REAL OPTIONS ANALYSIS OF CARBON FORESTRY UNDER THE NEW ZEALAND EMISSIONS TRADING SCHEME

A thesis submitted in fulfillment

of the requirements for the degree of

Master of Philosophy

in

Economics

at

The University of Waikato

by

James Seng Khien TEE

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2011

To my beloved parents and late grandfather

Abstract

In 2008, the New Zealand government passed climate change legislation called the New Zealand Emissions Trading Scheme (NZETS), designed to create a carbon price in the economy. Under the NZETS, new forests planted on and after 1st January 1990 (known as post-1989 forests) are eligible to earn carbon credits and sell them domestically and internationally, with a condition that the credits will have to be repaid back upon harvest of the forests. The amount of credits that have to be surrendered is proportionate to the extent that carbon stocks decrease in the forest land.

This research explores the effects of the NZETS on new post-1989 forests. The NPV/LEV and the Real Options valuation methods are respectively employed to analyze fixed harvest and flexible harvest forest management decisions. This approach is applied to study the cases of timber-only forestry (i.e. no NZETS) and carbon forestry (i.e. with NZETS). The major advance of this research is the development of a double Random Variable Real Options methodology that incorporates both stochastic timber and stochastic carbon prices into the calculation of the bareland forestry investment opportunity under the NZETS.

Through the work of this thesis, it is shown that the NZETS increases the valuation of bareland on which radiata pine is to be planted with a single rotation or a perpetual series of rotations, especially for the case of flexible harvest forest management. The NZETS will very likely lengthen the rotation age of forests and increase forest carbon sequestration, which contributes positively towards climate change mitigation in New Zealand.

The Real Options valuation method can generate optimal harvest price thresholds that help forest owners to decide when to harvest. This thesis concludes with a scenario analysis of potential implications of lengthening the forest rotation age on carbon stock management in New Zealand.

Acknowledgements

Throughout the course of this research, it has been a fantastic opportunity and privilege to work with Professor Riccardo Scarpa, Dr Dan Marsh and Professor Graeme Guthrie. I would like to express my deepest gratitude to both my supervisors, Ric and Dan, for making this research study possible. In particular, I am thankful for their confidence in my research ability and potential, and for their patience and guidance throughout the course of my part-time study for the past three years. I am also indebted to Graeme for his helpful advice and guidance on the Real Options methodology, which forms the core of this thesis. Last but not least, I am also grateful to the Ministry of Agriculture and Forestry for their kind financial support[1].

---

[1] All results, conclusions and any errors in this research are solely my own and not associated with the Ministry.

Table of Contents

List of Figures

List of Tables

List of Acronyms

CAPM	Capital Asset Pricing Model
CPI	Consumer Price Index
GHG	Greenhouse gas
LEV	Land Expectation Value
LULUCF	Land Use, Land Use Change and Forestry
MRP	Market Risk Premium
NPV	Net Present Value
NZETS	New Zealand Emissions Trading Scheme
OLS	Ordinary Least Squares
PDE	Partial Differential Equation
RV	Random variable

CHAPTER 1: INTRODUCTION

1.1 Motivation

According to the World Resources Institute (2011), global greenhouse gas (GHG) emissions are estimated at 43.2 billion tons. Figure 1 shows the breakdown of the global GHG emissions by sector.

