer are: (1) When is the fertilization of planted forest effective from an economic perspective? (2) How does this result change when we combine fertilization with thinning prescriptions? (3) What is the optimal rotation age? Our hypothesis is that, at higher site indexes, fertilization and high intensity thinning prescriptions generate the highest economic value.

We take advantage of an experiment implemented by the Forest Productivity Cooperative (FPC) where forest inventory data was collected yearly for different site indices with different thinning rates, where some were fertilized, and some were not. We contribute to the forest economics literature by providing the first empirical analysis based on an extensive data set collected in the field that sheds light on a better understanding of the theoretical findings presented in the forest economics literature. Our analysis contrasts with that of other empirical papers that are based on data generated through various simulation approaches [25]. Moreover, to our knowledge, there is no other empirical work in the literature addressing the economic implications of the response of even-aged forests to combinations of fertilization and thinning intensity at different site index levels.

The rest of the paper is organized as follows: First, we present a literature review where we describe how fertilization, thinnings and different financial analyses have been applied to maximize forest landowners' profits. Secondly, we present the methodology and assumptions used in this analysis. Thirdly, we present the results found and we finalize with a conclusion and discussion about which factors must be considered when following the results we present.

Chapter 2

Literature Review

2.1 Fertilization and thinning of loblolly pine planted forests

Although silviculture can provide forest production improvement by reducing costs [31], it is necessary to have a better understanding of site-specific limiting factors to understand how they can limit forest productivity [5],[24]. A strategic silvicultural plan is developed comparing achievable productivity with current productivity and once we understand how fertilization, thinning, site limitations and other silvicultural treatments can affect a forest site, managers will be able to maximize productivity on a per tract basis [31].

Fertilization has been a common practice in the planted forest sector throughout southeastern United States with its peak in 1999 when 1.58 million acres were fertilized [4] and it is responsible for possible financial gains in the Southeast forest plantations [20]. For example, on average, tree volume increases 50 ft3 ac–1 yr–1 for 8 years after a mid-rotation application of 200 and 25 lb ac–1 elemental nitrogen and phosphorus, respectively [30],[20],[1],[3]. Fox et al., 2007 found that for a fertilization cost of $90 dollars per acre and assuming stumpage prices from the first quarter of 2006, internal rate of return could be of 16% [20]. Another argument that supported the use of fertilization is that it increases Leaf Area Index and help trees develop better after thinning [2], [36].

Phosphorus and Nitrogen are the most applied fertilizers in the US South since the lack of these elements can create limitation for pine growth [20]. On the other hand, large fertilization application may cause nutritional imbalance and consequently the leaching of nutrients, which will demand a future fertilization process at mid rotation, which is guided by analysis of leaf area, geology, foliar, and weather information [31]. More important than frequency, a study done by Albaugh et al., 2015, on *Eucalyptus grandis* in Colombia showed that fertilization is dependent of site quality and rate [1]. Knowing the proper amount and where it is being applied can avoid environmental issues and maximize landowner's return on their investments.

Thinning, another silvicultural practice, is applied based on diameter and height parameters to generate individuals with higher values [31]. They can be applied to manipulate availability of light, water, and nutrients, so the trees left in the stand can benefit from resources left for less trees per unit area [3]. These decisions were grounded in empirical work, simulations, and operational experience [31]. Pruning was also utilized with the same objective. Now, however, its high implementation cost and lower value paid for a pruned wood decreased the incentive for these practices [31]. The more intense the thinning, the greater the diameter growth response of the residual trees [10],[21]. Thinning and fertilization can be used to manipulate and determine how the left resources will be used by the trees left in the stand [3].

Although we know that thinning and fertilization combined have positive impacts increasing leaf area index and individual and stand growth [12],[15],[22],[26], from a modeling perspective, there is not a lot of data with thinning combined with fertilization [3]. Fertilization and thinning have been added in the Faustmann framework as "management effort", first introduced by S. Chang (1982, 1983), [16],[8]. The landowner challenge now with this modification is to choose optimal management effort and optimal rotation length [6]. To help landowners and foresters taking optimal decisions, new tools such the use of geospatial and temporal information from remote sensing can be used to support the decisions [31].

Albaugh et al., 2017, established an experiment with four blocks in five different sites of Pinus taeda in the US South with the main objective of determining growth of individual trees when fertilization and thinning are applied, and to understand the tradeoff between individual growth, stem quality and stand growth with fertilization. Their establishment criteria was the density between 400 trees per acre, without fertilization in the past four years and that were at least 10 years old, with leaf area index between 2 and 3. The different treatments were fertilized or not, with four different thinning intensities (100, 200, 300, and 500 residual trees/acre) [3].

After all treatments were applied, volume was calculated using diameter at breath height and tree heights measured in the field for all sites. Six years after treatment, they found that thinning impacted diameter, diameter increment, height increment, basal area, basal area increment, and volume increment for all sites. At more intense thinnings, residual trees achieved larger diameter faster than less intense thinning. On the other hand, less intense thinning presented higher total volume and basal area. Fertilization increased diameter by 25% for two sites. For one of the sites with low initial leaf area index, a significant effect of fertilization combined with thinning provided the nutrients and space for low site index quality and improved crown development. For sites with initial high leaf area index, fertilization did not improve pos-thinning growth [3].

2.2 The assessment of silviculture optimal decisions

Decisions such as forest rotation age, forest management and silviculture treatments such as fertilization and thinning are important to assess the potential profitability of planted forests. It is important to notice that empirical models to calculate effectiveness of forest operations are preferred to process based models [14]. On the other hand, to facilitate forester‘s decisions, a variety of mathematical models for forest optimization have been developed [37],[32],[29],[37]. Dynamic Planning (DP), for example, is a mathematical technique used for the optimal control theory, which uses equations that satisfy the principle of optimality [11],[18], but that leads to artificial solution [9]. DP as a tool to obtain solutions for the timber business was begun by Amidon and Aking, 1968 [7].

Marutani, 2010, used Microsoft Excel Solver combined with the application of the perturbation method and a deterministic model excluding stochastic factors to find optimal rotation age, tree density at the beginning of forest plantation, and optimal thinning amount for different site indexes. He begins from the principle that a forest firm aims to maximize Net present Values (NPV) for an infinite number of rotations by including at the beginning of each cycle a control variable for the establishment cost, which varies according to the tree density desired, and an administrative cost throughout the forest rotation. The benefits considered were from thinnings and finally for clearcuts [25].

