2014

ECONOMIC ANALYSIS OF CARBON SEQUESTRATION UNDER CATASTROPHIC RISK AND PRICE UNCERTAINTY IN KENTUCKY

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Recommended Citation

Hu, Lijiao, "ECONOMIC ANALYSIS OF CARBON SEQUESTRATION UNDER CATASTROPHIC RISK AND PRICE UNCERTAINTY IN KENTUCKY" (2014). *Theses and Dissertations--Agricultural Economics*. 25.
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ECONOMIC ANALYSIS OF CARBON SEQUESTRATION UNDER CATASTROPHIC RISK AND PRICE UNCERTAINTY IN KENTUCKY

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Agriculture, Food and Environment at the University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2014

ABSTRACT OF THESIS

ECONOMIC ANALYSIS OF CARBON SEQUESTRATION UNDER CATASTROPHIC RISK AND PRICE UNCERTAINTY IN KENTUCKY

Internalizing carbon value for forest landowners has the potential to increase carbon supply in forest and mitigate CO_2 in the atmosphere. In this study, we developed a modified Hartman model to investigate how payments of carbon offsets impact the optimal management of hardwood forests in Kentucky under condition of catastrophic events. Different carbon markets were modeled and several sensitivity analyses were performed to examine varied management strategies to achieve maximized financial return or highest environmental benefits. Furthermore, another model was developed to incorporate the impact of risk aversion to price uncertainty using E-V model. We were able to identify the most favorable scenarios for landowners and society in the face of price variability and catastrophic risk.

KEYWORDS: Carbon sequestration, catastrophic risk, the modified Hartman model, E-V model, Kentucky forests

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07/16/14

ECONOMIC ANALYSIS OF CARBON SEQUESTRATION UNDER CATASTROPHIC RISK AND PRICE UNCERTAITNY IN KENTUCKY

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Acknowledgments

I would like to express my sincere gratitude to my advisor and the chair of my thesis committee, Dr. G. Andrew Stainback for his persistent encouragement and guidance throughout the last two years. Without his insight and support my research would have been much less productive and much more difficult to finish. I am deeply grateful to Dr. Jack Schiffer and Dr. Wuyang Hu for being in my committee and providing valuable inputs in my research. I am equally thankful for the important suggestions and guidance during the incorporation of E-V model by Dr. Carl Dillon. I would also like to thank Dr. Murali Kanakasabai for providing carbon data of Chicago Climate Exchange. I thank Department of Forestry and Depart of Agricultural Economics, University of Kentucky for providing me a platform to pursue my academic career and providing the opportunity to conduct on a topic of my interest. Last, but not least, I thank my family and friends for their constant support.

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Chapter 1 : Introduction and Literature review

Introduction

Forests are a valuable part of Kentucky's landscape for providing significant contribution in economics and environmental benefits for the Commonwealth. Statistically, there are 703 wood using facilities and more than 1,800 logging firms across the Commonwealth (Stringer et al., 2014). Analysis of Kentucky's forest and wood industries indicated $7.9 billon in direct contribution and a total economic impact of $12.8 billion in 2013 to Kentucky's economy, which increased 2.9% and 3.3%, respectively compared to 2011 (Stringer et al., 2014). Moreover, Kentucky's forests provide countless other environmental benefits as well; though the value is not documented. Environmental benefits of trees and forests include ecosystems services, such as cleaner air and water, carbon sequestration, biodiversity, wildlife habitat and provide Kentuckians with recreational opportunities, aesthetic beauty, and a host of other intrinsic values (Stringer et al., 2014). Therefore, forests play an important role in Kentucky in terms of economic contribution and environmental benefits and it is important to investigate how to maximize landowners' profits that includes both timber value and non-timber value.

Among the ecosystem services trees and forests provide, it is widely recognized that forests contribute greatly to the global carbon cycle by sequestering and storing carbon

(Brand, 1998). Carbon sequestration, as a result of photosynthesis, involves the uptake and conversion of atmospheric CO_2 into cellulose and other organic compounds, such as wood (Creedy and Wurzbacher, 2001). By sequestrating atmospheric CO_2, trees convert anthropogenic and natural greenhouse gases into carbon, which is stored in their biomass and released when the trees or their products decay (Creedy and Wurzbacher, 2001). Several studies have analyzed the role of carbon payments on the land value of forestry. For example, Dwivedi et al. (2009) assessed the value of forests including carbon payment using the modified Hartman model (1976) and results showed that there was an increase in profitability because of the carbon sequestered in forest biomass. Thus treating carbon as a forestry product could help mitigate Greenhouse gas (GHG) emission on one hand; on the other hand, it has the potential to increase forest landowners' financial return. In 1998, the Kyoto Protocol to the United Nations Framework Convention on Climate Change opened the opportunity to trade GHG emissions for increased sequestration of CO_2 by forests (Creedy and Wurzbacher, 2001).

Governments throughout the world are actively considering policies to reduce their GHG emissions via permits, GHG offsets, and financial incentives (i.e., taxes, subsidies, etc.) (van Kooten et. al., 1995). The increasing focus on climate change induced the emergence of carbon markets; they are usually categorized as voluntary or mandatory. Examples of voluntary carbon markets are the Chicago Climate Exchage (CCX), the Mountain Association for Community Economic Development (MACED), and the

National Carbon Offset Coalition (NCOC). Examples of mandatory carbon markets are the Regional Greenhouse Gas Initiative (RGGI), and California's Cap and Trade Program. It seems crucial to know how carbon markets influence forest management in aspects like optimal rotation age and stand supply.

Also, one major factor that forest landowners have to face is uncertainty. Uncertainty could come from the forest itself in the form of forest fires and other environmental hazards, like insect outbreaks or severe weather.[1] Catastrophic events can damage a fraction or the whole forest depending on the severity. Take, for example, fire; the interval between fires in southern forests may be as short as a year or as long as centuries. Fire in the understory generally does not kill the dominant vegetation or substantially change its structure, while the mixed fire regime causes selective mortality in dominant vegetation (Brown, 2000). Catastrophic events are inevitable, and once they happen, they will bring financial loss for landowners and ecological damage to forests. From the view of both forest landowners and society, the consideration of risk from fire is important and proper in management decisions

Unlike certain agricultural products like fresh vegetables that have to be harvested in time, forest landowners would not bear too much loss for delaying harvest for a year or two unless there is a dramatic price change, which makes it harder for landowners to decide the cutting time. What complicates the decision is financial uncertainty, which is

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[1] In the following, catastrophic events will be referred as fire risk for simplicity.

another type of uncertainty in forestry and it is reflected in the uncertain input and output prices of forest products. It is difficult to control or predict the fickle market, especially when trees have a relatively long production period and their maturity age ranging from 10 years to hundreds of years depending on growth rate. Due to the unpredictable nature of economy, forest landowners need to adjust their management to cope with price uncertainty. In order to do this, it is essential to know ahead of time how price uncertainty will affect the financial return, which is the primary concern for landowners.

In Chapter 2, the modified Hartman model focuses on the impact of carbon sequestration and fire risk. In Chapter 3, an E-V model is added into the modified Hartman model to examine the effect of risk aversion level to price uncertainty. Even though the model adopted in Chapter 3 also includes the impact of carbon sequestration and fire risk, which overlaps with the result from Chapter 2, Chapter 2 is still an important section for the following two reasons. First, the model in Chapter is the foundation of the model used in Chapter 3. Additionally, the joint effect of carbon sequestration and fire risk has not been investigated in Kentucky, therefore, it is essential to illustrate the results. Second, the results from Chapter 2 help explain the results generated in Chapter 3. Ultimately, this paper will present a modified Hartman model that takes into account carbon sequestration, catastrophic risk, and price uncertainty along with an E-V model. This model will be used to investigate how payments for carbon offsets impact the optimal management of hardwood forests in Kentucky under conditions of risk and price uncertainty. Identifying the optimal rotation age and highest expected value of land can help guide forestry owners' decisions about management with timber and carbon, both as forest products.

Literature review

Role of carbon sequestration

As an essential product from forests, carbon's value in forest has been studied extensively. Shrestha (2013) gave a comprehensive literature review about forest carbon sequestration, forest carbon life-cycle analysis, and the financial implications of net carbon payments. It is well established from the literature that carbon payments have a positive impact on forestland value and increase optimal rotation age (Shrestha, 2013; Dwivedi et al., 2009; Stainback and Alavalapati, 2002; van Kooten, Binkley, and Delcourt, 1995).

Impact of catastrophic events

Several studies have analyzed the impact of catastrophic events like fire on the land expectation value (LEV) and the optimal rotation age. Most papers have extended the Faustmann model (1984) to incorporate fire into the model, like Routledge (1980), Reed (1984), Stainback and Alavalapati (2004), and Susaeta, Alavalapati, and Carter (2009). All previous studies have shown that catastrophic events have significant influence on

LEV and optimal rotation age; LEV decreased when considering fire risk and the optimal rotation age tended to be shorter with fire risk.

Martell (1979) described a stochastic model that could be used to determine the optimal rotation age for a flammable forest stand. The stand rotation model used an extension of the Markov decision model proposed by Wagner (1969). The risk rate of fire was estimated by a probabilistic dynamic programming and the rate was set from 0.0% to 5.0%. Results showed that the optimal rotation age decreased as the conditional annual fire probability increased.

Routledge (1980) brought up the idea of the extended Faustmann model since the traditional model did not cover the effect of potential catastrophes. In Routledge's paper, the Faustmann model incorporated estimates of the likelihood of catastrophes. Also, the researcher presented the consequence of ignoring catastrophes. Results showed that the size of the error factors of neglecting catastrophes depended on growth rates, hazard rates, and expected salvage portion.

Reed (1984) investigated the effects of risk of fires or other unpredictable catastrophes on the optimal rotation age using extended an Faustmann model. One assumption of the model was that when fire occurred, it caused total destruction. It raised the idea that the effect of fire risk was equal to adding a premium to the discount rate, which implied that risk of fire would decrease optimal rotation age. The risk rate of fire was set at 0.0%, 1.0%, 2.0%, and 5.0%. Two extensions were suggested; one was that the destruction through fire or other catastrophe was only partial, which was more realistic. The other one was that the probability of fire depended on the age of the stand other than following a Poisson process.

Yin and Newman (1996) analyzed the effect of catastrophic risk on forest investment using a forest-level neoclassical profit function of timber production. Unlike the traditional Faustmann, price and cost changed over time under Yin and Newman's model; prices and growth process in the profit function followed a geometric Brownian motion and cost rose deterministically at an instantaneous rate. Property tax was set at \$2.5/ac/year, and the mean rate of the catastrophic event was set at 0.8%. Results showed that catastrophic risk decreased the value of an investment project, and increased the threshold of forest investment.

Englin, Boxall, and Hauer (2000) explored the joint effect of fire risk and amenities on timber harvesting using a Faustmann framework. Amenity represented the wilderness recreation, which was estimated using a linear damage function. Martell (1994) determined the actual risk of fire in the Canadian Shield was about 1.5%. Therefore, the fire risk ranged from 0.0% to 4.0% with intervals of 0.5%. Results showed that the rotation age decreased as fire risk increased. However, the inclusion of amenities in the model increased the rotation age at every level of risk. This implied that delaying harvesting might be substantial for many forests in the Canadian Shield.

Stainback and Alavalapati (2004) extended Reed's (1984) model by including salvage value and carbon into the analysis. In the 2004 paper, fire risk was set from 0.0% to 4.0%, which was based on Runkle (1985), and Hooper and McAdie in Haight, Smith, and Straka (1995). The portion of the stand that is salvageable after a catastrophic event was set for 0% and 70%. Results showed that risk of catastrophic mortality decreased the land value and rotation age for all carbon prices; these decreases were greater for higher carbon prices.

Susaeta, Alavalapati, and Carter (2009) extended the Hartman model by incorporating the probability of catastrophic events and then combined it with Black-Scholes formula to examine the impact of price uncertainty and catastrophic disturbance. There were two scenarios: no thinning scenario and thinning scenarios. Slash pine plantations under no thinning scenario and thinning scenarios were expected to have different rates of catastrophic risk. In general, catastrophic disturbance rates in forests were around 1.0% annually. Results showed that LEV increased when risk rate decreased.

Impact of price uncertainty

A few studies have analyzed the importance of taking price uncertainty into account in forest management and the impact of price uncertainty. Norstom (1975), Kaya (1987), Haight and Smith (1991), and Buongiorno (2001) adopted dynamic programming to present price uncertainty, while only Susaeta et al., (2009) developed a modified Hartman model based on the Faustmann model and Black-Sholes formula. The Faustmann model is not the most frequently used method to incorporate price uncertainty in the literature and there needs to be more research in this area.

Norstorm (1975) applied Markov Decision Process to estimate the optimal rotation age problem. A comparison between policies – one that considered price uncertainty and the other that didn't - was made to investigate the importance of price fluctuation. The results of the comparison showed that on average, individual forest owners were better off with fluctuations in prices than with a constant price equal to the long-run average of actual prices, which indicated the importance of taking price fluctuations into account in the determination of harvesting.

Kaya (1987) presented how to determine economic management strategies for uneven-aged stands using Markov Decision Process that takes into account the uncertainty of future product prices and stand growth. The method needs to define different state and transition probabilies. The transition probability matrix for the stand was computed by simulation, using a stochastic model of stand growth for northern hardwoods. Then a method of successive approximations was used to find the management policy that would maximize the expected net discounted value of the returns from the stand. Results showed that on average, the expected cutting cycle was 8.4 years, which was the average and the stand would be cut at irregular intervals that are all multiples of 5 years. Also, the expected yield was 2.52 ft^2/ac/yr.

Brazee and Mendelsohn (1988) applied an asset sale model to estimate the optimal rotation age with unpredictable price fluctuations. The basic idea of this method was to compare the current price of stumpage and the reservation price which was the present value of the maximum expected timber value; if the current price exceeded the reservation price, forestry owner could harvest. If the current price was lower than the reservation price, it was rational to delay harvest for at least another year. The paper presented two examples: Douglas-fir and loblolly pine. Results showed that the expected age of harvest was slightly longer than the Faustmann rotation; the optimal rotation age was about two years longer than the Faustmann age for Douglas-fir. The optimal rotation age was one year longer than the Faustmann age for loblolly pine. The Faustmann harvest age could be seen as the rotation length with zero price variation.

Haight and Smith (1991) analyzed the effects of stochastic stumpage prices on economic optimal thinning and rotation ages for loblolly pine plantations in the Piedmont region of North Caroline using dynamic programming. Two standard deviations of sawtimber price were presented: 17.19 and 34.38. Results showed that with a higher level of price variation, the optimal rotation age would decrease and the expected value of plantation management would increase as price variation increased.

Klemperer et al. (1993) adopted the common way to account for investment risk to add a risk premium to the risk-free discount rate when computing present values of expected revenues which are uncertain. Risk premium is the rate that could make the value received with certainty give the same satisfication as the uncertainty revenue. Results showed that the risk premium for short term (i.e. 5 years) was around 7.0%, and that the appropriate risk premium might decline with lengthening payoff period for many forest investments.

Brazee and Bulte (2000) used flexible management model to incorporate thinning decisions into optimal harvesting models with fluctuating stumpage prices. The reservation stumpage prices were estimated with a random draw stumpage price model. Results showed that the land expectation value increased with the spread of the stumpage price distribution; expected thinning age decreased sharply while expected harvest age increased under flexible management compared to the Faustmann management, due to an increase in the precommercial incentives to thin from an increase in net present value of older stands.

Buongiorno (2001) studied how to apply Markov decision process to decide the optimal rotation age. Both growth and stumpage prices were assumed to be stochastic. Buongiorno’s paper clarified that the optimal harvesting policy was related to the current state of forestry instead of the initial condition. The author also showed that the Faustmann formula was a special case of a Markov decision process model, in which the transition probabilities were unity or zero. But it failed to demonstrate how they incorporated stochastic prices into the model and focused mainly on the stochastic forest growth.

Susaeta, Alavalapati, and Carter (2009) developed an integrated Black-Scholes and modified Hartman model to analyze the impacts of price uncertainty on nonindustrial private forest management in the southeastern United States. The authors adopted Black-Scholes formula, which was widely used in finance, to calculate the volatility of stumpage price. Results showed that increasing price volatility increases LEV slightly, which could offset the cost of performing silvicultural activities like thinning, and it was profitable when pulpwood or forest biomass was incorporated in the model.

The application of the Faustmann model

Optimal rotation age has been widely investigated using a variety of methods and models, since it concerns the investment decisions in forestry management. The Faustmann model is one of the foundations in forest economics and it is the standard approach for the optimal rotation age problem, thus it is used in numerous applications. Assuming that future stumpage prices and yields are known and constant, the optimal rotation in the Faustmann model is the age at which the marginal gain in value of the forest resource equals the marginal cost of capital invested (Forboseh et al., 1996). Gaffney's (1957) classic paper is generally regarded as the beginning of the modern attempts and the first definitive analysis in establishing the superiority of the land expectation value method over other methods of rotation age determination (Chang, 1998).