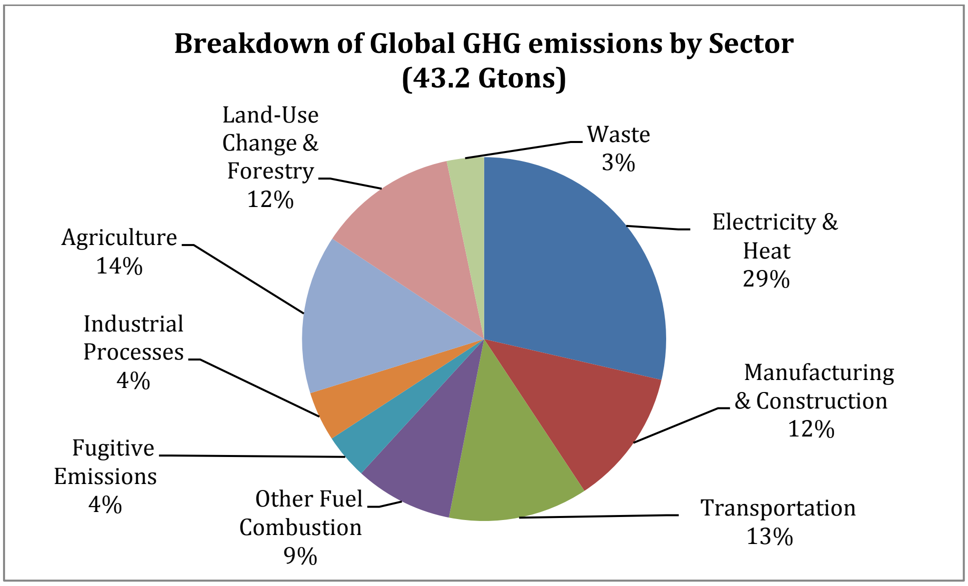


Figure 1: Breakdown of global GHG emissions by sector.

New Zealand is doing its share of climate mitigation actions by implementing a cap-and-trade system known as the New Zealand Emissions Trading Scheme (NZETS) to limit GHG emissions and incentivize climate change mitigation actions. Under the NZETS, forests planted on or after 1st January 1990 (known as post-1989 forests) qualify to earn carbon credits, proportionate to the amount of carbon the trees sequester. Upon receiving the credits, they can be accumulated or immediately sold in domestic and international carbon markets, thereby, generating a new set cash flow for forest owners. Carbon credits must be repaid back by the forest owner upon eventual harvesting of the forests, by an amount proportionate to the extent that carbon stocks decrease in the forest land.

Credits would be repaid back by purchasing carbon credits from domestic or international carbon markets at the market price, and surrendering these credits back to the government (Ministry of Agriculture and Forestry, 2007).

The new revenue stream from carbon credits alters the traditional timber-only cash flow business model for forest owners, and affects the harvesting decision of forests. This change poses a very interesting research question:

"How does the New Zealand Emissions Trading Scheme (NZETS) affect post-1989 forestry harvesting decisions?"

As an inquisitive economics student who has also worked as a forestry climate change policy analyst, this question is intriguing, both academically and professionally.

This research seeks to develop an improved method to model newly planted post-1989 forest harvesting in New Zealand under the NZETS. From this research, a powerful set of economic analysis tools will be developed. This work is of significant interest to other domestic and international researchers because New Zealand is the first and only country in the world with an emissions trading scheme that allows forests to earn internationally tradable carbon credits. The effect of the NZETS on harvesting decisions of forest owners is therefore a very interesting topic that contributes to advancing knowledge in the fields of forest management, economics and more broadly public policy.

1.2 Research Method, Objectives and Scope

This research employs two primary valuation methodologies, namely the Net Present Value / Land Expectation Value (NPV/LEV) method, and the Real Options Valuation approach using the Binomial Tree method. Throughout this thesis, the term “valuation” is used to imply the value of bareland on which radiata pine is to be planted with a single or a perpetual series of rotations.

The work here focuses on analyzing the effect of NZETS on the NZ forestry sector by seeking answers to the following questions:

1) How does the NZETS affect the bareland valuation of new post-1989 forests?
2) How do analytical methodologies and assumptions of flexible versus fixed harvest ages affect bareland value?
3) To what extent will carbon pricing affect harvesting decisions?
4) What is the optimal harvesting decision for new post-1989 forests in New Zealand?
5) What are the impacts of these effects on New Zealand?

It is noted that questions 1, 3, 4 and 5 have previously been addressed using the conventional discounted cash flow (NPV/LEV) fixed harvest analysis method, by the works of Turner et al (2008), Maclaren et al (2008a), Maclaren et al (2008b), and Manley and Maclaren (2010). The work in this thesis is aimed at complementing these existing works by comparing the fixed harvest with flexible harvest approaches.

The scope of this research is limited to the most commercially valuable forest crop in New Zealand (i.e. radiata pine[2]) and it is also narrowed down to new post-1989[3] plantation forests, excluding pre-1990[4] plantations forests and all pre-1990 indigenous natural forests as they are unable to earn carbon credits under the NZETS.

---

[2] About 89% of New Zealand's plantation forests (by area) are of the Radiata Pine species, with Douglas fir estimated at 6%, other softwoods at 2%, and hardwoods at 3% (Ministry of Agriculture and Forestry, 2009).

[3] Post-1989 forests refer to new forests planted on and after 1st January 1990.

[4] Pre-1990 forests refer to forests that are already in existence prior to and on 31st December 1989.