Some authors have used process-based growth models to estimate tree growth and estimate profitability potential. [28], for example, used a 3PG model (Physiological Principals Predicting Growth [23]), which allows the input of fertilization, thinning and growing site conditions. With the estimated Mean Annual Increment (MAI) for production of woody biomass with 12 years rotation, they calculated Land Expectation Value and Internal Rate of Return for even aged Pinus taeda planted in the southern USA. They found that southern Texas, north of Florida, and southwest Louisiana have the highest MAI potential. On the other side, southern Virginia and most of North Carolina had the lowest potential. They found that highest LEV and IRR are on uplands, since they had lower site preparation cost, even though they present lower projected yield, compared to lowland soils. Finally, the greatest LEV was in norther Florida, and gradually decreased up to Virginia Piedmonts, with IRR presenting similar patterns.

Zhao et al.,2016 trying to maximize carbon sequestration and forest productivity by analyzing different silviculture treatments, found the existence of a maximum productivity and response to silvicultural activities in the US South for Pinus taeda. The idea used was the comparison of site index quality before and after silviculture activities. They found that biomass response to silvicultural management had better response in lower site index quality compared to the same activities on higher site index quality, which is an indicator that silviculture prescriptions can be tailored to specific site index quality. The maximum site index found was around 32 meters and the maximum response to silviculture was for the lowest site index classes [39].

2.3 The Land Expectation Value methodology and optimal rotation age

The decision of when is the best time to harvest a forest is an important and old challenge to foresters [27]. The approach of many foresters to define optimal rotation age for a forest is when average forest growth (mean annual increment) is equal to marginal forest growth (current annual increment) [6]. This approach is defined only on terms of forest growth, which does not include important factor such as costs and benefits. Some other approaches are the Net Present Value for one rotation [35], Internal Rate of Return [13] and the Faustmann formula, [19]. Faustmann, 1849, replace the biological optimal decision with economic theory, where he defines that the optimal decision should be made when the marginal benefit of waiting one more unit of time is the same as the marginal cost (opportunity cost of land and capital) of waiting the same amount of time ([19], [6]).

The forest economics literature has found inconclusive economic results emanating from fertilization and thinning prescriptions for different site indices [6]. These models build upon Faustmann's seminal work [19], which provides the basis for the theoretical framework that seeks the maximization of land value from forests considering as opportunity costs not only the forgone gains of the capital invested in trees but also that of the capital invested in the land.

Chapter 3

Methodology

3.1 Data

The data used in this thesis was collected throughout the US South by the Forest Productive Cooperative (FPC). The FPC created an experiment on established mid-rotation loblolly pine stands across seven sites with the objective of studying individual tree growth and quality in nutrient rich environments when stand density is reduced through thinning [3]. The data for each stand has been collected annually for 10 years on average, with age at the start of the experiment varying between 12 and 16 years old. At the beginning of the experiment, all loblolly pine stands were at least 10 years old. For the forest inventory data, diameter at breast height (DBH) was collected for all living trees before the treatments were installed and for each subsequent year. Height information was collected for all living trees before the treatments and six years after treatment [3]. Two different equations from Tasissa et. Al (1997) were utilized separately to calculate volume for thinned, and not thinned areas [34].

Each one of the seven experiment sites contains four blocks for each of the silvicultural treatments. Silvicultural treatments consist of eight combinations of thinning and fertilization prescription, as depicted in Fig. 3.1.

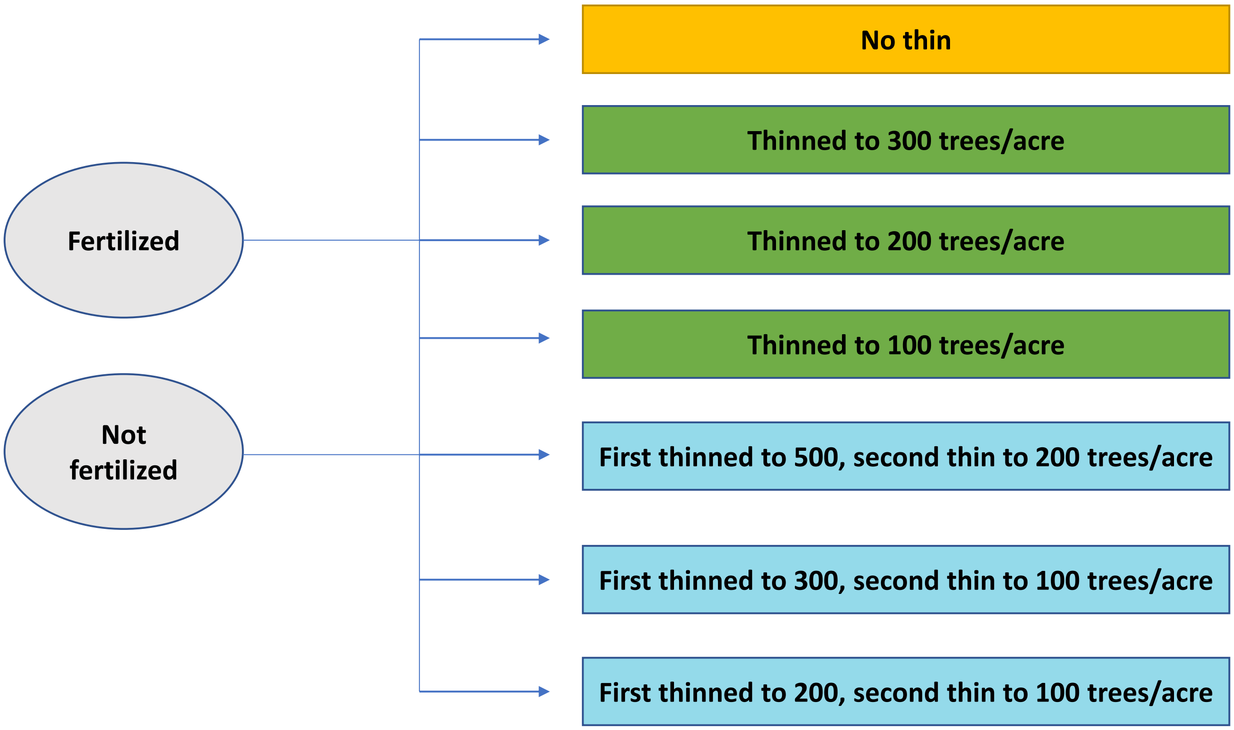

Figure 3.1: Treatment combinations.