Yet, the Faustmann model's validity is still questioned because it rests upon a series of over-simplified assumptions, which rarely, if ever, accord with reality (Grainger, 1968). The most common criticism is that Faustmann's formula gives the value of forestland under deterministic assumptions regarding future growth and prices (Buongiorno, 2001). The underlying assumption is that price and cost for the whole rotation is constant, which is unrealistic. People have attempted to address this problem. For example, Susaeta, Alavalapati, and Carter (2009) inserted a Black-Scholes model into Hartman model to represent the volatility of prices.

Not only are the price and cost in the Faustmann model assumed to be constant over one rotation, but also they are repeated in perpetuity, which is rarely achieved in practice. Chang (1998) was able to find the generalized Faustmann formula that allowed the harvest age to vary from timber crop to timber crop by varying stumpage price, cost, and interest rate from timber crop to crop. The resulting formula was a function of its own stand value and the land expectation value immediately after harvest.

Furthermore, even-aged forest is one of the assumptions in the Faustmann model that gets criticized, because it requires clear-cutting when harvesting. However, Zhang (2011) mentioned that if we treated the merchantable volume left after each partial harvest of an uneven-aged stand as a cost of regenerating the forest stand, the theoretical basis for maximizing the land and forest value in an uneven-aged stand was similar to that for maximizing the land expectation value of an even-aged stand. Thus, the Faustmann model has evolved into a more nuanced model.

Despite all the shortcomings with the Faustmann model, it is still a strong tool compared to other methods that estimate optimal rotation age in forest economics for the following two reasons. First, because of the simplicity of the Faustmann model, it could be modified to a more sophisticated formula depending on the needs of a variety of studies. For example, Hartman (1976) extended the Faustmann model to include standing trees' value; Reed (1984) combined a probability model and the Faustmann model to consider the risk coming from catastrophic events that can affect management strategy. Even though methods like linear programming could serve the same purposes, it requires more complicated estimation process. Additionally, several models that have more strict assumptions can be viewed as the variations of the Faustmann model. For instance, Buongiorno (2001) adopted a Markov Decision Model and derived that the Faustmann formula was a special case in which a few of the transition probabilities were equal to one and all others to zero. Thus the fundamental role of the Faustmann model cannot be neglected. Second, though LEV resulting from Faustmann tends to be higher, it is a good reference and the relative value could be used to compare different situations and scenarios. Furthermore, it is used extensively to examine which and how the factors affect land value and optimal rotation age, which is the primary goal of this study. Therefore, the Faustmann model is an appropriate foundation for the model that is used here and it also facilitates the comparisons of this study with those many others.

Summary

The above literature suggests that studies that could combine the effect of fire risk, carbon sequestration, and price uncertainty are rare, even though Sustaeta et al., (2009) did it with a mortified Hartman model and Black Sholes formula. Additionally, no comparison was made in Sustaeta's paper between strategy with and without price uncertainty. In particular, none of the studies investigated the joint effect of three factors on forests in Kentucky. However, Kentucky forests should attract more attention for being an important part of the Central Hardwood Forest Region (CHFR).

The CHFR is said to be the most extensive forest type in the United States. There are about 60 species of oak found in the United States of which at least 20 are important timber trees of the eastern forest (Brandt et al., 2014). Its various forest resources make significant environmental and economic contributions. On one hand, an average of 53 metric tons per acre carbon is stored aboveground and belowground (Brandt et al., 2014), which contributes largely to reducing the amount of greenhouse gases in the atmosphere. On the other hand, these forest resources play an important role with impacts ranging from employment and other value-added economic contributions to improving and protecting soil and water resources to providing wildlife habitat (Schmidt, and McWilliams, 2003).

Thus, this study aims at partially fulfilling this research gap by developing an integrated model to assess the individual and joint effect of carbon sequestration, fire risk, and price uncertainty on Kentucky forestland. Furthermore, it intends to make forest landowners and governments more environmentally and socially conscious.

The analysis is divided into two Chapters. Chapter 2 estimates in detail the influence of fire risk and carbon sequestration on forest land value, optimal rotation age and stand supply using a modified Hartman model, which lays a foundation for Chapter 3, which describes a model including price uncertainty. Different scenarios are modeled to provide information about carbon markets, and sensitivity analyses are made to investigate different levels of impacts of fire risk and price uncertainty.

Chapter 2 : Impact of carbon payment and fire risk on forestry management

In this chapter, a modified Hartman model (1976) was developed to determine the Land Expectation Value (LEV), optimal rotation age, and stand supply of sawtimber and carbon under risk of catastrophic mortality for a forest stand that produces both timber products and carbon benefits. By applying this model to forests in Kentucky, carbon price and fire risk's individual impact, as well as their joint effect on LEV, optimal rotation age, and stand supply was investigated.

In this model, two carbon market scenarios were chosen: *carbon market one* that assumes carbon payments start at age 1 and *carbon market two* that assumes carbon payments start after a baseline determined by the optimal rotation age when carbon price is $0 per metric ton. Scenarios are designed to look into the reactions of forest landowners' financial return and management decisions towards different carbon payment systems. In the first scenario (*carbon market one*), landowners get paid from the beginning of the rotation (year 1). However, since most mixed-hardwood stands would be managed for traditional timber products even without carbon offset payments (thus sequestering some carbon), some payment programs may want to consider additionality requirements. Therefore, an additional scenario (*carbon market two*) is modeled in which the landowner only gets paid for carbon sequestration that would occur in addition to that which would have occurred without carbon offset payments. Optimal rotation age without carbon benefits were determined first and then only carbon sequestered after this baseline age would be credited to landowners. The differences of LEV and optimal rotation age between two carbon markets could be seen through comparing the results.

In addition, a sensitivity analysis about fire risk and salvageable portion were made to test whether fire risk and the degree of damage could change forest landowners' harvest plans. By modifying carbon price, carbon's impact under various market conditions could be analyzed. There are three major parts in this section: first, a description of how the model was developed is laid out; second, data resource required in the model is described; third, results and conclusion are drawn.

Carbon Offset Scenarios

The way to internalize carbon benefit is that landowners are assumed to be paid for sequestrating and storing carbon while the stand is growing and also assumed to be charged a penalty for releasing carbon after harvest at the same price. The *carbon market one* scenario assumes that landowners get payment annually for carbon sequestration, which reflects the current carbon market situation. The results from *carbon market one* facilitate comparison to many others studies (Shrestha, 2013; Susaeta et al., 2009) similar one that also assumes *carbon market one* scenario. The owner is credited when the forest generates positive amounts of carbon above their baseline inventory and debited if the forest is managed in a manner that leads to a reduction in stored carbon (CXX, 2009).

Accounting for additionality, *carbon market two* assumes that forest landowners get paid annually for each year's carbon dioxide equivalent after the optimal rotation age when carbon price is $0 per metric ton. The optimal rotation age when carbon price is $0 per metric ton is treated as a baseline, and only additional carbon sequestrated after the baseline is paid for. Since landowners are paid after the baseline, they are only charged for carbon emission for carbon sequestered after the baseline year. It may be challenging to implement this rule in the real world. First, multiple factors besides financial return are considered in making decisions about when to harvest; second, not all forests are managed as even-aged stands. Yet, efforts have been made to deal with the obstacle. For example, the Chicago Climate Exchange provided approved quantification methodology including direct measurement and remote sensing technology to establish the baseline. In order to encourage high quality inventories, smaller discounts are applied to projects with a higher degree of accuracy for a given level of precision (CCX, 2009).

There are two main timber products in Kentucky: sawtimber and pulpwood. Since the pulpwood market is limited in Kentucky (Catron 2013), it is assumed that pulpwood is sold as woodenergy for free. Residue, which is defined as bark, leaves, or twigs, which is usually left on the site to decay, is sometimes sold as woodenergy[2]. In addition, carbon sequestration and carbon emission are included as forest products. Therefore, forest products in this model consist of sawtimber and carbon (sequestration and emission).

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[2] Woodenergy will be ignored in the analysis, since it does not make any profits.

Net carbon accumulated is found by subtracting emissions from the decay of forest products and emissions from catastrophic events (e.g. fire) from the total carbon accumulated in the living biomass (aboveground) (Dwivedi, 2009). Carbon sequestration volume refers to the amount of carbon stored in the total aboveground tree biomass[3] through photosynthesis and it can be derived from the volume of sawtimber and pulpwood. There are two sources of carbon emissions: one involves the carbon emitted at harvest from decay of forestry products and it can be calculated using a half-life function; the other is carbon emissions caused by catastrophic events such as fire.

The forest products composition as a function of stand age is demonstrated in Figure 2.1. As shown, the total aboveground tree biomass consists of sawtimber, pulpwood, and residue. In terms of non-traditional forest products, carbon sequestration is from the volume of total aboveground tree biomass; carbon emissions of decay are estimated from volume of sawtimber[4] while carbon emissions from catastrophic events are estimated from the volume of the total aboveground tree biomass.

Under each scenario, there are three sensitive analyses: one considers carbon price ranging from $0 per metric ton to $25 per metric ton; one considers fire risk, rates ranging from 0.0% to 3.0%[5], and the last one considers salvageable portion ranging from 0% to 50%. When carbon price is $0 per metric ton, sawtimber is the only forest product,

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[3] Carbon sequestration from underground is not considered, since it is a conservative estimation.

[4] Carbon emission from pulpwood and residue is not included is because that they are sold as woodenergy, which could be offset by the reduction of carbon emission compared to that from using fossil fuel for electricity.

[5] Scenarios that fire risk is 4.0%, 5.0%, and 10.0% were modeled. Since the results demonstrate the same trend as the one when fire risk is 3%, they are not presented.

which represents the Faustmann model. The optimal rotation age of the situation where carbon price is \$0 per metric ton reflects the optimal decision without the influence of the carbon market. When carbon price is above \$0 per metric ton, forest products include sawtimber and carbon. Furthermore, when fire risk is zero, forest landowners' decisions will not be affected by the fact the fire could happen, damage the forest, and reduce their financial return. The effect of fire on the final decision of management is considered when probability of fire is not zero. When fire risk is 3.0%, it means that there is a 3 in 100 chance each year of a fire occurring. In general, after a fire, part of a forest will be destroyed and the other part will survive – this is referred to as salvageable portion. When salvageable portion is 0%, it means that after a fire, all the trees are destroyed; when salvage portion is 50%, it means half the trees survive.

Table 2.1 shows the scenarios structure in this study: there are two scenarios and three sensitivity analyses under each scenario. First, probabilities of fire occurring of 0.0% and 3.0% are modeled; second, salvageable portion of 0% and 50% are considered; third, carbon prices of \$0, \$1, \$5, and \$25 per metric ton[6] are included.

According to the aforementioned scenario definitions, carbon emission without fire risk only comes from decay after harvest; carbon emission with fire risk is from both decay of forest products after harvest and immediate release due to catastrophic mortality.

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[6] Scenarios that carbon price is 10 and 1\$5 per metric ton have modeled. Since the results follow the pattern when carbon price is \$5 per metric ton, they are not presented. Also, carbon price higher than \$25 per metric ton is assumed to have similar impact on forestry management.

Methodology

The foundation for modified Hartman model (1976) is Faustmann model (1995) that is a traditional model developed for estimating LEV and optimal rotation age when the only value from the forest is from the products produced upon harvest. The Hartman model extends the Faustmann model to include income streams from standing trees. Thus we use the Hartman model to model the value of carbon sequestered in trees as the stand grows. Later, catastrophic events' impact was introduced by Reed's model. In this study, the priority is to investigate the influence of both catastrophic event and carbon price. Therefore, the model adopted is the combination of Hartman and Reed's model. Following other studies using Faustmann model, the analysis is built on four specific, simplifying assumptions. The first assumption is that the decision is about when to harvest and regenerate a single, even-aged stand. To do so, trees are supposed planted on a bare land at the same time and when harvest, clear cutting is the only option. Second, it is assumed that price and expenditure will be repeated over rotations and is spread uniformly over every productive acre. Third, forest landowners can harvest and reinvest in a new stand on the same land. Forth, there is no management cost included in this model. It implies that the financial return and change in market will not change the individual's ownership of land. Forth, there is no cost included in this model because passive management is the typical management in Kentucky. [7]More realistic assumptions will impact on the results. First, selective harvest usually generates higher land expectation value. However, since passive management is the typical management in Kentucky, selective harvesting is not adopted widely. Second, price fluctuation from year to year makes the land value and optimal rotation age even harder to predict depend on the variance of price data. Third, forestland owners opt to invest more land if high prices of forest products are foreseen or choose to do the opposite if price of forest products keep decreasing.

In the following, introductions are given about traditional Fuastmann, Hartman, and Reed's model and the modified Hartman model is described; stand supply model is laid out, since any change related to optimal rotation age can cause a change of stand supply including both sawtimber and pulpwood.

Modified Hartman model

Faustmann model (1995) is used to maximize Land Expectation Value (LEV) and determine the optimal rotation age. LEV is the present value of profit from growing an infinite number of identical forest rotations, and optimal rotation age is the age that could maximize the land expectation value of forest and is theoretically the best age to harvest. Equation (2.1) lists the general form of Faustmann model.

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[7] Model that includes a property tax as management cost was run, and it showed the similar result as model without cost, since cost was small.

$$LEV(t) = \frac{P*Q_t*e^{-rt}}{1-e^{-rt}} \tag{2.1}$$

Where *LEV (t)* is the land expectation value at time *t*, *P* is the price of forest products, Q_t is the volume of forest products as a function of *t*, *r* is the real discount rate, *t* is the stand age, and *t* ranges from 0 to 80 years[8].

Function (2.1) gives the present value of the stand for each year *t* if forest is harvested. The year *t* that yields the highest LEV is the optimal rotation age. In Faustmann model, forest products can be sawtimber, pulpwood, woodenergy, or any product obtained from the harvest of trees.

Traditional Faustmann model only applies to forestry products that have value only after harvest. Timber products like sawtimber are paid when they are harvested, while carbon sequestration is paid annually before harvest. Therefore, the ways to calculate the values of timber products and carbon products are different. Hartman model (1976) is developed on the basis of Faustmann model and can include annual income from forest, like recreational value, wildlife value or carbon sequestration benefits. Carbon emission is from decay of timber products, so it is assumed to begin after harvest. Thus, carbon emission shares the same payment method with sawtimber. The general form of Hartman model that includes carbon value is listed in equation (2.2).

$$LEV(t) = \frac{PS*QS_t*e^{-rt}+\sum_0^t PC*(QCS_t-QCS_{t-1})*e^{-rt}-PC*QCE_t*e^{-rt}}{1-e^{-rt}} \tag{2.2}$$

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[8] 80 years is the limit for trees biologically. Also, since the data set is up to 80 years, it can not be assured that the prediction data beyond 80 years is with high accuracy.

Where, PS is price of timber products (sawtimber), QS_t is the volume of timber products, PC is carbon price for both carbon sequestration and carbon emission, QCS_i is the carbon sequestration increment of each year, and QCE_i is the carbon emission volume. Carbon emission value is separate from timber products to differentiate traditional forestry products and non-traditional forestry products.

Faustmann model sets decision-making process in a deterministic situation. However, forest landowners face risks like fire, insect out break or severe weather, which could influence their management strategy. Traditional Faustmann model fails to include this factor, therefore Reed (1984) modified Faustmann model to incorporate fire risk. This model is presented in equation (2.3).

$$LEV(t) = \frac{\lambda+r}{r*(1-e^{-(\lambda+r)*t})} * \left(PS * QS_t * e^{-(\lambda+r)*t}\right) + \frac{\lambda+r}{r*\left(1-e^{-(\lambda+r)*t}\right)} * \sum_0^t \lambda * k * PS * QS_t * e^{-(\lambda+r)*t} \qquad (2.3)$$

Where λ is the risk of fire each year, k is the salvage part that represents the survival rate of trees from fire risk. Basically, function (2.3) consists of two parts: the first part stands for the value if it reaches the optimal rotation age adjusted for the probability of reaching that age, and the second part represents the value of the forest stand if fire occurs before the optimal rotation age. When fire risk λ is zero, the model reduces to traditional Faustmann model.