1.3 Chapter Outline of Thesis

Chapter 2 consists of a review of timber forestry valuation methods drawn from academic literature, namely, NPV/LEV and Real Options. A review of carbon forestry literature is also included, with a focus on carbon forestry modeling work in New Zealand. This chapter concludes with an overview of the New Zealand Emissions Trading Scheme (NZETS).

Chapter 3 introduces the single random variable (RV) Binomial Tree method that is used in this thesis. The application of this method to a flexible harvest decision and a fixed harvest decision is described.

Chapter 4 covers the data used and assumptions made in this research. Results of timber-only forestry valuations using NPV/LEV and Real Options are presented and compared. These results were presented at the New Zealand Agricultural and Resource Economics Society (NZARES) conference in August 2010 (Tee et al, 2010).

Chapter 5 applies the single RV Binomial Tree method to analyze the forestry sector under the NZETS (i.e. carbon forestry). In this analysis, there are two prices, namely, timber price and carbon price. Because the single RV Binomial Tree method can only model one random variable at a time, one of the prices is treated in a stochastic manner while the other is held constant. Results are presented for the case of stochastic timber price with a constant carbon price (Model I), and stochastic carbon price with a constant timber price (Model II). Part of this work was presented at the Australian Agricultural and Resource Economics Society (AARES) conference in February 2011 (Tee et al, 2011a).

Chapter 6 overcomes the limitation of the single RV Binomial Tree method by developing a double RV Binomial Tree method to enable simultaneous stochastic modeling of both timber and carbon prices. Results of this method are discussed. This work has been accepted for presentation at the European Association of Environmental and Resource Economists (EAERE) conference in July 2011 (Tee et al, 2011b).

Chapter 7 presents a scenario analysis of potential implications of the NZETS on New Zealand's existing post-1989 radiata pine forests and the annual carbon stock change. Suggestions for future studies are also highlighted.

1.4 Areas of Original Contribution

The following areas of this thesis are considered to be original contributions:

- Application of an existing methodology (single random variable Binomial Tree method by Guthrie, 2009) to a new set of data (i.e. New Zealand forestry). This work is covered in Chapter 4.
- Adaptation of the methodology to analyze carbon forestry in New Zealand using a stochastic timber price with a constant carbon price, and modification of the model for further analysis using a stochastic carbon price with a constant timber price. These works are covered in Chapter 5.
- Development of a double RV Binomial Tree model to simultaneously model both the timber and carbon prices stochastically. This work is covered in Chapter 6.
- Scenario analysis of potential implications on existing post-1989 radiata pine forests and the annual carbon stock change in New Zealand. This is covered in Chapter 7.

CHAPTER 2: LITERATURE REVIEW

In this chapter, a review of relevant literature is conducted, drawing from key academic journals and research publications, both internationally and domestically. An overview of the NZETS is also provided.

2.1 Timber Forestry Valuation Methods

Fixed Rotation Forestry Valuation

The Net Present Value (NPV) formula for valuing forests with infinite rotations is also known as the Faustmann formula, named after the German civil servant who is credited with being the first to formulate the optimal rotation problem, Martin Faustmann (Faustmann, 1849). Faustmann approached the problem by posing the question *"How much is a piece of land worth if it is devoted to the growing of trees?"* He was first to identify the problem as *"choosing the harvest period to maximize the NPV value of a series of future harvests"*. He showed that the NPV of a forest can be expressed as a sum of discounted net cash flow over an infinite time horizon (Esa-Jussi, 2006).

Under the NPV approach, the value of the investment is determined at the present day by forecasting expected future cash flows and discounting them at a specific discount rate. Advantages of using this approach include:

- Being relatively simple numerically, with relatively easy implementation;
- Being forward-looking, as it explicitly models future cash flows;
- Accounting for riskiness of the investment and time value of money.

To the present day, the NPV approach is widely accepted as the key method in forestry investment decision-making. Despite its popularity, the method has a few notable weaknesses. Often, adjustments for risks are captured by the discount rate, which is assumed to be constant throughout the forest's lifetime[5]. The NPV approach does not account for flexibility due to the assumption of a fixed investment path where the decision is made in advance, and remains unchanged, even when unexpected favourable or unfavourable events arise. It also ignores the value that alternative opportunities and choices bring to the investment.

Flexible Rotation Forestry Valuation

Flexibility in decision-making is valuable when investors face risks and uncertainty about the future, especially when there is a degree of irreversibility attached to the decisions being made (Dixit and Pindyck, 1995).