The thinning prescriptions are: 500, 300, 200, and 100 trees/acre. Part of the study sites went through additional thinning prescriptions (which happened around six years after the first one): first thin to 500, second thin to 200; first thin 300 and second thin to 200; first thin to 200 and second thin to 100 trees/acre. Fertilization treatments are no fertilization or fertilization with 200 lbs/acre of nitrogen and 25 lbs/acre of phosphorus. Thinning prescriptions were carried out in the summer or fall whereas fertilization took place in the winter or spring following the first thinning [3]. For each block, the data set contains information on forest volume per year and separated by merchantable or product class: waste, chip-n-saw, saw timber, and pulpwood. Albaugh et al. (2017) provides further details on the experiment. Implementation, thinnings, fertilizations and clearcuts are described in the following timeline. See Fig. 3.2 for a map with the location of experiment sites.

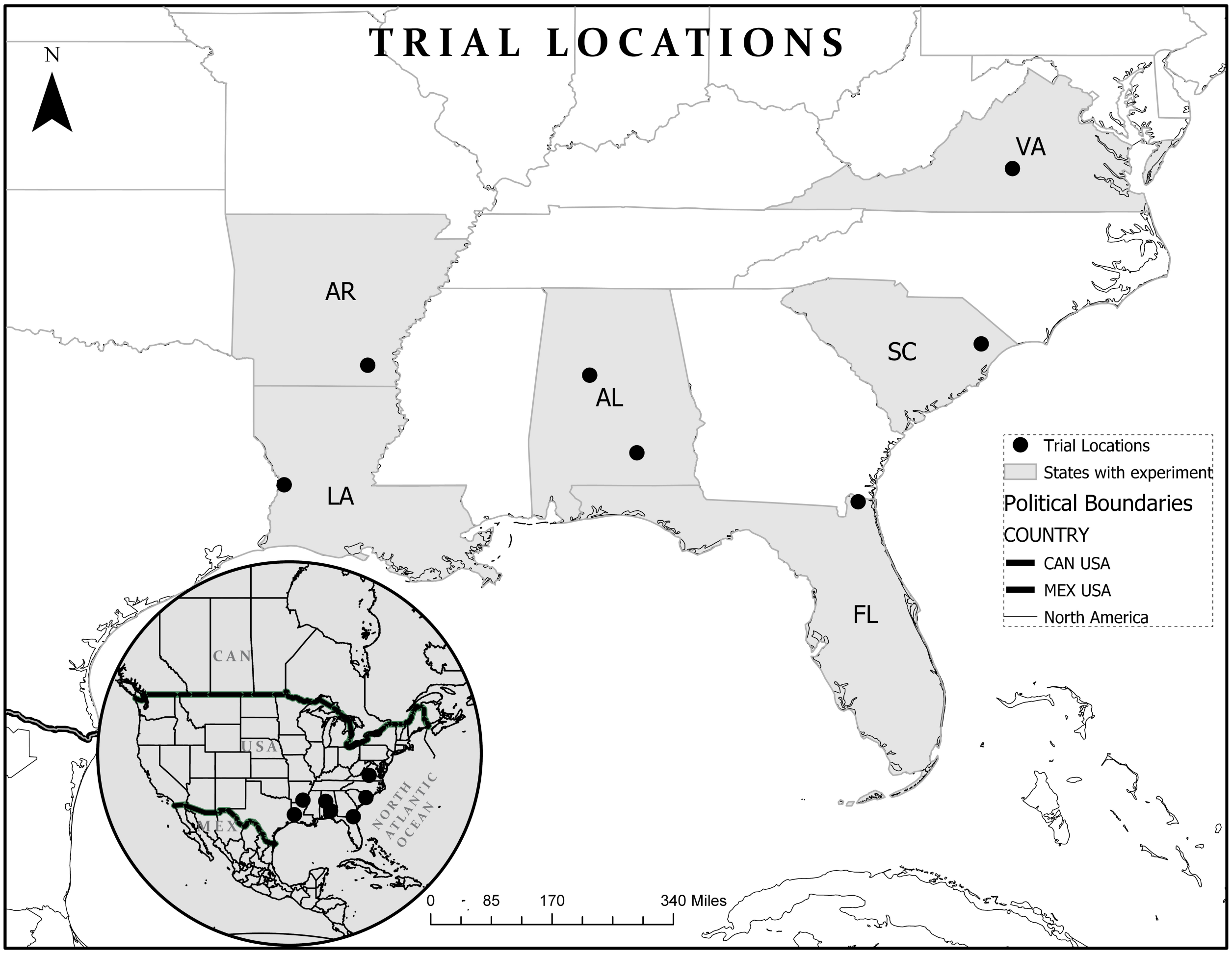

Figure 3.2: Map with trial locations.

3.2 Management effort and Land Expectation Value: The role of fertilization and thinning

In order to answer our research question on the economic impacts of different fertilization and thinning forest management prescriptions, we apply the Land Expectation Value framework, which has been widely used to study the economics of forest management decisions in even aged forests. Faustmann (1894) was the first to correctly present an analysis of the stand rotation length problem as he considered in the harvest timing decision not only the opportunity cost of capital invested in the forest stand along with the suite of initial costs the landowner incurs into when starting the stand from bare land, but also the opportunity cost of the land in which the stand is established [32]. The Land Expectation Value takes the following assumptions:

1. Future stumpage prices and costs for forest cycles are constant and known. We assume the price of each product type at each harvesting year for infinite rotations is equal to the current stumpage prices as shown in table 1. The establishment cost (site preparation and planting) considered was of 245.07 USD/acre (Maggard and Barlow, 2018) and we assume it happens at the beginning of every forest cycle (year zero), and fertilization cost, which happened in mid rotation was of 97.03 USD/acre (also assuming the same cost for all five states).

2. Interest rate for the future is constant, and we know what it is: For the analyses, we use the real interest rate of 5%.

3. Knowledge of forest yield: Forest volume is important to calculate forest revenue. It is assumed to be constant for all infinite rotations.

4. Markets and financial capital markets are perfect: Here we assume that there will be perfect markets for the forest products, so the landowner is able to make the optimal decision and sell the products once the forest cycle is over.