Susaeta (2009) and Stainback (2004) incorporated carbon and catastrophic risk into one function based on Hartman model and Reed's model, which provides references for the modified Hartman model used for this study that is listed in the following.

$$LEV(t) = \theta * (f_1(t) + g_1(t) - h_1(t)) + \theta * \sum_0^T(\lambda * k * f_1(t) + \lambda * g_1(t) - \lambda * h_1(t) - \lambda * k * h_2(t)) \qquad (2.4)$$

Where $f_1\ (t)$ is the discounted timber value, $g_1\ (t)$ is the discounted carbon benefit, $h_1\ (t)$ is the carbon emission value from decay when there is fire risk, $h_2\ (t)$ is the carbon emission from catastrophic events, and θ is the discounted factor that discounts future rotations.

$$\theta = \frac{\lambda + r}{r * (1 - e^{-(\lambda + \square) * t})} \qquad (2.5)$$

$$f_1(t) = PS * QS_t * e^{-(\lambda + r) * t} \qquad (2.6)$$

$$g_1(t) = \sum_{i=1}^{t}(PC * (QCS_i - QCS_{i-1}) * e^{-(\lambda + r) * t} \qquad (2.7)$$

$$h_1(t) = PC * QCED_t * e^{-(\lambda + r) * t} \qquad (2.8)$$

$$h_2(t) = PC * QCEF_t * e^{-(\lambda + r) * t} \qquad (2.9)$$

Equation (2.5) is the discounted factor in detail. Equation (2.6) represents the discounted timber value. Equation (2.7) represents the discounted carbon value. In equation (2.8) $QCED_t$ is carbon emission from decay of forest products and in equation (2.9) $QCEF_t$ is carbon emission from fire, λ is fire risk for each year, and k is the salvageable portion, which indicates (1-k) of the stand was destroyed. Therefore, Equation (2.4) is the development of Hartman model and Reed's model with two products and fire risk in consideration: the first part stands for the value including sawtimber, carbon sequestration, and carbon emission if it reaches the optimal rotation age adjusted for the probability of reaching that age, and the second part represents the sawtimber, carbon sequestration, and carbon emission value of the forest stand if fire occurs before the optimal rotation age. Like Reed's model, the modified Hartman model could be easily applied to no fire risk situation by making fire risk zero.

Stand supply model

The net carbon sequestered in forest biomass will conceivably improve the profitability of forestry management by providing an extra income to the landowner. Carbon payments are also expected to influence the optimum rotation age of the forest stand, which will have an indirect impact on timber supplies (Puneet Dwivedi et. al, 2009). As a result, it becomes imperative to investigate the impact of optimal rotation age and carbon price on forestry products supply (sawtimber and carbon).

Supply of sawtimber as a function of optimal rotation age was estimated for two carbon market scenarios. The amount of sawtimber is annualized by modeling a regulated forest[9] stand as shown in Equation (2.10) (Shrestha, 2013).

$$SS_T = \frac{QS_T}{T} \tag{2.10}$$

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[9] A regulated stand is on where an equal portion, 1/T, of it is harvested each year, where T is the rotation age.

Where SS_T is the annual supply of sawtimber from a regulated forest stand; QS_T is the volume of sawtimber in the stand at the optimal rotation age T. The supply model is applied for each carbon market scenario and sensitivity analysis.

Function (2.10) yields the average sawtimber supply every year under different carbon prices and scenarios, thus an analysis of carbon price and fire risk's influence on sawtimber was conducted. However, the part of sawtimber supply burned is not included in this model.

Carbon supply is modeled as the average amount of carbon sequestered in the stand over the length of one rotation. The function to estimate carbon supply is shown is equation (2.11).

$$SC_T = \frac{\sum_0^T QC_T}{T} \tag{2.11}$$

Where SC_T is the supply of carbon as a function of carbon price; QC_t is the quantity of carbon sequestered at age t. As shown, total carbon supply is simply the average of cumulative carbon over time T and fire risk's direct impact on biomass is not factored.

Data

Study area is the forest area in Kentucky and site index 65 is chose. Site index represents the forest quality and is commonly measured by tree height: if the average height of tallest trees at age 50 on that site is 55 feet, then the site index is defined as 55. In Kentucky area, site index 65 is the average site index. Kentucky belongs to the Central

Hardwood Forest Region (CHFR) where the dominant forest type is oak-hickory. Kentucky’s forests cover an estimated 12.4 million acres or 49% of the State, among which 98% of the forestland is considered available for timber production and the remaining forestland area is unproductive forestland and reserved forestland where timber removals are prohibited by law (Kentucky Division of Forestry, 2011). Over the last several years, there has been relatively no change in ownership patterns in forestland. Private individuals own 88.5% of the forested land. The U. S. Forest Service manages 6.5% and other federal, state and local ownerships manage the remaining 5% (Kentucky Division of Forestry, 2011).

Growth and yield data

Research was conducted by the U.S. Department of Agriculture (USDA) Forest Service that lasted more than 20 years to measure the growth and yield of hardwoods in the Central States including Kentucky, Ohio, Missouri and Iowa. Based on this research, Gingrich (1971) predicted the volume of sawtimber and pulpwood from age 20 to age 80 with 10-year intervals according to the stand characteristics.

The yield data from Gingrich (1971) was fitted using nonlinear regression estimated by Stata to equation (2.12):

$$QS(t)/QP(t) = a * t^{b} * e^{-c\square} \tag{2.12}$$

Where *QS (t)* is the volume of sawtimber with respect to time, *QP (t)* is the volume of pulpwood with respect to time, *t* is stand age, and *a*, *b*, *c* are parameters to be estimated. Shrestha (2013) gave the estimated parameter of *a, b, c* that is shown in Figure 2.2 and Figure 2.3. As listed in Figure 2.2 and 2.3, the R^2 and adjusted R^2 are relatively high, which means the estimated parameters predict realistic timber yields. Figure 2.2 and Figure 2.3 shows the original and fitted yield data.

The amount of residue volume is the difference between total aboveground tree biomass and merchantable volume. The ratio of above ground tree biomass to merchantable volume for hardwoods in South Central area of the U.S. was estimated to be 2.12 (Birdsey, 1996). The merchantable volume was calculated by adding the volume of sawtimber and pulpwood.

The amount of carbon sequestration was estimated by multiplying the total aboveground tree biomass by the conversion factor 19.82 to obtain carbon in pounds (Birdsey, 1996). This could transfer merchantable biomass in cubic feet to carbon equivalent volume in pounds. Sequestered carbon was converted into carbon in metric tons and then was multiplied by 3.67 to convert it to carbon dioxide equivalents. The process is presented in Figure 2.4.

Carbon emitted from decay was modeled based on a half-life decay function. Here the half-life is assumed to be 100 years for sawtimber (Dwivedi et al., 2012). This means that half of the carbon stored in sawtimber will be released in the atmosphere in 100 years after harvest. Carbon emissions here only account for emissions from sawtimber. In terms of carbon emissions from pulpwood and residue, it is assumed to be sold as woodenergy, so it is offset by the carbon emissions avoided if that quantity of electricity was produced from fossil fuel. The decay function is given in equation (2.13):

$$QCAD(t) = QI * e^{-\mu * t} \qquad (2.13)$$

Where *QCAD (t)* is the current quantity of sawtimber at age *t* that accounts for carbon emission from decay, *QI* is the initial quantity, μ is the half-life, and *t* is stand age.

Price data

Timber prices were from Timber Market South. The data set included quarterly stumpage price of sawtimber in Kentucky from the second quarter in 1980 to the second quarter in 1994 for a total of 57 quarters. After 1994, Timber Market South stopped collecting timber price data from Kentucky. Prices were converted to 2013 dollars using the Consumer Price Index (CPI) provided by the Bureau of Labor Statistics (2013). It can be seen that the price tends to increase overall over time but there does not appear to be any particular seasonal trend: the lowest price was $10.38 per ton and occurred in 1985; the highest price was $30.37 per ton and it occurred in 1994. The average for the 57 quarters was $18.81 per ton, which is used for sawtimber price.

A sensitivity analysis of carbon price was conducted based on current carbon market and social cost of carbon. They are several carbon markets, including voluntary and mandatory carbon markets, existing in U. S. and Europe. According to a literature review by Shrestha (2013), the carbon price ranges from $0.11 per metric ton (CXX, 2010) ton to $16.53 per metric ton (MACED). In general, social cost of carbon is higher than carbon price in current carbon prices. Tol (2008) did a meta-analysis about 211 estimates of social cost of carbon. Data set of carbon prices ranges from $20 per metric ton to $200 per metric ton. Results show that the mean price of carbon is $23 per metric ton and the certainty-equivalent is $25 per metric ton with the consideration of risk. More importantly, there is a 1% probability that the social cost of carbon is greater than $78 per metric ton. Therefore, carbon prices of $0, $1, $5, and $25 per metric ton were chosen based on different current carbon markets and social cost of carbon. Specifically, the choice of $25 per metric is to reflect social cost of carbon.

Results and discussion

Results were generated based on modified Hartman models and the analysis is divided into three major parts based on carbon markets: the first part analyzes the impact of carbon price and fire risk in *carbon market one* scenario; the second part analyzes the impact of carbon price and fire risk in *carbon market two* scenario; the third part involves the comparison of results between the two scenarios. Under each part, the organization follows the sequence: impact on LEV; impact on optimal rotation age; impact on stand supply.

Impact of carbon price and fire risk on carbon market one which carbon payment starts at age one of stand

1. *Impact on LEV*

The results for LEV and optimal rotation age in *carbon market one* scenario are shown in Figure 2.5 and Figure 2.6. It is expected that when carbon price increases, LEV increases no matter whether fire risk and salvage portion are considered or not. When carbon price is $0 per metric ton, LEV reflects the financial return to forest landowners without the influence of carbon market and it is relatively low compared to LEV with carbon benefit, which indicates that carbon benefit could be a potent financial source for forest landowners. The role of carbon in the total land expectation value escalates as carbon price goes up. Especially, for carbon price of $25 per metric ton, LEV is increased from $11 per acre to $1,174 per acre when salvageable portion is 50%, which is more than 100% increase[10].

Theoretically, LEV when fire risk is taken into account is less than that when fire risk is not considered, owing to the fact that fire could cause damage to the stand. Based on Figure 2.5, LEV when salvageable portion is zero is always lower than LEV when there is no fire risk at all, which complies with the above theory. As carbon price increases, the difference between LEV when salvageable portion is zero and LEV when

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[10] Results of LEV reflect the average level of financial return that landowners could achieve under optimal practice.

fire risk is zero gets bigger. Also, LEV when salvageable portion is zero is always lower than LEV when salvageable portion is 50%.

Generally, fire risk is a negative influence to financial return because it causes depreciation of stand value and releases carbon back into the atmosphere. However, when salvageable portion is 50%, LEV result contradicts with this trend. Contradiction does not show until carbon price is above or equal to $5 per metric ton. The reason originates from the model itself. With fire risk the model assumes a small portion (determined by the level of risk) is burned each year and some of this unburned portion (the salvageable part) is sold as sawtimber. Recall equation (2.4), the model consists of two sections: one models the value when there is no fire; the other one models the accumulated annual value when there is fire. Based on the observation of result data, the value of first part is always lower than the land expectation value assuming no fire risk. When fire happens forest landowners are still paid if fire happens for the part of the stands that is not harmed. This payment is represented by the second part in the model with fire risk. Thus when carbon prices and/or sawtimber prices are high enough, the value of the unburned part becomes large, which makes LEV higher with risk than without. In this case, when carbon price is $0 per metric ton, LEV with 50% salvageable portion is lower than LEV without fire risk. This indicates that sawtimber value does not cause the high LEV with 50% salvageable portion. Therefore, in our model LEV is larger with risk than without risk when carbon price is above $5 per metric ton.

In this model, fire risk is modeled 3% and the salvageable portion is 50%, which means that there is 3% chance that fire will happen before maturity age and destroy half the trees, which is a relative small damage to the trees considering the low probability of fire. Furthermore, it means that there is 3% chance that landowners are paid for the unburned half of stand for sawtimber and carbon each year. This amount of payment is supposed to be small, but it increases due to the high carbon price. When there is fire risk, the model is analogous to uneven-aged management. The intuitive interpretation of this result is that with no fire risk the landowner has to harvest all trees or none—in other words even-aged management is the only option. However, the theoretical basis of this model for maximizing the land value under fire risk is similar to that for maximizing the LEV of an uneven-aged stand. Besides, the year after a fire, new trees are planted and landowners are by carbon immediately for new tree biomass (on the burned portion). Therefore, LEV with 50% salvageable portion is higher than LEV without fire risk under current assumptions of this model. Since the higher LEV result is an artifact of the model, caused by the limitation of this model, it does not mean forest landowners prefer fire risk in reality. In addition, optimal rotation age and stand supply results with 50% salvageable portion are affected by limitation that assumes even-aged management. However, results without fire risk and with 0% salvageable portion are not compromised because they reflect results of even-aged management.

2. *Impact on optimal rotation age*

In terms of the impact on optimal rotation age, it exhibits similar trends with LEV as shown in Figure 2.6. In the absence of carbon market, it is most profitable for forest landowners to harvest at age 61 if fire is not involved. However the optimal rotation age slightly declines when fire risk is considered and declines even more when the salvageable portion is reduced to zero. This means that both the increase of fire risk and reduction of salvageable portion could reduce optimal rotation age in the situation where carbon market is not available. This is consistent with expectation. The fear of fire could force forest landowners to cut earlier so that they could benefit from total tree biomass. Otherwise, they could suffer loss from catastrophic events. Moreover, with the deterioration of salvageable portion, it is in forest landowners' best interest to harvest even earlier.

As carbon price increases, optimal rotation age in the three sensitivity analyses keeps increasing. Since carbon becomes more valuable due to the price increase, it seems more beneficial to delay harvesting. In particular, when salvageable portion is 50%, rotation age increases up to 80 years or beyond[11] when carbon price reaches $1 per metric ton. This implies that forest landowners receive a healthy profit for carbon sequestration as long as they keep the stand, which pushes the optimal rotation age to 80 years, or even beyond. It was mentioned in the section on LEV that fire plays the role of uneven-aged management. In this model, the probability of fire is 3.0%, it means that

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[11] In this model, rotation age ranges from 0 to 80 years.

there is 3.0% chance that half of the stand will be replaced by new trees after a fire. The new biomass from replanted trees delays the maximized point of total tree biomass, and it causes the LEV to keep increasing until 80 years or beyond, thus ending with a longer rotation age than others. Theoretical and empirical results from other studies have also indicated that, under some situations, it is optimal never to harvest the trees. Zhang (2011) mentioned that a logical extension discussion of the Hartman model is that for some standing forests, the non-timber benefits might be so great that it would not be economically feasible to harvest the forests at any time in the future. Van Kooten et al. (1995) shows that for costal British Columbian and northern Alberta the optimal strategy is to never harvest under certain carbon tax regimes. However, optimal rotation age only increases 5 years without fire risk and 10 years with 0% salvageable portion from $0 to $25 per metric ton of carbon price.

The presence of carbon market influences the impact of fire risk on optimal rotation age. Normally, rotation age with fire risk should be shorter than rotation age without fire risk. From Figure 2.6, it is noticed that optimal rotation age with 0% salvageable portion is shorter than that without fire risk; yet, optimal rotation age with 50% salvageable portion is longer than that without fire risk. This is because of the way risk is incorporated in the model, as is discussed above in the section on LEV. Since carbon is so beneficial that it causes the LEV to keep increasing with respect to stand age when salvageable portion is 50%. Therefore, forest landowners should postpone harvesting as long as possible because they can make great profits from carbon. However, if the landowners are given the option of selective cutting or uneven-aged management in this model, LEV with 50% salvageable portion may not be higher than LEV without fire risk.

3. *Impact on stand supply*

Price variation of carbon leads to different optimal rotation ages, which results in the alteration of stand supply. Accordingly, carbon price indirectly changes supply of sawtimber and carbon. Stainback and Alavalapati (2002) found that as carbon price increases, optimal rotation age increases, which results in the increase of sawtimber and the decrease of pulpwood. Because volume of sawtimber kept increasing with respect to rotation age while pulpwood started to decline after a certain age.

The corresponding annual sawtimber supply and total carbon supply with respect to varying optimal rotation age are shown in Figure 2.9. Both sawtimber annual supply and carbon total supply are the average supplies; sawtimber supply is the average supply provided by forests for each year depending on the optimal rotation age. Carbon supply is the average supply provided by forests for the entire rotation depending on the optimal rotation age. The direct relationship of optimal rotation age and annual sawtimber supply/carbon supply is presented. Sawtimber annual exhibits a two-stage development. First, supply increases as optimal rotation age increases, which is caused by fast growth in stage one. Then, supply slowly decreases after maximization in stage two. Also, the year yields highest annual supply is 73. Carbon total supply keeps increasing with optimal rotation age.

Moreover, it is important to find the dynamic linkage of carbon price and stand supply, because it reveals how sensitive stand supply is to carbon price alteration. Figure 2.10 shows the annual sawtimber in relation to varied carbon prices for *carbon market one* scenario. For carbon price sensitivity analysis, annual sawtimber supply displays an increasing trend as carbon price increases with and without fire risk, which means that carbon has a positive influence on sawtimber. When salvageable portion is 0%, annual sawtimber supply is most sensitive to the change of carbon price and the increase is around 50% for carbon price changing from $0 per metric ton to $25 per metric ton. Yet, when fire risk is not considered, carbon price has the least impact on sawtimber supply, and the increase is about 10% for the same price range. Also, fire risk does not necessarily decrease sawtimber supply. When salvageable portion is 50%, supply is higher with risk if carbon market is available. This higher supply arises from the optimal rotation age: the sawtimber annual supply reaches its highest point at age 73. When salvageable portion is 50%, the optimal rotation age is 80 years under this model and it is closer to the maximized sawtimber supply point than without fire risk[12]. Therefore, when optimal rotation age is 80 years, it creates a higher sawtimber supply.

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[12] The assumption under this model is that rotation age is 80 years. If optimal rotation age is much higher than 80 years, supply with 50% salvageable portion is not necessarily closer to the maximized point of supply than without fire risk.

Figure 2.12 lays out the total carbon supply with respect to carbon prices. As displayed in the figure, carbon total supply increases with the increase of carbon price. Because high carbon price generates high optimal rotation age, and high optimal rotation age yields high carbon total supply on average. When salvageable portion is 50%, carbon supply significantly increases as carbon price increases, and it is caused by high optimal rotation age. Indirectly, it suggests that higher carbon price increases total carbon supply in *carbon market one* scenario.

Impact of carbon price and fire risk on carbon market two which carbon payment starts at baseline

1. *Impact on LEV*

For *carbon market two* scenario, carbon payments only start after the stand age exceeds the optimal rotation age with no carbon payments. They occur at different stand ages with different assumptions of risk and salvageable portion. The results of LEV and optimal rotation age for *carbon market two* are shown in Figure 2.7 and Figure 2.8. LEV seems to have an increasing trend as carbon price increases with and without fire risk. For example, when salvageable portion is 50%, LEV increases from $11 to $19 per acre when carbon price increases from $0 to $25 per metric ton. Also, it conveys the tendency that LEV without fire risk is always higher than LEV with fire risk; LEV with 50% salvageable portion is always higher than that with 0% salvageable portion most of the time. When carbon price is $25 per metric ton, the LEV with 0% salvageable portion is slightly higher than the LEV with 50% salvageable portion. Since the two situations have distinct baseline optimal rotation age, they have separate start point for carbon payment. When salvageable portion is 50%, carbon payments begin at age 58. However, when salvageable portion is 0%, carbon payments begin at age 55. Therefore, the cumulative carbon value with 0% salvageable portion is much higher than that with 50% salvageable portion when carbon price is $25 per metric ton, high enough to cover the 50% more value loss from fire.

2. Impact on optimal rotation age

As carbon price increases, optimal rotation age becomes longer as expected. For instance, optimal rotation age is 55 years when carbon price is $0 per metric ton whereas optimal rotation age is 68 years when carbon price is $25 per metric ton with 0% salvageable portion. Furthermore, the increment ranges from 10 years to 15 years for carbon price changing from $0 to $25 per metric ton in general. Regarding of the comparison of results with and without the impact of fire, optimal rotation age without fire risk is longer than that with 0% salvageable portion for all carbon prices. When carbon price is equal to or below $5 per metric ton, optimal rotation age with 50% salvageable portion is lower than that without fire risk. While when carbon price is $25 per metric ton, result is the opposite. This is caused by the different times o start carbon payments. The baseline of carbon payment is age 61 without fire risk. The baseline of carbon payment is age 58 for 50% salvageable portion. The baseline is age 55 for 0% salvageable portion. Earlier baseline of carbon payments result in being paid earlier to landowners, which causes bigger impact by carbon price. When carbon price is relatively low, fire risk plays an essential role in the joint effect. However, when carbon price is high, carbon payment mitigates the impact of fire risk and has a bigger influence in the joint effect on optimal rotation age. It is expected that optimal rotation age becomes longer with greater impact from carbon value. Therefore, optimal rotation age with 50% salvageable portion is slightly higher than that without fire risk due to impact of carbon value.

3. Impact on stand supply

Figure 2.11 shows the annual sawtimber for *carbon market two*. Annual sawtimber supply displays similar trend as *carbon market one*. Generally, sawtimber supply increase with respect to carbon price. Under most of the situations, fire risk and decreasing salvageable portion cut down sawtimber supply. One exception is that when carbon price is $25 per metric ton, the sawtimber supply with 50% salvageable portion is higher than the one without fire risk. This is caused by two year longer optimal rotation age with 50% salvageable portion.

Figure 2.13 shows the total carbon supply with respect to carbon prices. It shows the similar trend with the optimal rotation age in *carbon market one* scenario, but the high carbon supply when salvageable portion is 50% only shows for carbon price $25 per metric ton. Because the baseline optimal rotation age mitigates the impact of carbon payments.

Comparisons of results between two carbon scenarios (carbon market one and carbon market two)

The design of carbon market system is not only related to the financial benefit for forest landowners, but also concerns the impact and efficiency of carbon markets.

Carbon payment of *carbon market one* begins much earlier than *carbon market two*, therefore, it is expected that LEV of *carbon market one* is higher than that in *carbon market two*. Besides, the difference of LEV from two markets becomes more distinctive as carbon price increases. The most significant change happens when carbon price is $25 per metric ton. For example, LEV is $996 per acre increasing from $33 per acre in market one scenario while LEV is $52 per acre increasing from the same value in *carbon market two* scenario. This result shows that both increasing carbon price and longer carbon payment period could be effective tools to promote financial return for forest landowners.

Optimal rotation age with fire risk and with 0% salvageable portion is shorter in *carbon market one* than that in *carbon market two*. This indicates that even though forest landowners are paid much more in *carbon market one* scenario, they are not willing to harvest later under the two situations. Since carbon payment of *carbon market one* scenario start as soon as there is positive tree biomass, it means that they can receive payment of carbon immediately after the trees are regenerated after harvest. Therefore, harvesting does not mean the stop of carbon benefit. For forest landowners under *carbon market two*, harvesting means that they could not receive payment for carbon until baseline optimal rotation age is reached in this study, so they wait longer to harvest.

When salvageable portion is 50%, optimal rotation age is 80 years or is over 80 years under *carbon market one* scenario. However, optimal rotation age in *carbon market two* does not exhibit this trend.

The results show that sawtimber annual supply increase in both carbon market scenarios with respect to carbon prices, which implies that the presence of carbon market and the increasing of carbon price would not decrease sawtimber supply. Sawtimber annual supply in *carbon market one* scenario is lower than that in *carbon market two* scenario when fire risk is not considered and when salvageable portion is 0%. However, when salvageable portion is 50%, the sawtimber supply in *carbon market one* scenario is higher.

In terms of carbon supply, two carbon markets generates similar carbon supply trend. In *carbon market two* scenario, optimal rotation age is slightly higher under most circumstances (without fire risk and with 0% salvageable portion) than that in *carbon* *market one*, which causes slightly higher carbon supply. However, when salvageable portion is 50%, carbon supply in *carbon market one* is much higher than that in *carbon market two* due to 80 years optimal rotation age, which is the result under this model instead of the situation in real world.

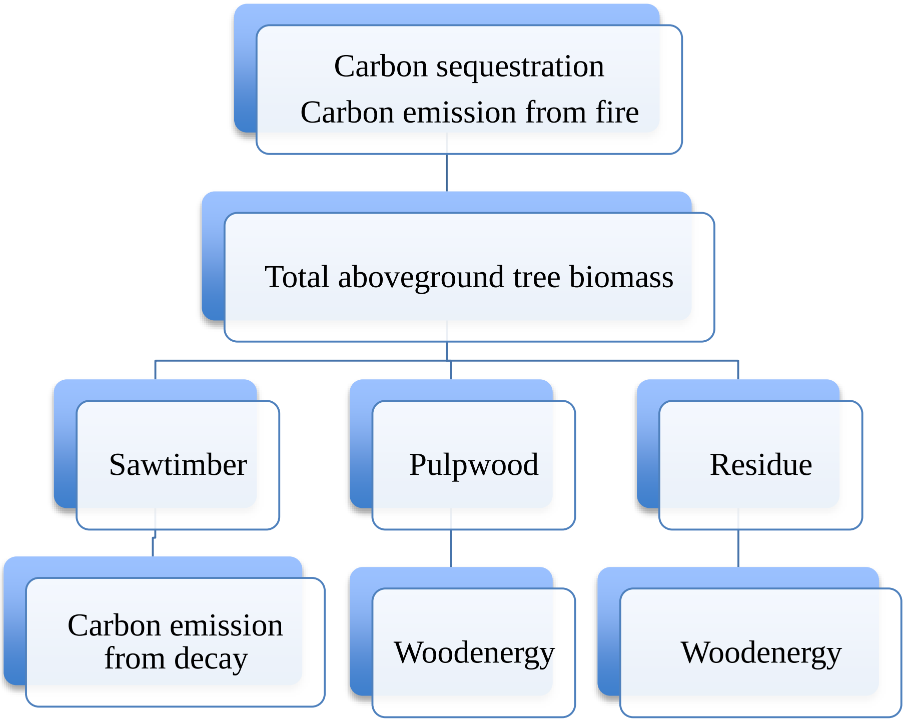

Figure 2.1. Derivative of sawtimber volume, woodenergy volume, carbon sequestration, and carbon emission from the total aboveground tree biomass

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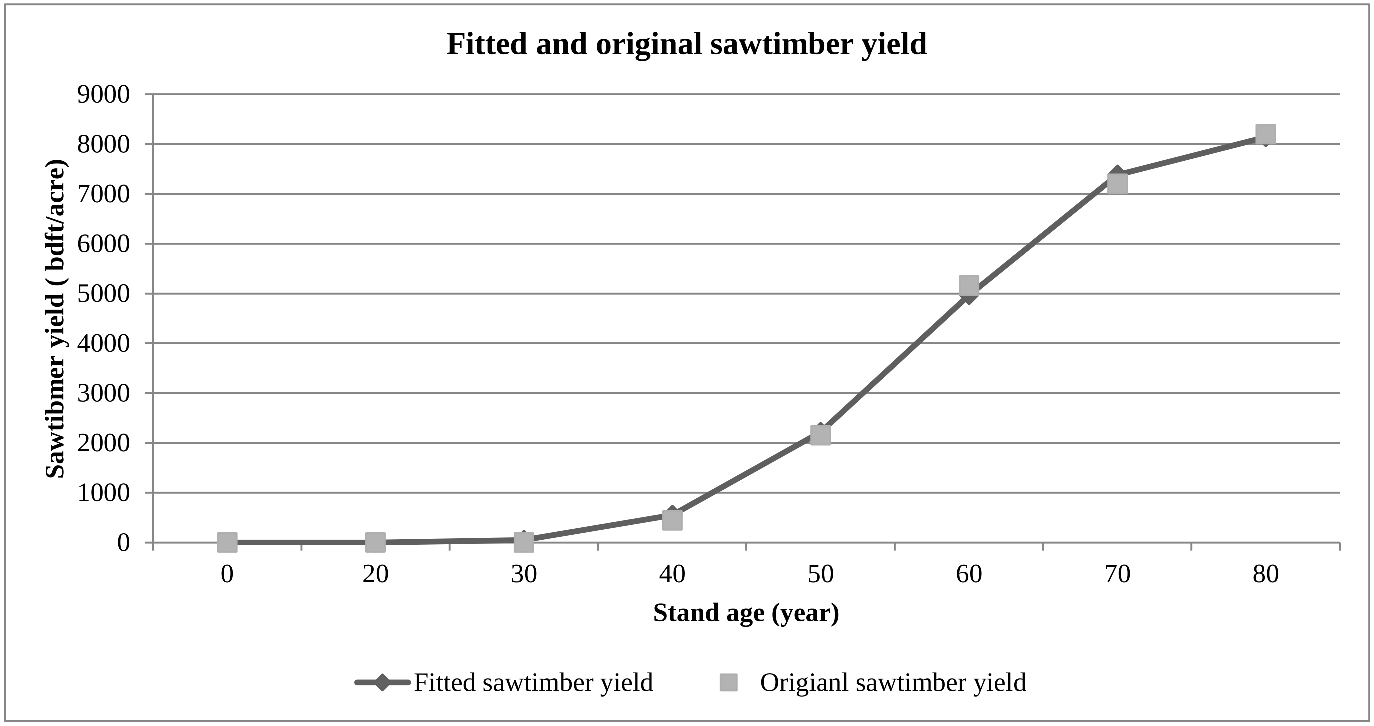

Figure 2.2. Comparison of original and fitted yield data for sawtimber (bdft)

The estimated parameters a, b, and c for fitted pulpwood yield is 0.0076, 3.856281, and 0.050801.

The R^2 for regression is 0.9983 and adjusted R^2 is 0.9974.

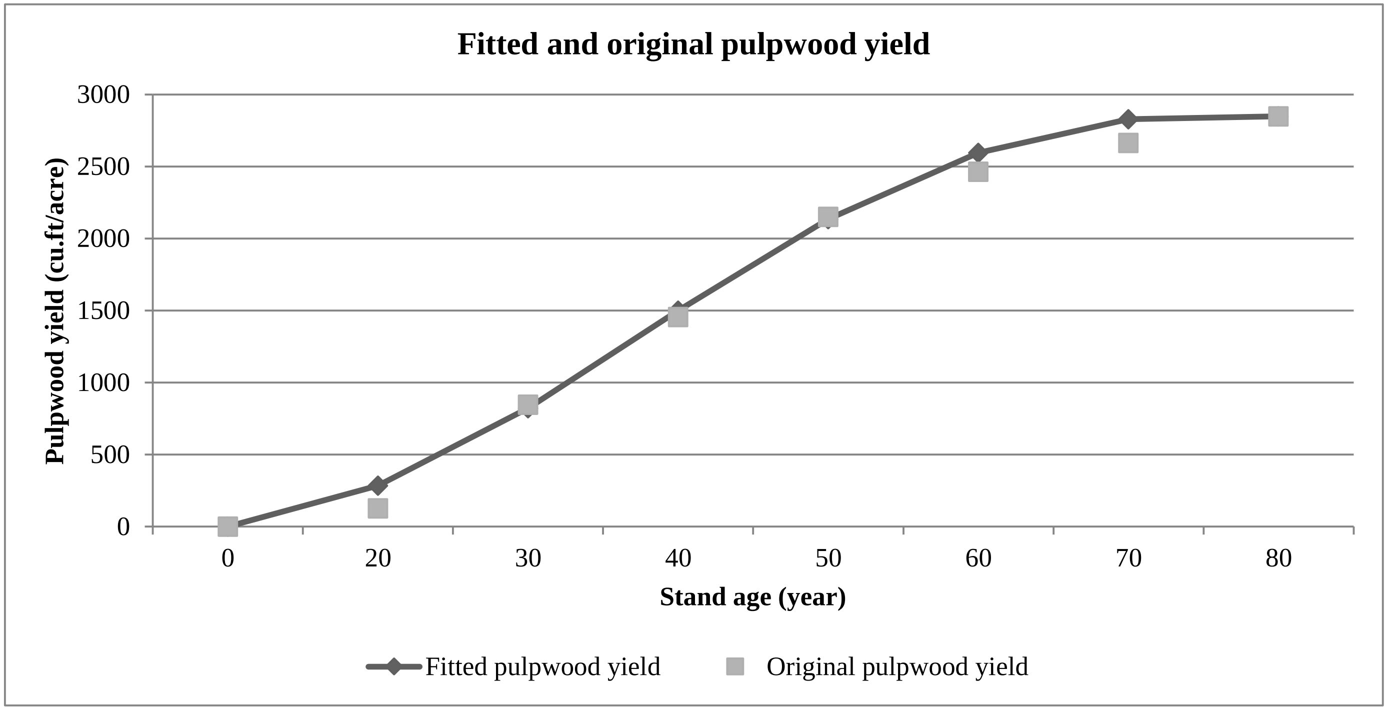

Figure 2.3. Comparison of original and fitted yield data for pulpwood (cuft)

The estimated parameters a, b, and c for fitted pulpwood yield is 0.0076, 3.856281, and 0.050801.

The R^2 for regression is 0.9983 and adjusted R^2 is 0.9974.