Assuming that the landowner (our decision maker) is a rational individual, the problem he/she faces is to determine the stand rotation length that maximizes her rents from land through time:

$$V = (1 - e^{-rT})^{-1}[pf(T)e^{-rT} - c] \tag{3.1}$$

where V is the volume of harvested timber at the optimal rotation length, p is the stumpage price, c is tree stand establishment and maintenance costs, T is the rotation length, and r is the real interest rate. The term represents the landowner's discounted net benefit (revenues minus costs) from harvesting the tree stand at the optimal rotation age minus the costs of establishing and maintain the stand, that is, the net present value of tree stand for infinite rotations. The term e^{-rT} is the discount factor, and we assume that the landowner will devote the unit of land to forestry indefinitely.

The solution to equation 3.1 , known as the Faustmann Solution, is:

$$V_t = pf'(T) - rpf(T) - rV = 0 \tag{3.2}$$

To guarantee this is a maximum, we take the second derivative and expect the result to be smalled than zero:

$$V_T T = pf"(T) - rpf'(T) < 0 \tag{3.3}$$

At equation 3.2 V is defined by equation 3.1 and the optimal rotation age is exactly when the marginal benefit of waiting one extra year of stand growth is equal to the marginal cost of waiting that year – composed by the foregone revenues from harvesting the stand in the current and all future rotations. The maximum value generated from harvesting the stand is referred to as the Land Expectation Value (LEV) or Bare Land Value. We use equation 3.1 to find the LEV and optimal rotation age for each fertilization and thinning prescription detailed further below.

The benefits used in the analysis are those from the thinning activities (where present) and the clear-cuts. To calculate revenue from these activities, we multiplied the green weight obtained by the price of the product class it represented. Thinning happened at mid-rotation when forests were around 14 years old. Fertilization happened at the same time.

The form we analyze the data is divided into three main parts. In the first one, we look at the impact of fertilization alone on forest rotation age and its influence on average Land Expectation value. Secondly, we do the same for thinning. It is important to mention here that when we present average results, we are averaging over the optimal rotation age, which is also the highest LEV for each treatment. Lastly, since it is a dynamic decision we combine all information about fertilization, thinning, and site index quality. To better organize our data and analysis, we ordered the observations by site index and grouped them in the ranges described in table 3.1. Site index (SI) was calculated before thinning and fertilization using the average height of dominant and co-dominant trees at age of 25 years.

Tab. 3.1

Table 3.1: Site index categories.

Site Index Class	Lower limit (ft)	Upper limit (ft)
1	59	65.8
2	65.80	72.60
3	72.60	79.40
4	79.40	86.20
5	86.20	93.00

The first part of the thesis was the calculation of Land Expectation Value for each treatment with their respective rotation ages. I separate the highest LEV per treatment with their respective optimal rotation age and use them for my following analysis. To get an overview of our data, the first graph describes how site index affects rotation age and average Land Expectation Value. After that, we start looking at the fertilization effect per-si by calculating the average Land Expectation Value and rotation age for each of the five site index categories by separating fertilized from those which were not fertilized. A table with LEV with % improvement as a consequence of fertilization was created.

Secondly, we start analyzing the thinning effect on LEV. In a single graph, we combine average Land Expectation Value for each thinning class with their average respective rotation age. Since this is actually a dynamic process, the combination of thinning, fertilization and site index must be combined.

To combine all the information regarding thinning and fertilization with site index classes, we created a new category that separates site indices into three broad classes: low, medium and high. To delimit each of these new classes, we looked at the fertilization impact on average Land Expectation Value for site index classes of 1 ft each. That way we can separate the positive from the negative impact of fertilization on average Land Expectation Value. With the 3 new classes separated, we plot a graph that presents average LEV for each thinning intensity and fertilization treatments. That way, we can compare impact of thinning and fertilization across the whole data.

Finally, we do sensitivity analysis to understand the effect of interest rate change on LEV, followed by a price sensitivity analysis with focus on changes in saw timber price.

Chapter 4

Results

4.1 General Results

As explained below (and expected considering the inconclusive results from the mathematical comparative statics derivations of the Faustmann solution presented above), our results will vary according to stand Site Index (which is the reason why we have separated the various stands into groups).

After analyzing the data, firstly we present the results showing the effect of fertilization, followed by thinning, and lastly the effect of the combination of both on Land Expectation Value and average rotation age.

First, we present an overall representation of the data where we analyze the impact of site index category on average rotation age and on the average Land Expectation Value. This is represented by Fig. 4.1 bellow.