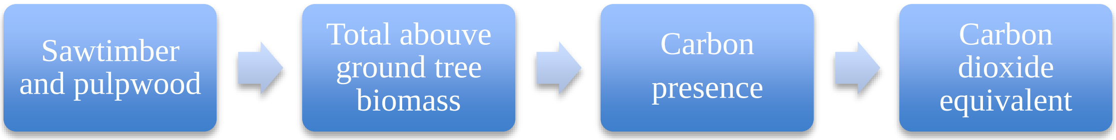

Figure 2.4. Process to convert tree biomass to carbon dioxide

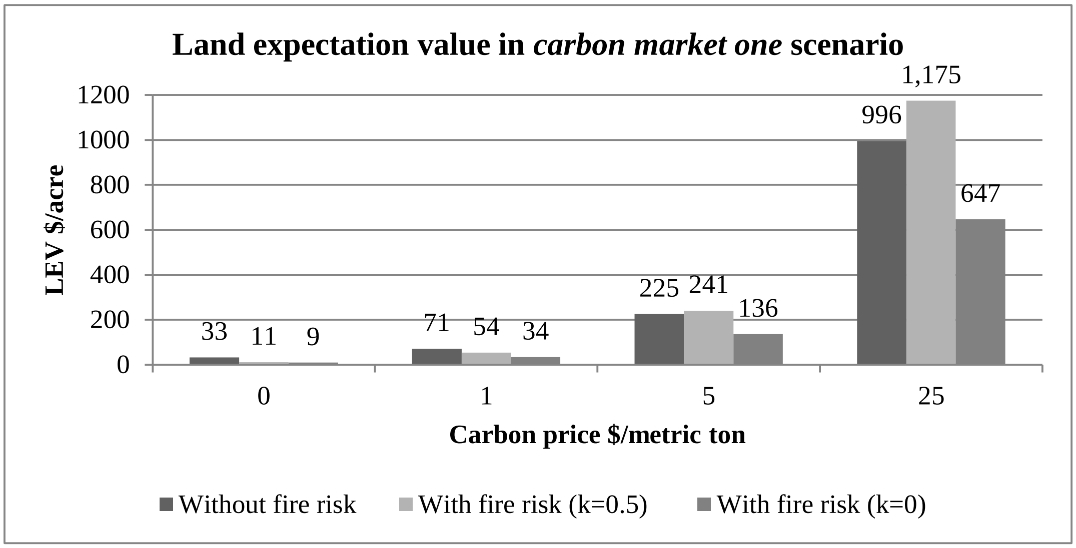

Figure 2.5. LEV results in *carbon market one* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

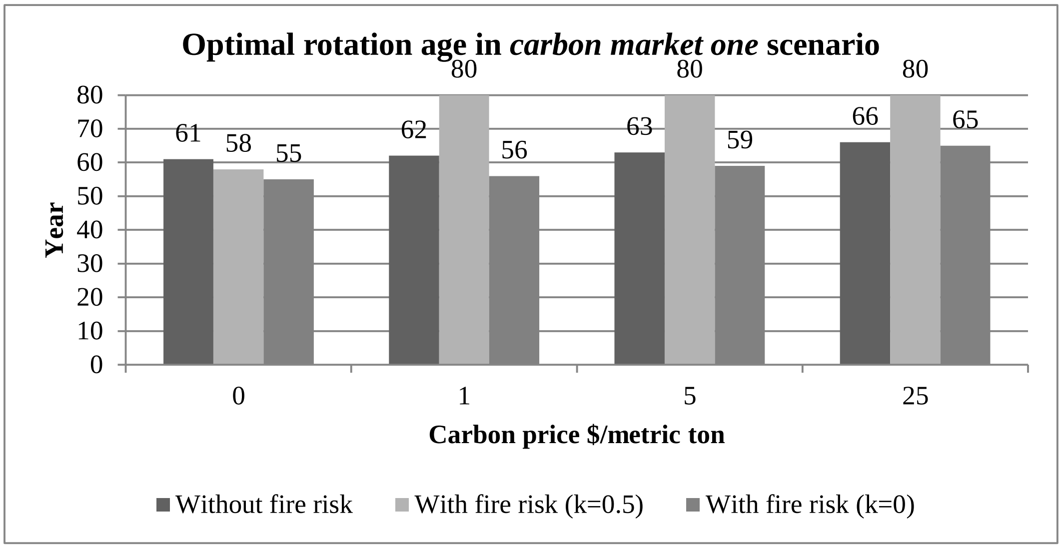

Figure 2.6. Optimal rotation age results in *carbon market two* scenario

Note: "Without fire risk" indicates the situation where fire risk is not considered; "With fire risk" (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; "With fire risk" (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

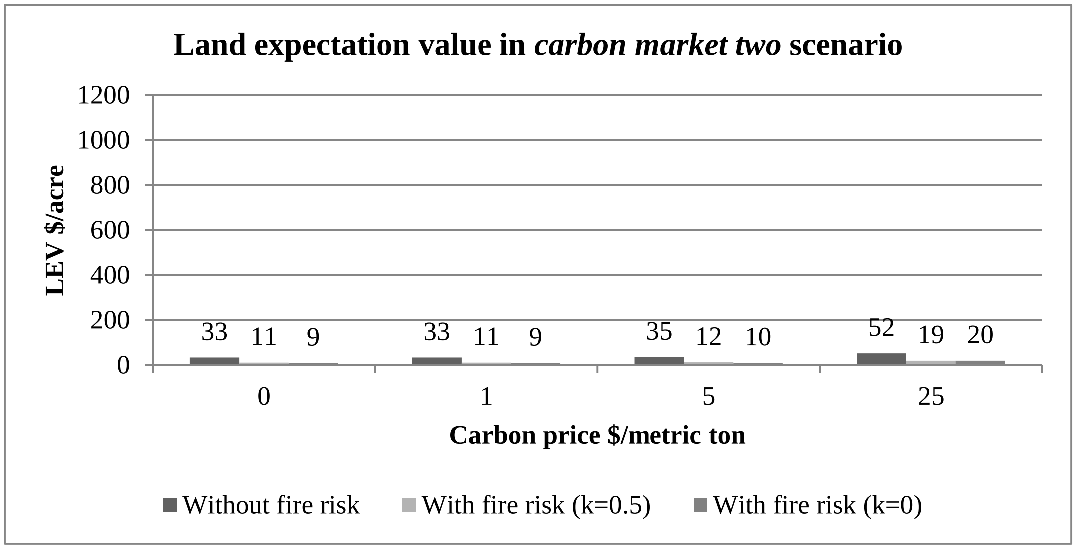

Figure 2.7. LEV results in *carbon market two* scenario

Note: "Without fire risk" indicates the situation where fire risk is not considered; "With fire risk" (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; "With fire risk" (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

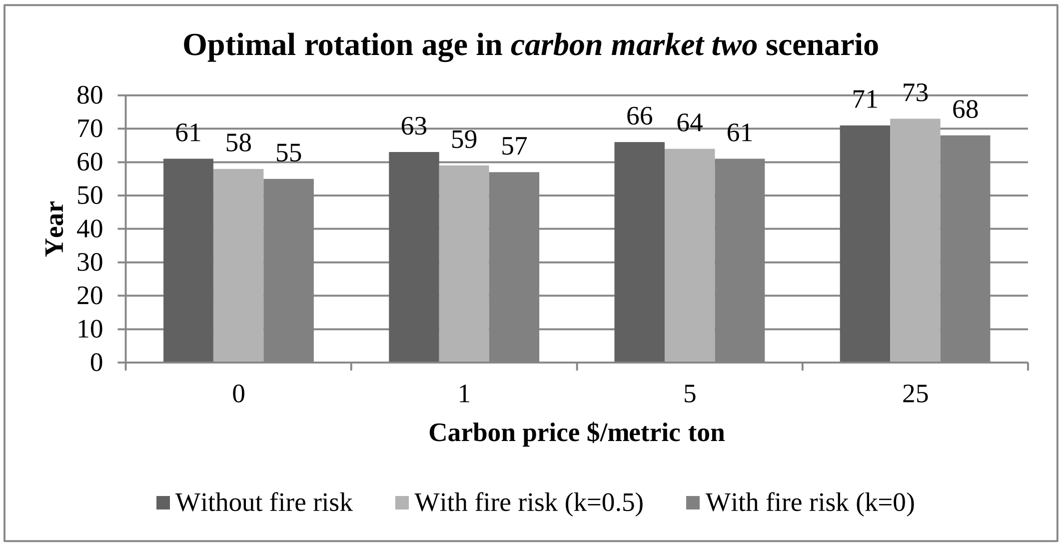

Figure 2.8. Optimal rotation age in *carbon market two* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

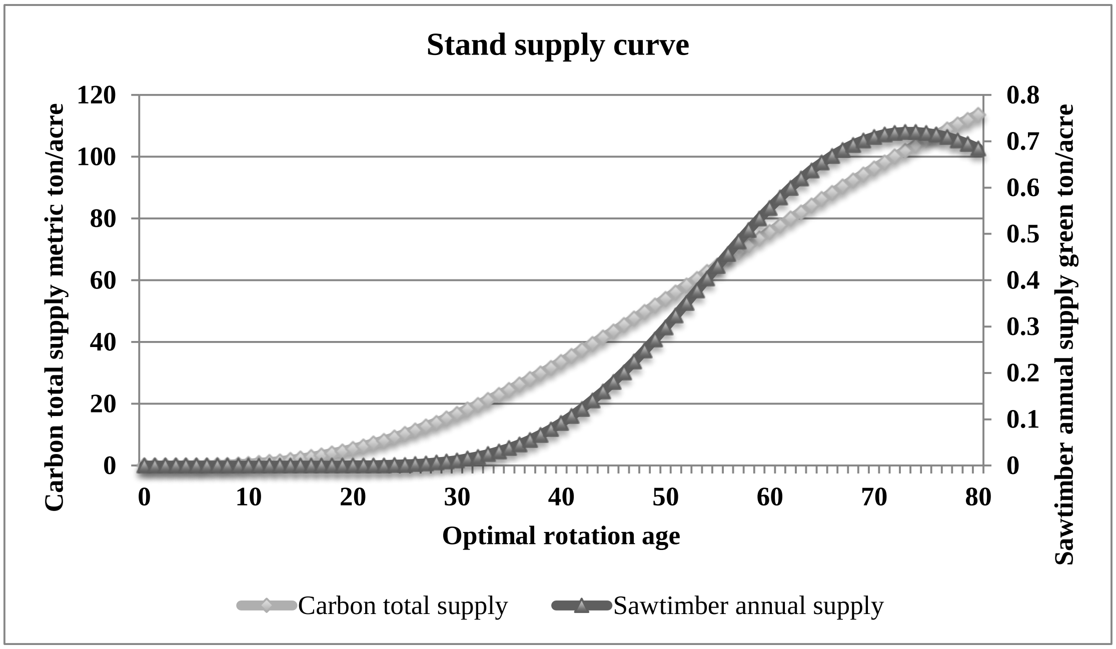

Figure 2.9. Annual sawtibmer supply and carbon supply with respect to optimal rotation age

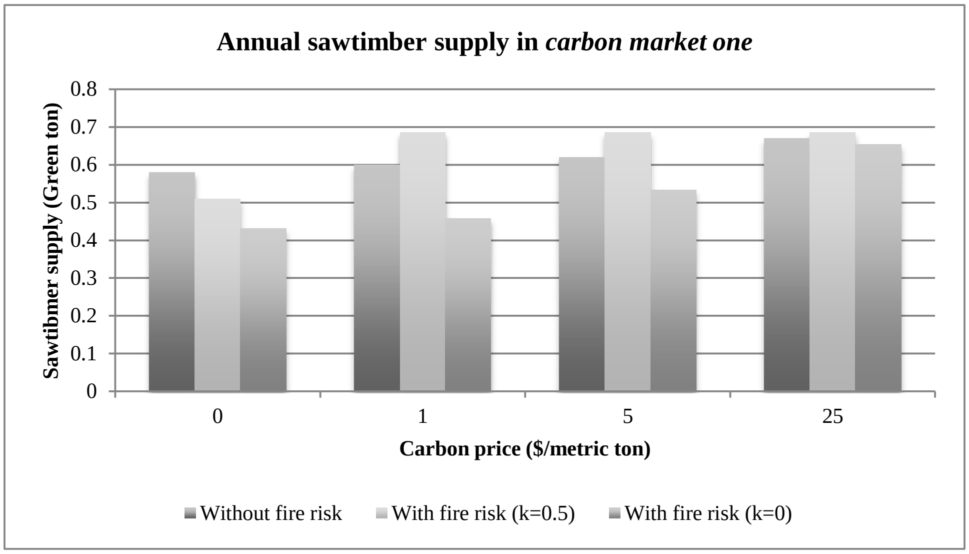

Figure 2.10. Annual sawtimber supply in *carbon market one*

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

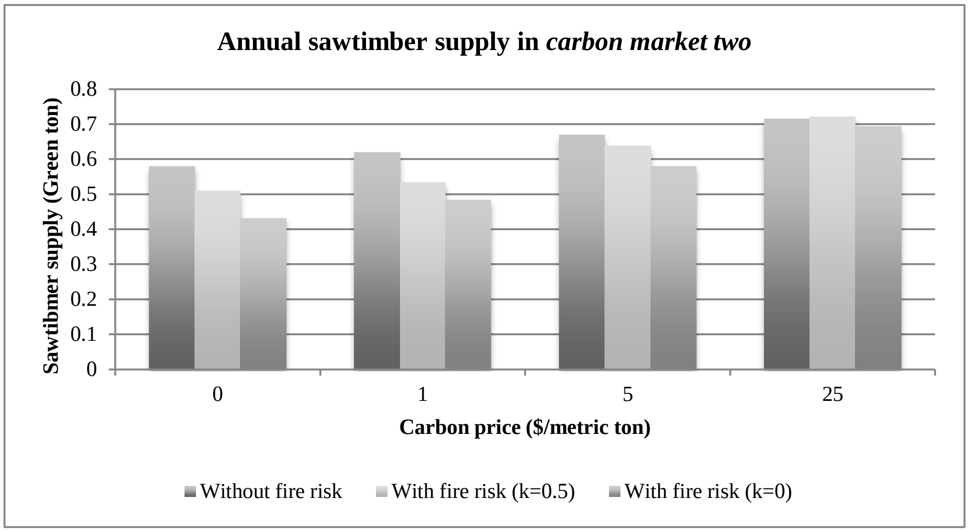

Figure 2.11. Annual sawtimber supply in *carbon market two*

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

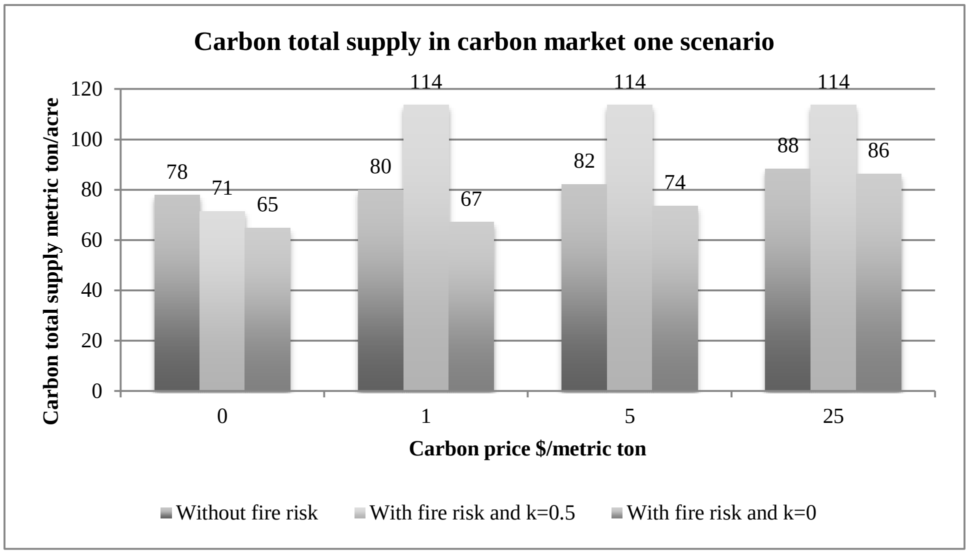

Figure 2.12. Total carbon supply in *carbon market one*

Note: "Without fire risk" indicates the situation where fire risk is not considered; "With fire risk" (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; "With fire risk" (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

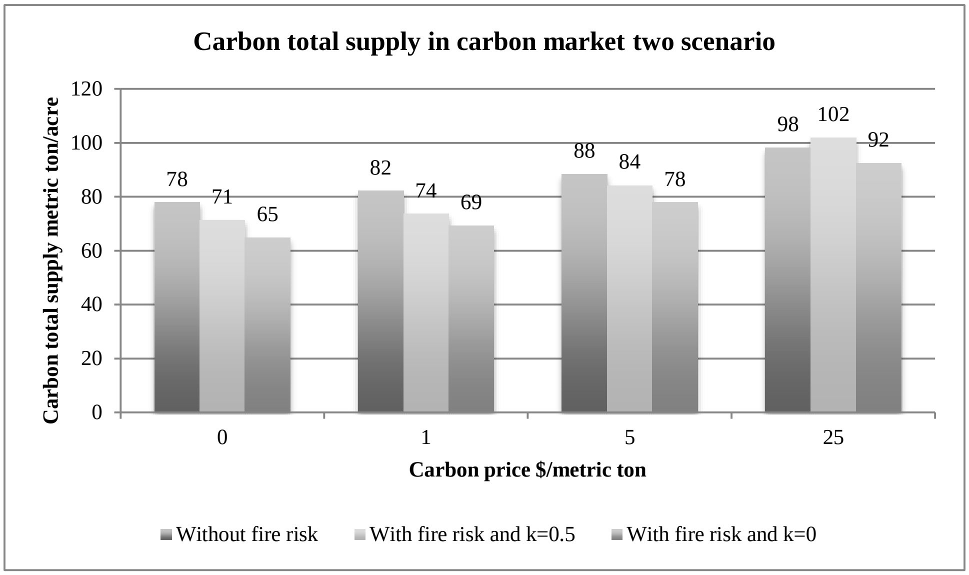

Figure 2.13. Total carbon supply in *carbon market two*

Note: "Without fire risk" indicates the situation where fire risk is not considered; "With fire risk" (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; "With fire risk" (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

Table 2.1. Scenario structure and sensitivity analyses

Main scenarios	*Carbon market one*	Carbon markets two
Sensitivity analyses	Carbon prices sensitivity analysis (0, 1, 5, and 25) Fire risk sentivity analysis (0 and 3%) Salvage portion sensitivity analysis (0% and 50%)	

Chapter 3 : Impact of price uncertainty on forestry management

The importance of the consideration of risk in the decision-making process in forestry economics has been well established. In Chapter 2, the impact of catastrophic events on management strategy has been investigated, in addition to which, there are many other types and sources: production, price, and market. Besides fire risk, forest landowners face uncertainty as a result of output price variability, given the fact that forestry products have a long production period and the assumption that the stand age varies from 1 to 80 or more years, which will affect forest landowners' benefit and harvest time, and stand supply. Furthermore, the impact of price uncertainty on forest landowners' decisions will vary depending on their attitudes towards risk. Many efforts have been endeavored to address the issue of price uncertainty, among which the most frequently used technique and the one that could satisfy the requirements that include both price uncertainty and attitudes towards price uncertainty is the mean variance (E-V) formulation originally developed by Markowitz (1952). It has been widely used in agricultural economics to study price uncertainty's influence (Barham et al., 2011; Coffey, 2001; Hueth et. al., 1999; Vassalos et al., 2013).

A risk averse farmer may in fact be willing to sacrifice some expected yield in order to decrease the variability of yields, thereby reducing the fluctuation of overall profits (Carl Dillon, 1992). In this study, a forest landowner is assumed to be willing to sacrifice some profits to decrease the variability of Land Expectation Value caused by price uncertainty of sawtimber and carbon. A question arises to the degree of profit sacrifices that the landowner would be willing to accept. Furthermore, price uncertainty may have an impact on the optimal rotation age, LEV, and forest products supply.

There are three objectives in this study. First, a model with price uncertainty and fire risk seeking economic optimization is developed. Second, it examines the effect of different attitudes towards price uncertainty on forestry benefits and optimal management practices with and without fire risk. Third, the comparison of economics outcomes and estimation of optimal harvest timing for forest landowners for three different scenarios is investigated.

The paper is organized as follows. In the next section, the mathematical model and the data used in the study are described. Further, the results of the model are discussed. Finally, some conclusions about forest landowners' optimal management practices are drawn and a few implications about the design of carbon markets are made.

Theoretical model

This section provides the theoretical background for the model that will be implemented in the study. The divergence between observed and modeled behavior led Markowitz to include a variance term resulting in the E-V model. The underlying assumption of mean variance theory involves people's attitudes towards risk: risk averse is the reluctance of a person to accept a bargain with a lower but certain payoff; risk seeking is the willingness to take a risk to seek high payoff, yet with a chance of losing value; risk neutral is attitude of indifference towards uncertainty and certainty. The aforementioned theory dictates the selection of the E-V model: it provides the interaction of price movement with different attitudes toward price variability. It not only answers the question of whether price movement affects landowners' conscious decisions based on the historical price trends, but it also reveals the impact associated with different levels of risk preference. Therefore, the E-V model relaxes the assumption about constant price and cost in Chapter 2.

Generally, if the aversion to price uncertainty coefficient is higher, decision makers are more averse to price uncertainty and are willing to pay more to reduce it; if the aversion coefficient is zero, decision makers are neutral to price uncertainty. Under this methodology, the function consists of real price plus a penalty reflecting aversion to the variability of product price. The E-V model for price uncertainty is listed in equation (3.1):

$$\mathrm{PR} - \Phi * \mathrm{VPR} \tag{3.1}$$

Where PR is the profit, Φ is the aversion coefficient, and VPR is the variance of profit. Even though uncertainty is from output price or other factors (input price of quantity), profit uncertainty is modeled. For practical purposes it is, however, easier to consider the net revenue of the unit level as the random variate under consideration and obtain the probability distribution from this variate than it is to obtain the distributions of the various factors that go into the net revenue and then to attempt to combine these into a distribution of net revenue (Rudolf J. Freund, 1956).

The Pratt risk aversion function coefficient is a measure of a hypothetical producer's aversion to risk (Carl Dillon, 1992). This coefficient is estimated by the McCarl and Bessler approach, wherein a producer is said to maximize the lower limit from a confidence interval of normally distributed net returns (Carl Dillon, 1992). Specifically, the resultant formula used to estimate the risk aversion coefficient is:

$$\Phi = 2Z_a / S_y \tag{3.2}$$

Where Z_a is the standardized normal Z value for a level of significance and S_y is the standard deviation of expected value for the risk-neutral case. Simply stated, solve for the Pratt risk aversion coefficient as a function of a representative standard deviation and appropriate normal Z value to reflect a decision maker who maximizes a target level of net returns that is α percent likely (where $100 \geq \alpha > 50$ for a risk-averse individual) (Carl Dillon, 1992). Under this circumstance, net return refers to Land Expectation Value. The risk neutral producer attempts to maximize the LEV that is 50% likely; a more risk averse producer might wish to maximize LEV that is at least, for instance, 75% likely and presumably with a lower expected value.

One of the conditions must be satisfied for the results of E-V analysis: 1) the decision-maker has a quadratic utility function; 2) the stochastic decision variables are normally distributed; 3) the stochastic decision variables differ only by location and scale.[13]

Data and Scenarios

Price data

Sawtimber price is still from Timber Market South, and annual data is adopted. Price trend is illustrated in Figure 3.1, which exhibits unstable trend with respect to time. The average of sawtimber price is $18.83 per green ton and the variance of sawtimber is 26.42.

Carbon price is the trade price of carbon from Chicago Climate Exchange. Chicago Climate Exchange is the world's first and North American's only voluntary, legally binding integrated trading system to reduce emissions of all six major greenhouse gases (GHGs), with offset projects worldwide (CXX, 2010). Even though it was closed in 2011,

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[13] Unfortunately, none of them can be proved under the model used in this paper, since the objective function is not linear.

the up and down characteristic of carbon price is the proper data to test how price uncertainty affects forestry management.

Carbon data is daily trade data from 2003 to 2011, which is compressed to annual data and is deflated to 2013 value using CPI. The adjusted carbon price is presented in Figure 3.2. Carbon price is relatively low around 2003 when this project started and around 2010 when the projected closed. Carbon price is unstable for the whole period, but the significantly decrease begins in 2008 around the time of economic crisis, which tells that carbon market was fragile to bear shocks from world market. The average price of carbon is $2.34 per metric ton, and variance is 3.16. The volatility of sawtimber and carbon prices could cause fluctuation of LEV.

Scenarios

There are three scenarios modeled in this chapter. The first scenario (*sawtimber only* scenario) assumes that sawtimber is the only forestry product that forest landowners can make profits. It serves as a base scenario to test whether LEV still will increase if carbon value is added with the influence of price uncertainty. The second scenario (*carbon market one* scenario) assumes that carbon payment for landowners start at age one of stand. The third scenario (*carbon market two* scenario) assumes that carbon payment start at baseline optimal rotation age, which is the optimal rotation age when there is no carbon payment. All the three scenarios include the risk from price uncertainty.

Sensitivity analysis

There are two sensitivity analyses in this model: one is the risk from catastrophic events (fire risk) and the possibility of fire risk being 0% and 3% are chosen; the other one is the different level of risk aversion to price uncertainty, and 10 levels of risk aversion are modeled.

Empirical model

This section discusses in detail the formulation of the economic model that is used in this study. Specifically, an E-V formulation is implemented to depict the economic environment of a hypothetical forest stand in Kentucky. The objective of forest landowners is the maximization of Land Expectation Value facing price uncertainty of sawtimber and carbon. In this model, forestry owners are assumed to be risk averse to price uncertainty, which is that they will choose to sacrifice a certain amount of benefits (LEV) to decrease the impact of price uncertainty. In order to seek the reactions of landowners to price uncertainty, mean variance formulation was implanted into the modified Hartman model developed in Chapter 2. Following is the procedure to estimate the variance of LEV and to implement the E-V model.

Data stimulation (Risk aversion parameter)

As mentioned, both sawtimber and carbon price embody uncertainty and will be the factors to cause the variance of LEV. There are 15 years sawtimber price, and there are labelled as PS_1, PS_2, ……PS_{15}. Also, there are 9 years carbon price, and they are labelled as PC_1, PC_2, ……PC_9. In order to estimate the variance of LEV, all the LEVs under each carbon price and sawtimber need to be calculated. The combination of price matrix is listed in the following:

$$\begin{bmatrix} P_{(1,1)} & \cdots & P_{(1,9)} \\ \vdots & \ddots & \vdots \\ P_{(15,1)} & \cdots & P_{(15,9)} \end{bmatrix} \tag{3.3}$$

Where $P_{(1,1)}$ is the first price of sawtimber and carbon, $P_{(1,9)}$ is the first price and the last price of carbon, $P_{(15,1)}$ is the last sawtimber price and the first carbon price, and $P_{(15,9)}$ is the last price of sawtimber and carbon. As shown, the first number in the bracket represents the sawtimber and the second number refers to carbon price.

In the matrix, all the possibilities of prices combination are included. Next step is to estimate the LEV under each price combination of sawtimber and carbon in the matrix. For example, When $P_{(1,9)}$ is adopted, the equations to assess LEV are listed in equation (3.4) to equation (3.9).

$$LEV(t) = \theta * \left(f_2(t) + g_2(t) - h_3(t)\right) + \theta * \sum_0^T \left(\lambda * k * f_2(t) + \lambda * g_2(t) - \lambda * h_3(t) - \lambda * k * h_4(t)\right) \tag{3.4}$$

Where $f_2\ (t)$ is the discounted the timber value, $g_2\ (t)$ is the discounted carbon benefit, $h_3\ (t)$ is the carbon emission value from decay that includes the impact of price uncertainty when there is fire risk, $h_4\ (t)$ is the carbon emission from catastrophic event, and θ is the discounted factor that could discount land value to be perpetual, λ is possibility of fire each year, and k is the salvageable portion of forestry after fire.

$$\theta = \frac{\lambda + r}{r * (1 - e^{-(\lambda + r) * t})} \tag{3.5}$$

$$f_2(t) = PS_1 * QS_t * e^{-(\lambda + r) * t} \tag{3.6}$$

$$g_2(t) = \sum_{i=1}^{t} (PC_9 * (QCS_i - QCS_{i-1}) * e^{-(\lambda + r) * t} \tag{3.7}$$

$$h_3(t) = PC_9 * QCED_t * e^{-(\lambda + r) * t} \tag{3.8}$$

$$h_4(t) = PC_9 * QCEF_t * e^{-(\lambda + r) * t} \tag{3.9}$$

Where PS_1 is annual sawtimber price in the first year, and PC_9 is annual carbon price in the ninth year, r is the interest rate, t is the stand age, QS_t is the volume of sawtimber with respect to stand age, QCS_t is the carbon sequestration volume with respect to stand age, $QCED_t$ is the carbon emission volume from decay, and $QCEF_t$ is the carbon emission volume from fire.

Through the estimation of LEV under each price, a LEV matrix will be generated and is shown is equation (3.10).

$$\begin{bmatrix} LEV_{(1,1)} & \cdots & LEV_{(1,9)} \\ \vdots & \ddots & \vdots \\ LEV_{(15,1)} & \cdots & LEV_{(15,9)} \end{bmatrix} \tag{3.10}$$

Where $LEV_{(1,1)}$ is the LEV when sawtimber price and carbon price of first year are adopted, $LEV_{(1,9)}$ is the LEV when sawtimber of first year and carbon price of ninth year are adopted, $LEV_{(15, 1)}$ is the LEV when sawtimber of fifteenth year and carbon price of first year are adopted, $LEV_{(15, 9)}$ is the LEV when sawtimber of fifteenth year and carbon price of ninth year are adopted. Each LEV contains the financial return from stand age of 1 to 80.

The use of E-V model involves mean value, variance and standard deviation. Thus the average LEV, variance, and standard deviation of all price combinations for each stand age are estimated. Figure 3.3, 3.4, and 3.5 show the average LEV for three scenarios. The average LEV reflects the financial return the forest landowners when they are risk neutral to price uncertainty. LEV in *sawtimber only* scenario and in *carbon market two* scenario is lower than LEV in *carbon market one* scenario. Under most circumstances, LEV with fire risk is lower than LEV without fire risk. However, LEV when salvageable portion is 50% in *carbon market one* scenario is higher than LEV without fire risk after stand age passes 75 years. This is also an anomaly due to the model, which was indicated in Chapter 2. Since the average price of carbon adopted in Chapter 3 is around $2.11 per metric ton, the result reflects the situation where LEV with 50% salvageable portion is higher than that without fire risk when carbon price passes $1 per metric ton in Chapter 2. The question arises that whether price uncertainty will change the trend as carbon sequestration becomes less profitable. Furthermore, risk averse parameters for each stand age are stimulated using equation (3.2). Risk averse parameters examine risk aversion levels starting from 50% (risk neutral) to 95% with a 5% increment in this study.

The Economic Model

Basically, mean variance formulation is the average value minus the penalty for price uncertainty to stand for the value that includes risk averse attitude and that would change by any alteration of risk averse level and variance of value. Equation (3.11) presents the E-V model described above:

$$LEV_t = MLEV_t - \Phi_t * VLEV_t \tag{3.11}$$

Where LEV_t is the adjusted LEV reflecting price uncertainty with respect to stand age, $MLEV_t$ is the mean LEV with respect to stand age, Φ_t is the risk aversion coefficient with respect to stand age, and $VLEV_t$ is the variance of LEV with respect to stand age.

Results and discussion

In this section, results that are presented are drawn from the modified Hartman model applied to different level of risk aversion to price uncertainty. Analyses about impact of risk aversion level to price uncertainty and fire risk on, *sawtimber only* scenario, *carbon market one* scenario and *carbon market two* scenario are shown separately, followed by the comparison between results from three scenarios. Under each part, the organization follows the sequence: impact on adjusted LEV; impact on optimal rotation age; impact on stand supply. Through this part, a general sense of how risk aversion level to price uncertainty works is presented. More importantly, how much does it affect landowners' financial return from stand and their decisions about harvesting time is discussed. Moreover, the influence of fire risk and salvageable is embedded with the effect of price uncertainty. Therefore, the joint effect of two risks is demonstrated.

Impact of risk aversion level to price uncertainty and fire risk where there is no carbon market

When carbon market is not available, sawtimber is the only forestry product in the assumption. Thus, this scenario tests how adjusted LEV, optimal rotation, and stand supply behave towards according risk aversion level of sawtimber price uncertainty and fire risk.

The result for adjusted LEV in *sawtimber only* scenario is shown in Figure 3.6. It illustrates that the adjusted LEV for without fire risk, with 50% salvageable portion, and with 0% salvageable portion is decreasing as risk aversion level to price uncertainty increases. When significant level of the standardized normal Z value [14]is 50%, it is the risk neutral situation and it represents the modified Hartman model without price

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[14] Significant level of the standardized normal Z value is adopted to express the risk averse level, because the risk averse parameters for sawtimber and carbon are different.

uncertainty; when significant level is 55%, it is the low level of risk aversion; when significant level is 75%, it is the middle level of risk aversion; when significant level is 95%, it is the high level of risk aversion. As risk aversion level of price uncertainty increases, its impact on the adjusted LEV increases. In terms of the impact of fire risk, LEV without fire risk is always higher than the adjusted LEV with 50% salvageable portion, and the adjusted LEV with 50% salvageable portion is always higher than the one with 0% salvageable portion for every level of risk averse to price uncertainty. It is presumed that adjusted LEV with and without fire risk should react differently to risk averse of price uncertainty, since fire risk could reduce the impact by depreciation of sawtimber and carbon. When there is no fire risk, adjusted LEV for risk neutral to price uncertainty is around $34 per acre, and it is as much as 7.5 times than the one for high risk averse level to price uncertainty. And it is almost the same situation when salvageable portion is 50% and 0, except the change for 50% salvageable portion is higher (4.5 times) and for 0% salvageable portion is slightly lower (8 times) than the one when there is no fire risk.

Result of optimal rotation age is shown in Table 3.1. It seems that risk aversion level to price uncertainty does not affect optimal rotation age. Also, it indicates that sawtimber annual supply does not change over different level of risk aversion to price uncertainty, whose result is shown in Table 3.2. In terms of the effect of fire risk, when salvageable portion is 50%, optimal rotation age is 58 years and it is 3 years shorter than that when there is no fire risk; when salvageable portion is 0%, optimal rotation age is 55 years and it is 3 years shorter than that when salvageable portion is 50%. Results of annual sawtimber supply and carbon supply could be derived from Figure 2.9. They show the same trend as optimal rotation age.