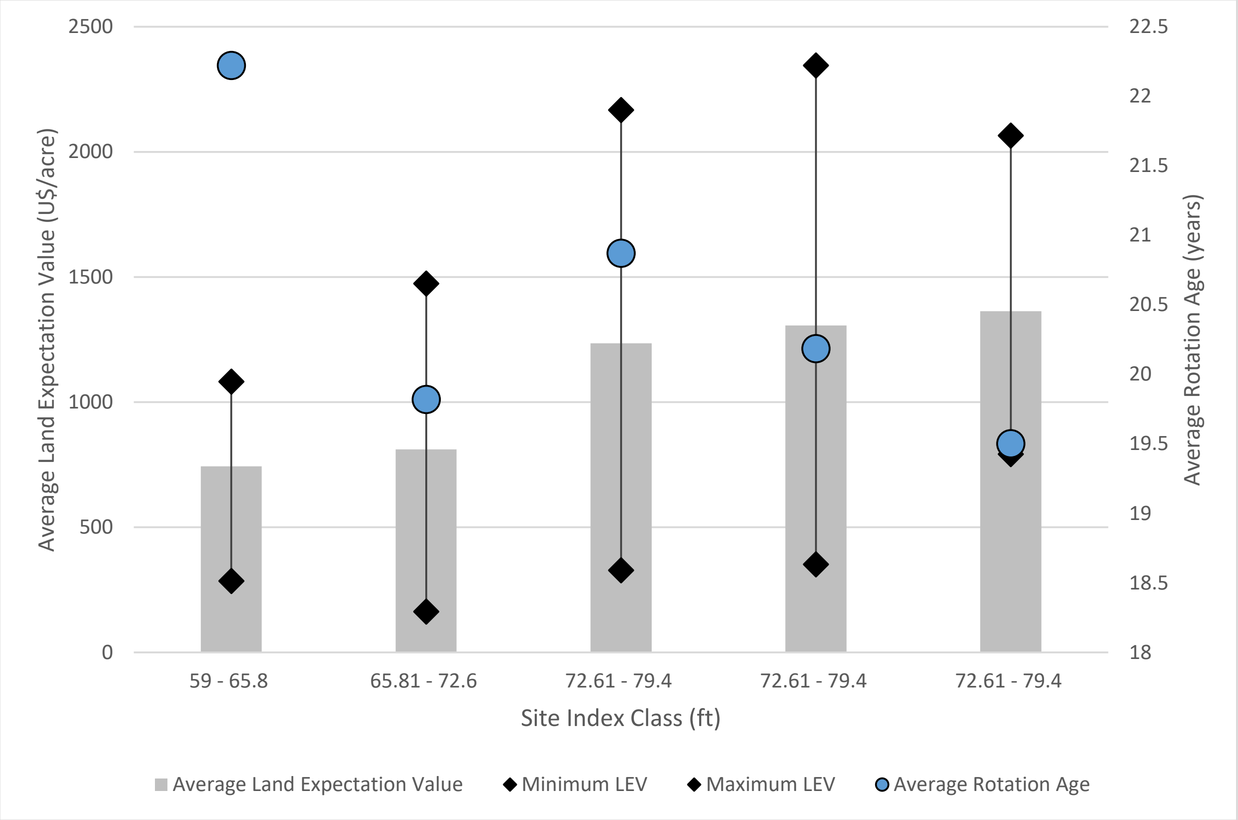

Figure 4.1: Average rotation age and average Land Expectation Value per site index class.

After calculating the LEV using equation 3.1 for each treatment and grouping them into the site categories described on 3.1 above, we find that the average LEV considering all treatments varies between U$744/acre for category 1 (lowest SI) and U$1364/acre for category 5 (highest SI). On the other hand, the average rotation age for all treatments varies between 22.22 and 19.5 years for category one and category five, respectively. Juxtaposing the results as presented in Figure 4.1 we see that, in general, the higher the SI, on average, the shorter the rotation age (with exception of site index class two (check – 2's rotation age is smaller than 3, 4, and 5) and the greater the average Land Expectation Value. This could be explained by the fact we are using empirical data, and not using a model for forest volume. The decrease in average rotation and increase in average Land Expectation Value as we increase site index quality is expected as the SI reflects the quality of the soil, and soils with higher quality are more productive.

Table 4.1 shows that for lower site indexes (1, 2) fertilization had a positive impact on Land Expectation Value, which implies that the money invested in fertilization brought returns greater than its costs. For higher site indices (3, 4 and 5), fertilization had a negative impact on average Land Expectation Value, which shows that lower site indices have better return on fertilization investments. This could be an evidence that fertilization provided essential nutrients for three growth on nutrient-limited stands and the benefits it provided were greater than the costs. Table 4.1 presents the LEV for both fertilized and non-fertilized treatments for each site index category as well as the percentage improvement between the two treatments.

Table 4.1: Fertilization improvement on average Land Expectation Value.

Site Index Class	Average LEV for Fertilized areas	Average LEV for Non Fertilized areas	Fertilization improvement
1	869.48	659.86	32%
2	849.98	776.22	10%
3	1195.18	1285.66	-7%
4	1196.83	1399.17	-14%
5	1183.90	1603.55	-26%

Considering LEV results per type of thinning treatment alone, stands that were thinned twice presented a higher average LEV compared to those that were thinned only once, as shown in Fig. 4.2. Although we do not see a pattern for the average rotation age, we see that the more intense the thinning, the higher the average LEV for the double thinning, and the opposite for the single thinning. Average rotation age for no thinning treatments is the shortest.

After analyzing the effect of fertilization and thinning alone by using optimal rotation age and their respective LEV for each treatment, I separated the data into three broad categories

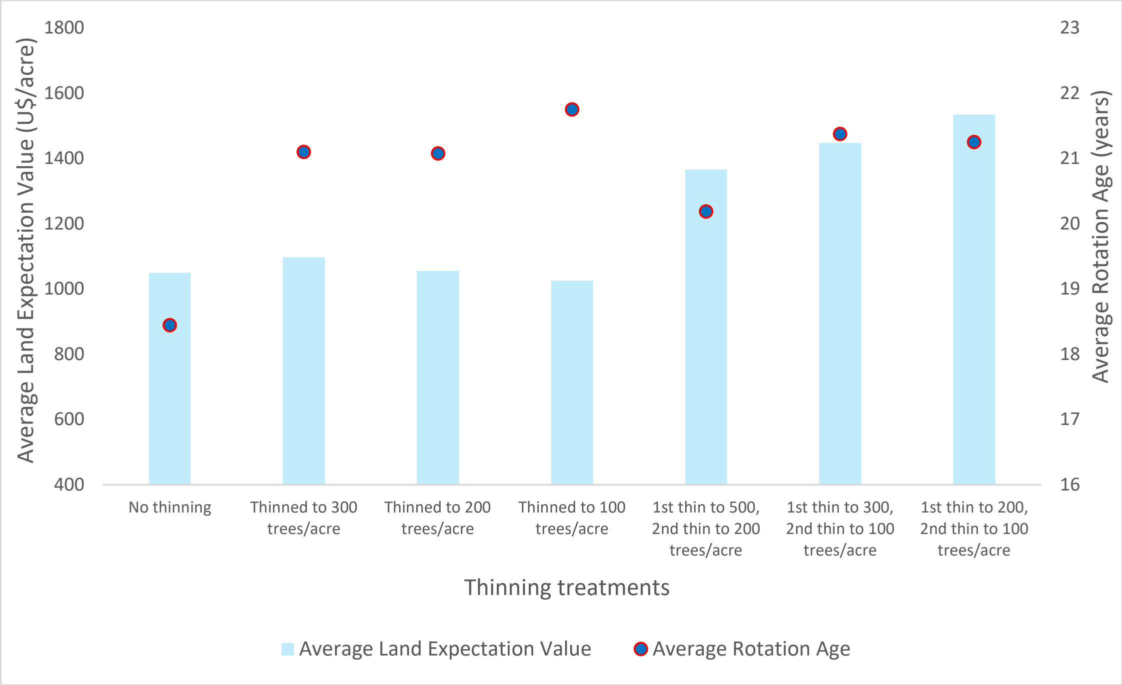

Figure 4.2: Average rotation length and average Land Expectation Value for different thinning rates.

(low, medium and high) in order to highlight where fertilization had positive, neutral and negative economic impacts (impact on LEV). This data division supports the illustration of treatments combined in broader groups as shown in Figure **??** below:

The final combination of thinning, and fertilization applied on the 3 main site index classes is described in Figure 4.3 below:

In Figure 4.3, we observe that stands located on land with lower SI presented higher LEV when they were fertilized compared to the non-fertilized counterparts. From our results, the best prescription for the group of lower SI of stands was fertilization combined with 300 trees/acre and a second thin to 100 trees/acre. As for the groups of stands presenting high SI, no fertilization resulted in better results than fertilization. From our results, the best treatments for the higher site indices was non fertilization with a double thinning of first thin to 300 and second to 100 trees/acre.

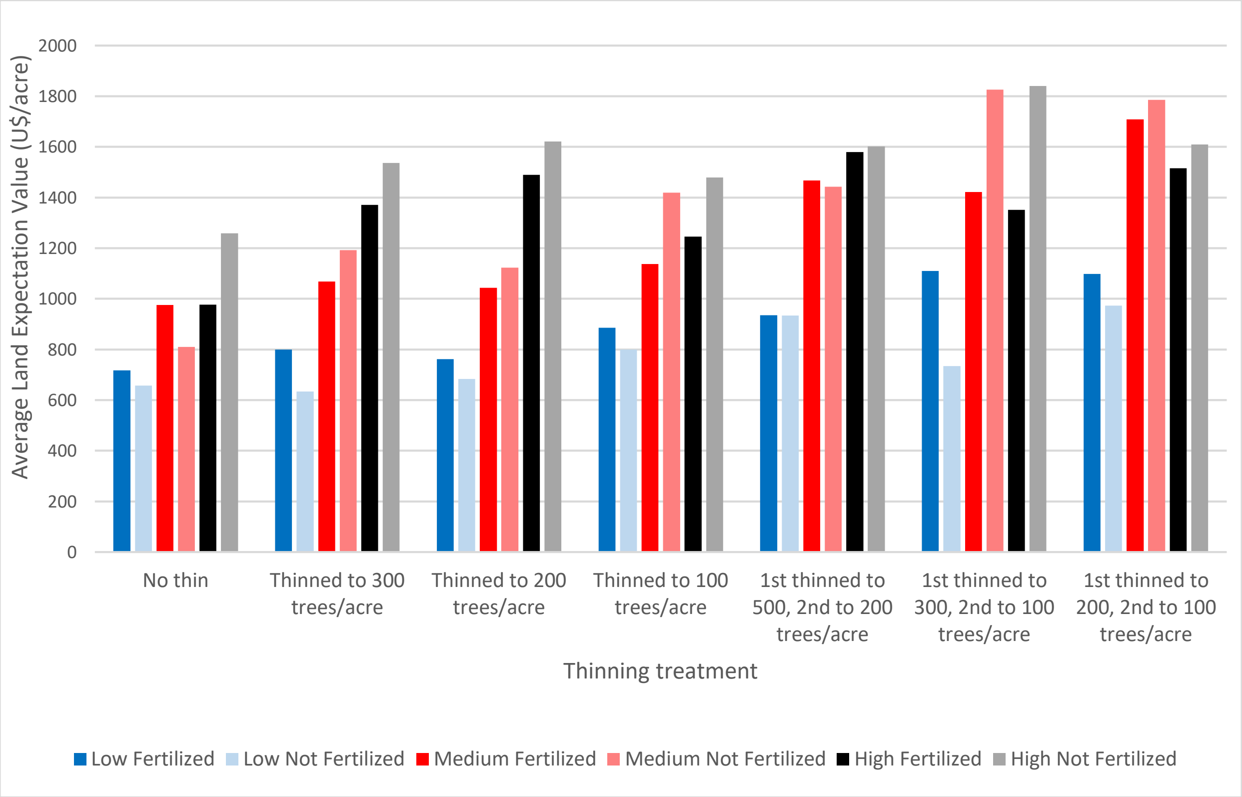

Figure 4.3: The Average Land Expectation Value combined for all treatments at different site index categories.

With these results we reaffirm that for lower site indices fertilization brought better results from an economic perspective. It also shows that from the thinning perspective, lower site indices fertilized with high intensity thinning presented higher LEV. For higher site index quality, medium to high intensity thinning also brought higher LEV.

Lastly, from the treatments and their respective optimal rotation age and LEV, we calculated the average rotation age for lower, medium, and high site index classes. We compared treatments that received fertilization with those that did not. Fig. 4.4 shows that for low and medium classes, fertilization increased the average rotation age. That could be explained by the fact that fertilization made it worth to wait longer since its effects could help saw timber production. On the other hand, fertilization on the high site index category decreased the average rotation age. That could be an indicator that fertilization does not increase or help saw timber production, so a shorter rotation age is more attractive from an economic perspective. Fig. 4.4 below presents these results.

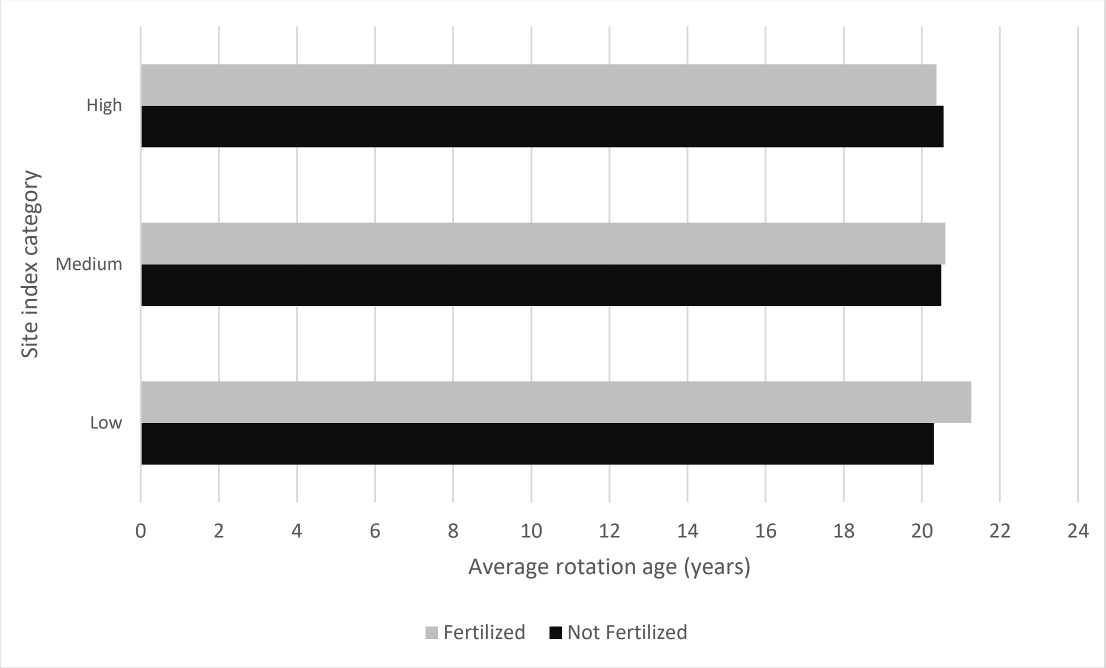

Figure 4.4: Average rotation age for fertilized and non-fertilized treatments.