Impact of risk aversion level to price uncertainty and fire risk on carbon market one which carbon payment starts at age one of stand

In this section, the modified Hartman model is applied to the scenario where carbon payment starts at age one of stand. The impact of risk averse to price uncertainty level and fire risk on adjusted LEV, optimal rotation age, and stand supply is presented in the following.

Results of the adjusted LEV for *carbon market one* scenario are illustrated in Figure 3.7. In general, adjusted LEV keeps declining as risk averse level to price uncertainty increases. Also, the decrement gets larger and larger until the risk averse level to price uncertainty is 75%. For example, when salvageable portion is 50%, the decrement between risk averse level to price uncertainty from 50% to 55% is about 16%, while the decrement from 70% to 75% is around 71%. After risk averse level reaches 80%, adjusted LEV becomes zero when fire risk is considered, after which, LEV becomes zero even without fire risk. It is noticed that land value from stand age 0 to 80 becomes negative after the significant level of risk averse is 75%, which makes the highest adjusted LEV is 0 under these situations. However, forest landowners will choose to plant and harvest in reality even though the model shows no positive profit from forests. Because landowners will achieve some benefits as long as there are trees on the stand. What the model indicates is that the amount of financial return could guarantee to gain is little, due to the highly unstable economy and high risk aversion to price uncertainty. Additionally, it shows the same trend when fire risk is zero and salvageable portion is zero.

The adjusted LEV without fire risk is higher than adjusted LEV with 50% salvageable portion; adjusted LEV with 50% salvageable portion is higher than adjusted LEV with 0% salvageable portion. Without considering price uncertainty (result from Chapter 2), adjusted LEV with 50% salvageable portion is higher than adjusted LEV without fire risk. This suggests that price uncertainty has a bigger impact on adjusted LEV with 50% salvageable portion and it drops the adjusted LEV to a level lower than the one without fire risk. Also, this hypothesis could be demonstrated by the result in Figure 3.7. For example, when risk averse level to price uncertainty increases from 50% to 75%, adjusted LEV decreases about 3 times without fire risk; adjusted LEV reduces around 14 times with 50% salvageable portion; adjusted LEV reduces around 9.5 times without salvageable portion. As mentioned in *sawtimber only* scenario there is no such distinct disparity. This combined with the fact that carbon value makes up a large proportion in the adjusted LEV indicates carbon is playing a significant role in this result. In Chapter 2, the abnormal result of adjusted LEV in *carbon market one* scenario (adjusted LEV without fire risk is lower than adjusted LEV with 50% salvageable portion for some carbon prices) reveals that carbon value has a bigger impact when salvageable portion is 50%. The factors above contribute to the consequence that adjusted LEV has a bigger decrease when fire risk is considered in carbon market one.

Since higher risk aversion to price uncertainty causes lower adjusted LEV, it is expected that higher aversion generates shorter rotation age or as in the scenario where there is only sawtimber, that the impact of risk averse to price uncertainty on optimal rotation age and stand supply is minor. Before significant level of risk aversion is 80%, optimal rotation age decreases slightly with and without fire risk. When risk averse level to price uncertainty is relatively low (before 70%), optimal rotation age is 80 years with 50% salvageable portion, which is much higher than without fire risk and with 0% salvageable portion, and is caused by the larger profit from carbon.

In *carbon market one* scenario, sawtimber annual supply and carbon total supply present similar trends: stand supply decreases as risk averse level to price uncertainty increases; stand supply with 50% salvageable portion is higher than without fire risk and with 0% salvageable portion. After the significant level of risk aversion is 75%, stand supply goes to zero.

Impact of risk aversion level to price uncertainty and fire risk on carbon market two which carbon payment starts at baseline

In *carbon market two* scenario, the probability of fire and salvageable portion affect the value of carbon and sawtimber. Also, the different start points of carbon payment influence the weight of carbon value in adjusted LEV. These two factors could interfere (slow down or fasten) the impact of price uncertainty on adjusted LEV, optimal rotation age and stand supply.

Results of adjusted LEV from the modified Hartman model are shown in Figure 3.8. The adjusted LEV decreases when risk averse level to price uncertainty increases, which confirms that risk averse level to price uncertainty has a negative impact on adjusted LEV. Also, adjusted LEV without fire risk is the highest for each level of risk aversion to price uncertainty; adjusted LEV without survival rate is the lowest. It evinces that the increase of fire risk and the decrease in salvageable portion could reduce adjusted LEV. In terms of the rate of decreasing of adjusted LEV, decrements of adjusted LEV show highly similarity (less than 1% difference) without fire risk and without salvageable portion, which means they are decreasing at a similar rate while decrement of adjusted LEV with 50% salvageable portion is bigger. *Carbon market one* scenario also shows identical trend, which means that sawtimber and carbon price uncertainties have a bigger influence on adjusted LEV with 50% salvageable portion.

Optimal rotation age exhibits increasing trend when risk aversion to price uncertainty increases under two situations: when probability of fire is zero and when salvageable portion is 50%. However, optimal rotation age decreases with respect to risk averse level when salvageable portion is 0%. Optimal rotation age is chosen by adjusted LEV, and adjusted LEV is the result of average LEV, variance, and risk aversion parameter. Even though risk aversion parameter tends to decrease as stand age increases, variance of LEV shows no positive or negative trend with stand age. Therefore, it is expected that the combination effect of variance of LEV and risk aversion parameter push the optimal rotation age later than usual.

Regarding the stand supply, sawtimber annual supply and carbon total supply show the same trend as optimal rotation age. Stand supply increases with respect to risk averse level when there is no fire risk and when there is 0% salvageable portion, while stand supply decreases with respect to risk averse level when there is 50% salvageable portion.

Comparison of results among three scenarios (sawtimber only, carbon market one, and carbon market two)

One goal of this paper is to investigate the different markets from the perspective of adjusted LEV, optimal rotation age, and stand supply. High adjusted LEV means high financial return for forest landowners, which is the primary concern for landowners. Sufficient sawtimber supply and carbon supply are needed for a stable market. It is challenging and important to balance the three targets, because they may work in different directions. This section will provide some information about the relatively suitable policy under certain setting of market.

Comparing the financial returns for three scenarios, *carbon market one* scenario has the highest adjusted LEV before risk averse level to price uncertainty is 80% (before adjusted LEV goes to 0), because of the carbon payment beginning from age 1 for every level of risk aversion to price uncertainty and *sawtimber only* scenario has the lowest adjusted LEV. However, this does not mean *carbon market one* scenario is the most advantageous in the face of price uncertainty. Since both sawtimber and carbon price are modeled, more value from sawtimber and carbon presume higher value loss from aversion to price uncertainty. In this paper, carbon price is from Chicago Climate Exchange, and it has a high variance caused by the period of economic downturn when it was closed in 2011. In *carbon market one* scenario, carbon value is the dominant source of financial return, therefore, adjusted LEV experiences largest decrement from alteration of risk aversion to price uncertainty. Also, it is expected that *sawtimber only* scenario has the smallest decrement, because it is free from the impact of price uncertainty of carbon.

It appears that risk averse level to price uncertainty has little impact on optimal rotation age: only in *carbon market two* scenario, optimal rotation age has obvious decline over the increase of risk averse level. If the optimal rotation age stays the same, this means that the stand supply does not change. Table 3.2 and Table 3.3 illustrate the comparison of three markets with regards to the stand supply. Carbon supply in *carbon market two* scenario is always higher than the one in *carbon market one* scenario when there is no fire risk and when there is no salvageable portion. Sawtimber supply in *carbon market two* scenario is higher than the one in *carbon market one* scenario under most conditions.

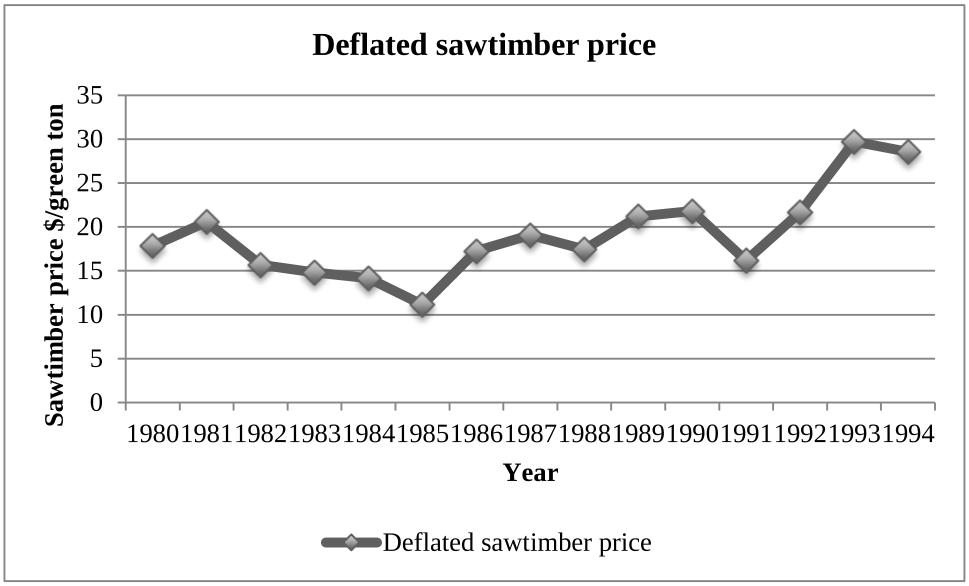

Figure 3.1. Annual deflated sawtimber price from 1980 to 1994

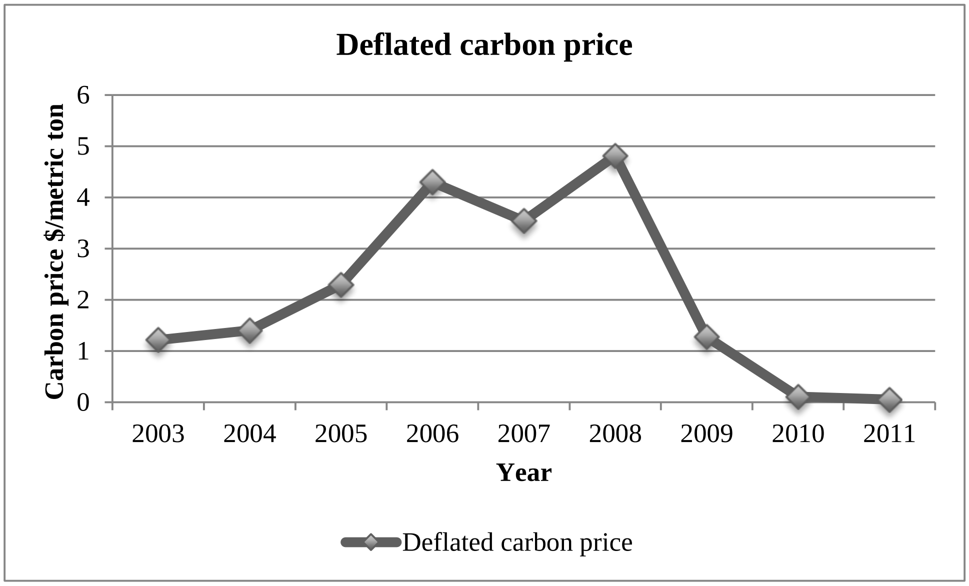

Figure 3.2. Annual deflated carbon price from 2013 to 2011

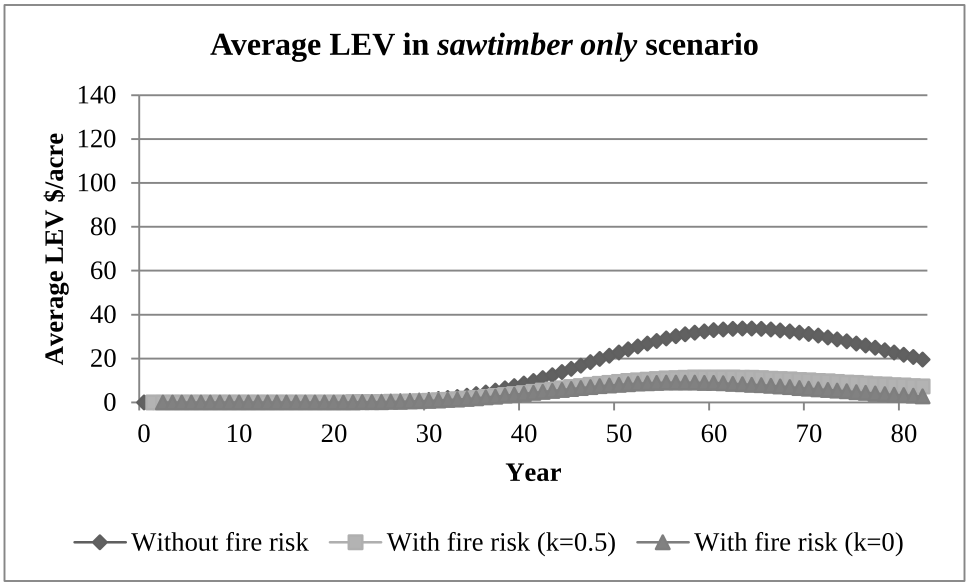

Figure 3.3. Average LEV in *sawtimber only* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

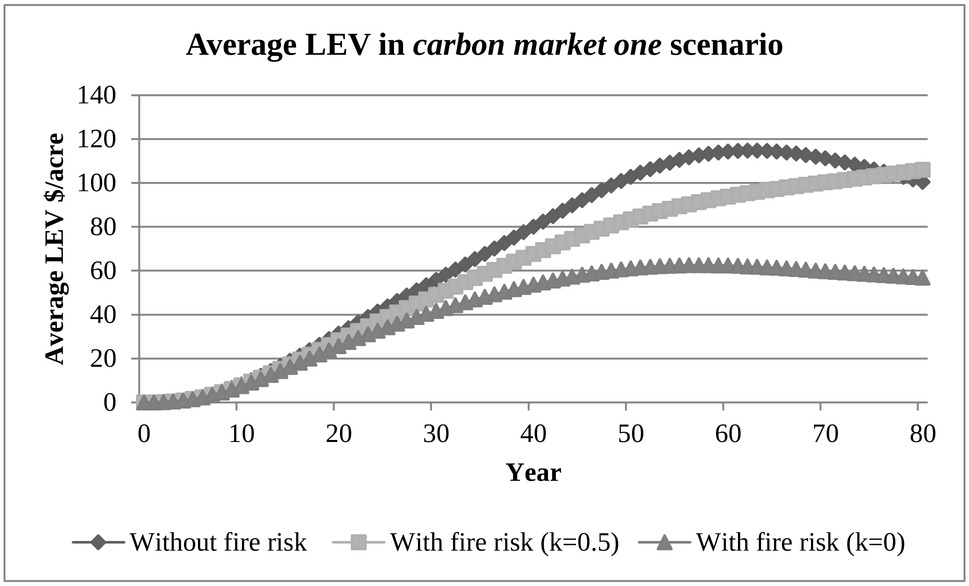

Figure 3.4. Average LEV in *carbon market one* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

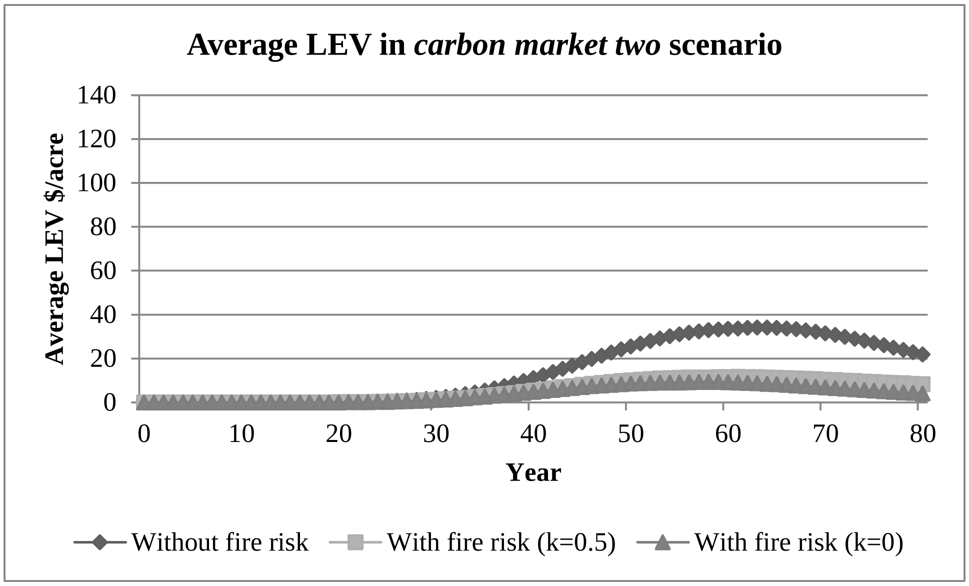

Figure 3.5. Average LEV in *carbon market two* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