The economic results represented by the Land Expectation Value methodology depend on the growth rate, stumpage price, interest rate, and costs of treatments. The sensitivity analysis's main objective is to understand how Land Expectation Values changes as the interest rate, stumpage prices, and forest costs change. The decrease in the price of saw timber because of higher supply after the 2008 crisis and the increase in pulpwood price along with the increase in pellet production, for example, created incentives to landowners to increase the number of trees per acre and are now planting densities from 400 to 650 seedlings per acre [17]. Considering that eventually saw timber price will increase once saw demand goes back to its normal, we judged it necessary to do a sensitivity analysis for an increase in saw timber price for the three broader site index categories. Tab. 4.2 shows us that although average rotation age decreases for fertilized high site index classes, no saw timber price justifies fertilization for higher site index class site when compared to not fertilized treatments. Table 4.2 presents the sensitivity analysis for saw timber price and highlights how dynamic the decision process is, in the sense that a change in saw timber price affects average rotation age, for example.

Table 4.2: Price sensitivity analysis for saw timber price.

Saw timber Price (U$/ton)	Delta Low Class	Impact on average rotation (years)	Delta Medium Class	Impact on average rotation (years)	Delta High Class	Impact on average rotation (years)
25	13.70%	0.92	-4.05%	1.00	-22.62%	-1.03
26	14.54%	1.02	-3.86%	0.40	-22.74%	-0.83
27	15.39%	1.02	-3.70%	0.49	-22.85%	-0.92
28	16.22%	1.02	-3.54%	0.41	-22.97%	-0.73
29	17.03%	1.02	-3.37%	0.45	-23.08%	-1.01
30	17.83%	1.02	-3.09%	0.94	-23.23%	-1.42
31	18.62%	1.02	-2.82%	0.95	-23.40%	-1.29
32	19.39%	1.11	-2.55%	0.95	-23.57%	-1.66
33	20.18%	1.11	-2.30%	0.95	-23.72%	-1.18
34	20.96%	1.11	-2.06%	0.73	-23.85%	-1.10
35	21.72%	1.11	-1.88%	0.73	-23.97%	-1.10

From the table above, we see that for the lower site index category, the increase in saw timber stumpage price increases average rotation age and impacts positively the difference between average Land Expectation Value of treatments that received fertilization from those that did not, which is an indicator of incentive to keep fertilizing lower site indices if saw timber price increases. For the high category class, on the other hand, saw timber stumpage price increase, although it reduces average rotation age, it does not affect the negative impact of fertilization on average Land Expectation Value which is around -23%. This could be explained from the fact that stumpage price increase affects both, fertilized and not fertilized treatments the same way, but as already shown, fertilization has a decreasing marginal benefit on site index quality. The decrease in average rotation age can be explained by the fact that higher revenues are achieved earlier, which creates incentives to harvest before.

After saw timber price sensitivity analysis, we proceed to the effect of different interest rates focusing on the extremes scenarios (lower and higher site index categories). I decided to make this analysis to account for the different costs for the money used to be invested in planting forests by different parties. The Weighted Average Cost of Capital, for example, is a calculation firms use which is weighted for different sources of capital. It is usually greater than the cost for individuals, which makes the investment less viable compared to lower costs of capital. For the lower site index classes, we can see in Fig. 4.5 that negative Land Expectation Value starts for single thinning when the interest rate is 12%.

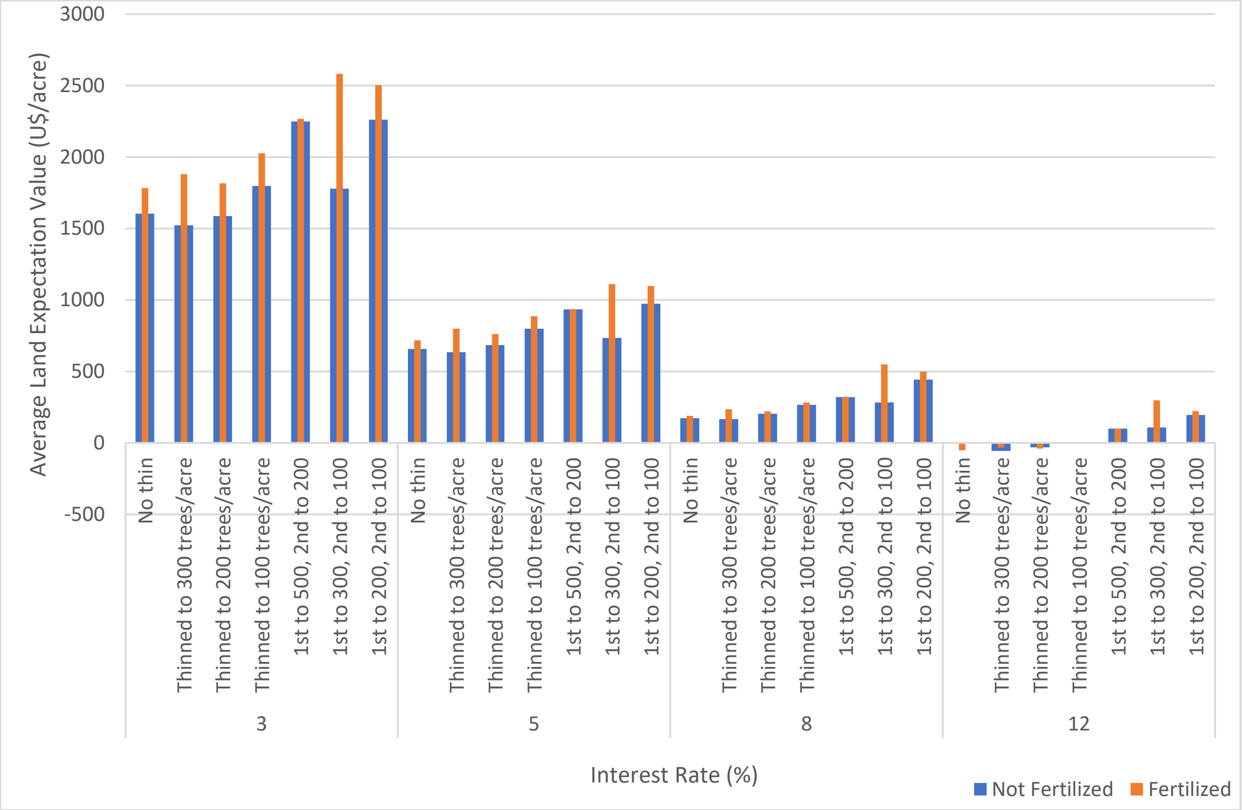

Figure 4.5: Sensitivity analysis for low site index category under different interest rates.

On the other side, for the high site index class, interest rate of 12% still yields a positive Land Expectation Value as shown in the Fig. 4.6.

These interest rate sensitivity analysis are important to define optimal investment deci-

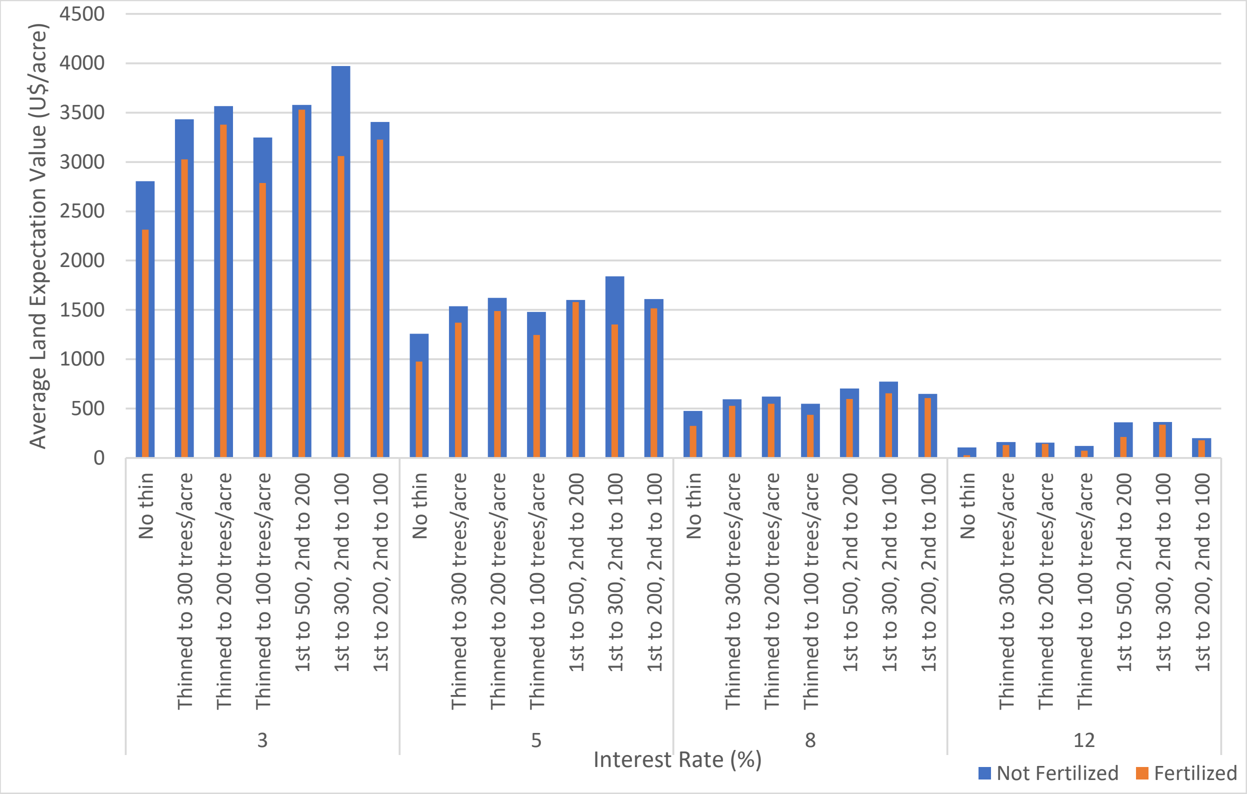

Figure 4.6: Sensitivity analysis for high site index category under different interest rates.

sions. For lower site indices, for example, if the second best investment opportunity offers a 12% interest and is compared to no thin, thinned to 300, thinned to 200, or thinned to 100 trees/acre, we realize that the hypothetical investment is a better choice under these circumstances compared to forestry.

Chapter 5

Conclusion

Financial returns on forest investments can be increased by tailoring silvicultural treatments in accordance with specific site index quality. Our findings on optimal rotation age can help landowners maximize their profits while being environmentally sound in the sense that its application could be tailored by the site real necessity as we know fertilization has a decreasing marginal benefit on site index quality. It must be taken into account that the forest decision-making process is dynamic and changes on factors such as stumpage prices of different merchantable classes, interest rates, or fertilization cost can completely change optimal scenarios of silvicultural treatments and rotation age.

The Land Expectation Value for different combinations of thinning and fertilization applied at different site indices using empirical data supports the clarification of how fertilization has a decreasing marginal benefit on site index class, which goes against our initial hypothesis that at higher site indices, fertilization prescription generates higher economic value. It is important to notice that we assumed an equal price of saw timber for both, higher and lower site indices, although the price received for saw timber on high site indices is expected to be greater than timber from lower site indices. This is because trees from growing under better conditions tend to present better form (rectilinear) and better quality.

Finally, the use of the Land Expectation Value is a methodology that must be used with attention to the assumptions already mentioned in this thesis. Literature exists comparing different methodologies such as Net Present Value, Internal Rate of Return, and Labor Wage

Expectation Value methodologies [38].

Chapter 6

Appendix

Stumpage prices used in this analysis is described below:

Table 6.1: Price sensitivity analysis for saw timber price

Merchantable Class	Price (U$/ton)
Pulpwood	11.59
Chip-n-saw	17.75
Sawtimber	25.71
Waste	0

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