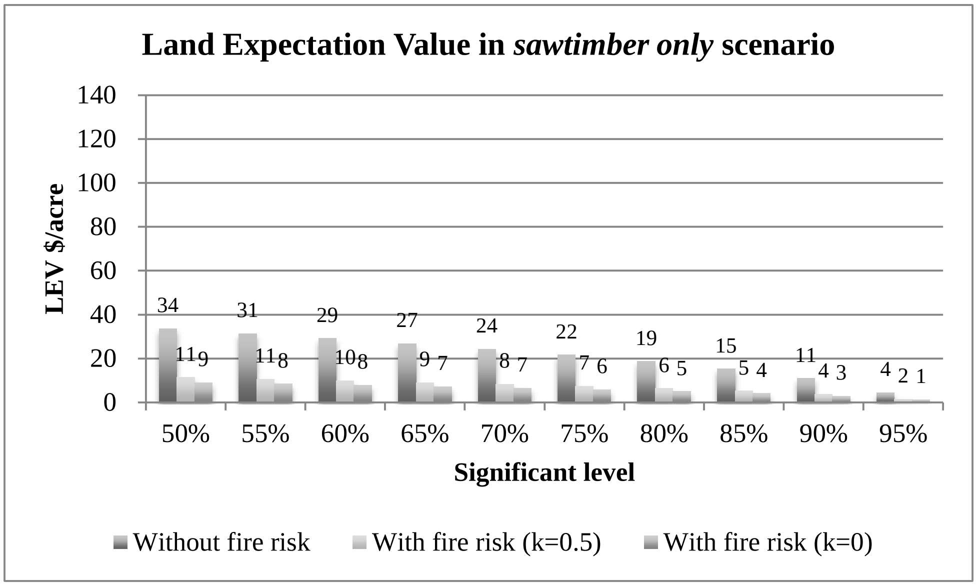

Figure 3.6. . Adjusted LEV result in *sawtimber only* scenario

Note: "Without fire risk" indicates the situation where fire risk is not considered; "With fire risk" (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; "With fire risk" (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

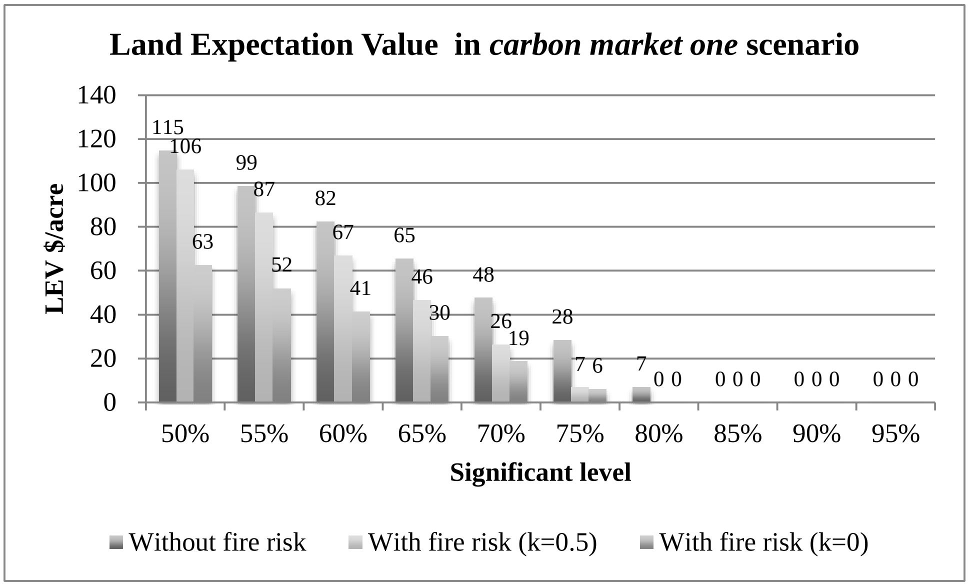

Figure 3.7. AdjustedLEV result in *carbon market one* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

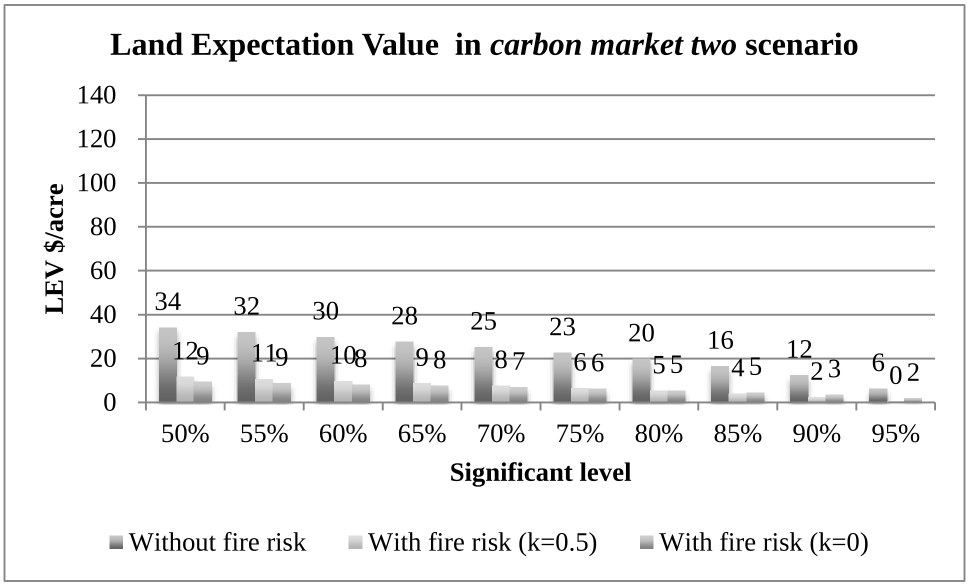

Figure 3.8. Adjusted LEV result in *carbon market two* scenario

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

Table 3.1. Optimal rotation age results for three scenarios (*sawtimber only, carbon market one, and carbon market two*)

	Optimal rotation age								
	Sawtimber only scenario			*Carbon market one* scenario			*Carbon market two* scenario		
Significant level	Without risk	With risk k=0.5	With risk k=0	Without risk	With risk k=0.5	With risk k=0	Without risk	With risk k=0.5	With risk k=0
50%	61	58	55	62	80	57	64	61	58
55%	61	58	55	62	80	57	64	61	58
60%	61	58	55	62	80	56	64	61	58
65%	61	58	55	62	80	56	64	61	58
70%	61	58	55	62	63	55	64	60	58
75%	61	58	55	61	57	55	64	60	59
80%	61	58	55	61	0	0	64	54	59
85%	61	58	55	0	0	0	65	53	59
90%	61	58	55	0	0	0	65	50	59
95%	61	58	55	0	0	0	67	42	60

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0.

Table 3.2. Sawtimber annual supply results for three scenarios (*sawtimber only, carbon market one*, *and carbon market two*)

Sawtimber annual supply									
	Sawtimber only scenario			*Carbon market one* sceanrio			*Carbon market two* scenario		
Significant level	Without risk	With risk k=0.5	With risk k=0	Without risk	With risk k=0.5	With risk k=0	Without risk	With risk k=0.5	With risk k=0
50%	0.58	0.51	0.43	0.60	0.69	0.48	0.64	0.58	0.51
55%	0.58	0.51	0.43	0.60	0.69	0.48	0.64	0.58	0.51
60%	0.58	0.51	0.43	0.60	0.69	0.46	0.64	0.58	0.51
65%	0.58	0.51	0.43	0.60	0.69	0.46	0.64	0.58	0.51
70%	0.58	0.51	0.43	0.60	0.62	0.43	0.64	0.56	0.51
75%	0.58	0.51	0.43	0.58	0.48	0.43	0.64	0.56	0.53
80%	0.58	0.51	0.43	0.58	0.00	0.00	0.64	0.40	0.53
85%	0.58	0.51	0.43	0.00	0.00	0.00	0.65	0.38	0.53
90%	0.58	0.51	0.43	0.00	0.00	0.00	0.65	0.30	0.53
95%	0.58	0.51	0.43	0.00	0.00	0.00	0.68	0.12	0.56

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

Table 3.3. Carbon total supply results for three scenarios (*sawtimber only, carbon market one, and carbon market two*)

Carbon total supply									
	Sawtimber only scenario			*Carbon market one* sceanrio			*Carbon market two* scenario		
Significant level	Without risk	With risk k=0.5	With risk k=0	Without risk	With risk k=0.5	With risk k=0	Without risk	With risk k=0.5	With risk k=0
50%	77.88	71.40	64.87	80.01	113.62	69.23	84.23	77.88	71.40
55%	77.88	71.40	64.87	80.01	113.62	69.23	84.23	77.88	71.40
60%	77.88	71.40	64.87	80.01	113.62	67.05	84.23	77.88	71.40
65%	77.88	71.40	64.87	80.01	113.62	67.05	84.23	77.88	71.40
70%	77.88	71.40	64.87	80.01	82.13	64.87	84.23	75.73	71.40
75%	77.88	71.40	64.87	77.88	69.23	64.87	84.23	75.73	73.57
80%	77.88	71.40	64.87	77.88	0.00	0.00	84.23	62.69	73.57
85%	77.88	71.40	64.87	0.00	0.00	0.00	86.31	60.52	73.57
90%	77.88	71.40	64.87	0.00	0.00	0.00	86.31	54.03	73.57
95%	77.88	71.40	64.87	0.00	0.00	0.00	90.40	37.48	75.73

Note: “Without fire risk” indicates the situation where fire risk is not considered; “With fire risk” (k=0.5) indicates the situation where fire risk is considered and salvageable portion is 50%; “With fire risk” (k=0) indicates the situation where fire risk is considered and salvageable portion is 0%.

Chapter 4 : Conclusions and future work

Conclusions

Impact of carbon sequestration and fire risk

The individual impact of carbon price and fire risk on forest landowners' financial return and management, as well as the joint effect of carbon and fire, has been studied. First, when carbon price increases, LEV and optimal rotation age tend to increase. This means internalizing carbon could benefit forest landowners on one hand, and it could result in longer rotation on the other. The large increase of LEV when carbon price increases implies that the existing of carbon market or the increase of carbon price could result in high profit for forestry landowners, thus drive more lands are converted into forestry land, which will increase carbon sequestration and timber supply. However, since the model adopted in this paper is not dynamic in terms of forestry land, it is hard to tell the magnitude of effect that carbon market has on carbon sequestration and timber supply resulting from additional investment on forestry land. Additionally, when there is no carbon market, which is the current situation in Kentucky, most of forestry landowners do not have insurance to reduce loss from catastrophic events due to the low risk of fire and relatively low financial return. However, when carbon market is available, the LEV considerably increases. This may open an opportunity for developing a more complete insurance system, since forestry landowners are more willing to protect the big profit from carbon sequestration. Second, fire risk and zero survival rate induce lower LEV and shorter optimal rotation age. This means forest landowners are willing to harvest earlier to reduce catastrophic events.

In the joint effect of carbon and fire risk, fire risk is the major factor affecting LEV and optimal rotation age, except in the following situations: carbon price has a bigger impact on LEV and rotation age in *carbon market one* with 50% salvageable portion when carbon price is high; it also has a bigger impact on rotation age in *carbon market two*, which indicates high carbon price could mitigate the effect of fire risk on LEV and optimal rotation age.

From the comparison of two carbon markets, a general rule can be draw that optimal rotation age in *carbon market one* is shorter than that in *carbon market two*. This implies that paying forest landowners more does not always make them harvest earlier, except when salvageable portion is 50% in *carbon market on*. This means that the design of a carbon market (e.g. when the payment and penalty starts) could be crucial to how landowners will respond. Under most circumstance, the earlier the payment starts, the higher financial return landowners will achieve, and the shorter the rotation age will be.

Regarding sawtimber supply, annual supply increases as carbon price increases and when salvageable portion is 0%, supply is most sensitive to carbon prices. This implies that the existence of carbon market does not have a negative impact on sawtimber market, which ensures a stable sawtimber market. In terms of carbon supply, total supply displays an increasing trend, which means that the increase of carbon price will increase the total carbon supply eventually. Therefore, carbon market has a positive on both sawtimber supply and carbon supply.

Considering forest landowners’ interest only, there is no doubt that *carbon market one* scenario is preferred, since it produces considerably higher financial return. But when it comes to the combination of individual and social benefits, choice of carbon market becomes a tradeoff between high financial return for forest landowners and high carbon supply for environmental benefits. The choice of carbon market depends highly on current forest landowners’ benefit from forestry, average fire rates, and damage situations in the region. For example, in areas where catastrophic events do not happen frequently or catastrophic events could cause widespread damage, *carbon market two* scenario is a better choice in terms of landowners’ profits and social benefits. Also, *carbon market one* scenario is preferred when the land is being converted to forest from anther land use. *Carbon market two* scenario is favored when the land was already in forests because it is not necessary to pay for the carbon that has already been sequestrated.

Impact of risk aversion to price uncertainty

Price uncertainty is an important factor that affects participants’ benefits and market decisions. More importantly, decision makers’ attitudes toward price uncertainty decide the degree of the price uncertainty’s effect. The impact of risk averse level to price uncertainty has been studied for three scenarios: sawtimber only, carbon market one, and carbon market two.

The model presents that risk aversion to price uncertainty has a negative impact on adjusted LEV. The adjusted LEV in carbon market two decreases least facing the increasing risk averse level to price uncertainty, even though it has a lower adjusted LEV than that in carbon market one. This implies that when carbon price could be highly unpredictable and unstable, carbon market two scenario may be more appropriate to stand less loss from carbon price uncertainty.

Compared to adjusted LEV, optimal rotation age shows a decreasing trend, yet less shock from risk averse to price uncertainty. In conclusion, optimal rotation age in carbon market one scenario is longer than that in sawtimber only scenario. Additionally, optimal rotation age in carbon market two scenario is longer than that in carbon market one scenario except when salvageable portion is 50%. This signifies that internalizing carbon value would lengthen the rotation, however, while continuously increasing carbon value would not necessarily do so.

Given the relation between optimal rotation age and stand supply, the latter does not change dramatically with the increase of risk averse to price uncertainty. Two points stand out: first, carbon market does not have a negative impact on sawtimber annual supply, which assures a steady market; second, carbon market two scenario could generate higher stand supply of sawtimber and carbon under most circumstances.

Future work

There are a few limitations in this paper that future work will try to adjust. First, the model makes the assumption that the market is static instead of dynamic with respect to change. For example, forest landowners would not expand lands responding to high price of forestry products or reduce lands facing low price of forestry products. Second, even-aged forestry and clear cutting are presumed in the model, which is against the reality that selective harvesting is also used. Selective harvesting may be a more profitable method. Third, even though risk aversion to price uncertainty is included in the model in Chapter 3, carbon and sawtimber price are still constant throughout rotations. In the future, a model that allows prices fluctuation from period to period will be considered, thus, decisions of harvesting plan for each rotation could be different. Forth, the way that price uncertainty is incorporated assumes that carbon and sawtimber prices are uncorrelated.

Appendices

Appendix A: Sawtimber prices in Kentucky

The stumpage prices for hardwood sawtimber for the models in Chapter 2 and Chapter 3 were obtained from Timber Market South. They are quarterly data from 1980 to 1994 and are listed in Table A.1.

Table A.1. Sawtimber price data in Kentucky from 1980 to 1994

Sawtimber price ($/green ton)				
Year	Quarter			
	1	2	3	4
1980	N/A	5.83	6.40	6.70
1981	7.77	8.80	8.76	6.78
1982	7.12	7.16	5.64	6.06
1983	6.55	6.40	5.79	6.59
1984	7.12	5.90	5.83	6.40
1985	5.03	4.80	5.14	5.60
1986	7.09	7.28	6.93	11.16
1987	7.85	8.46	11.62	9.26
1988	8.80	9.60	7.54	9.49
1989	9.71	11.43	12.00	12.00
1990	13.37	13.49	11.66	10.40
1991	9.60	8.69	8.11	11.43
1992	12.11	11.20	13.37	15.54
1993	18.86	17.83	18.40	18.63
1994	17.83	18.51	N/A	N/A

Appendix B: Yield data of sawtimber and pulpwood

The original yield data that is from Gingrich (1971) and the fitted data that is from Shrestha (2013) for sawtimber and pulpwood for upland oak-dominated mixed hardwood forests are shown in Table B.1. The fitted data are estimated by a non-linear regression using STATA and they reflect the average yield data in Kentucky.

Table B. 1. Original and fitted yield data for sawtimber and pulpwood

	Original data		Fitted data	
Age	Sawtimber (bdft)	Pulpwood (cu.ft)	Sawtimber (bdft)	Pulpwood (cu.ft)
0	0	0	0	0
20	0	128	1	286
30	0	848	41	822
40	440	1456	422	1501
50	2150	2152	1706	2135
60	5160	2464	3818	2595
70	7200	2664	5678	2829
80	8200	2848	6264	2849

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Publication

- Catron, J.F., G. A. Stainback, J. M. Lhotka, J. Stringer, and L. Hu. 2013. "Financial and Management Implications of Producing Bioenergy in Upland Oak Stands in Kentucky." *Northern Journal of Applied Forestry* 30:164-169.