Consider the situation in forestry where forest owners must decide when to harvest the forest. Under the Faustmann NPV approach, the harvesting decision (based on the optimal rotation age calculated from the NPV) is made regardless of the timber price at the time of expected harvest (i.e. it is already pre-decided upfront when the trees were first planted). The decision to replant will also have to be made immediately after cutting, as per the optimal rotation plan.

In addition, the harvesting decision is irreversible. Once harvested, the trees cannot be put back into the ground. If the timber price is low during the harvest, the *"loss"* in profits is also permanently irreversible.

Given that forest owners face uncertainty in future prices and irreversibility in the consequences of their decisions, it may be advantageous for them to remain flexible about forest harvesting decisions. If timber prices are low at the *"expected"* time of harvest, forest owners may want to delay harvest, wait-and-see before making a harvesting decision. Likewise, if timber prices are unusually high before the "expected" time of harvest, forest owners may want to harvest early to take advantage of the high prices.

---

[5] This is common, but is not always the case. It is noted here that the New Zealand Institute of Forestry's Forest Valuation Standards (p A4-22) specifies that "*the preferred approach in this situation is to adjust future cash flows rather than the discount rate*".

Uncertainty and irreversibility of an investment decision cannot be easily introduced into and anticipated by the NPV approach. In practice, the optimal rotation age is recalculated as a stand matures, using updated information about timber prices as well as actual yields from the inventory (rather than the growth model) and costs. In order to better manage the true potential of the returns, forest owners should use a framework or tool that can accommodate a flexible investment decision. The Real Options approach offers such form of flexibility.

The Real Options Approach to Valuation

Evaluation of an investment has traditionally been performed using cost-benefit analysis, which is oriented towards making a simple decision: *should an investment project be undertaken today?* This decision is essentially a *"now-or-never"* decision. Missing from this traditional approach is the possibility (or option) of delay.

The capacity to be flexible when uncertainty and irreversibility exist increases the value of the investment. The greater the degree of flexibility, the more value the investment can potentially return (Copeland and Antikarov, 2001).

A financial option is a derivative security whose value is derived from the worth and characteristics of another financial security, or the so-called underlying asset. By definition, a call option gives the holder the right, but not the obligation, to buy the underlying asset at a specified price (i.e. the exercise price) on or before a given date (i.e. the expiration date) (Reuer and Tong, 2007). In contrast, a put option gives the holder the right to sell the underlying asset.

Financial economists Black and Scholes (1973) and Merton (1973) pioneered a formula for valuing a financial option. Their methodology opened up subsequent research on the pricing of financial assets. This work paved the way for the development of Real Options theory by Myers (1977), who had the seminal idea that one can view a firm's discretionary investment opportunities as a call option on real assets, in much the same way as a financial call option provides decision rights on financial assets. As an analogy, a Real Option can have its underlying asset as the gross project value of expected operating cash flows, its exercise price as the investment required to obtain this underlying asset, and the time to maturity as the period of time during which the decision maker can defer the investment before the investment opportunity expires.

In short, Real Options are investments in real assets (as opposed to financial assets), which confer the investor the right, but not the obligation, to undertake certain actions in the future (Schwartz and Trigeorgis, 2004). There are three general approaches for implementing Real Options valuations:

- *Partial Differential Equation (PDE):* The PDE approach treats time as a continuous variable and expresses the present value of a cash flow stream as the solution to a PDE. The most famous such PDE appears in Black and Scholes (1973). This is the standard and most widely used Real Options valuation method in academic literature research due to its mathematical elegance and insights. For example, Pindyck (1993) studied the uncertain cost of investment in nuclear power plants, where he derived a decision rule for irreversible investments subject to technical and input uncertainties.
- *Simulation:* A simulation typically computes thousands of possible paths describing the evolution of the underlying asset's value from the start period to the end period. With simulations, one can handle complicated problems with a high number of variables (Gamba, 2003). With the advancement of computing power, large simulation programs are being used to construct value options that are very difficult to solve using PDEs. Though powerful, this method is not very insightful (compared to the closed form PDE solutions) because it only provides the answer (valuation) without insights into the relationships between variables and the key drivers for the valuation. Another form of simulation or modeling that is commonly used to analyse forestry valuation is Stochastic Dynamic Programming.
- *Binomial Trees* (also known as Binomial Option Pricing model): Developed by Cox, Ross and Rubinstein (1979), this approach treats time as a discrete variable and expresses the present value of a cash flow stream as the solution to a system of simple linear algebraic equations. This method's

precision can be improved to a very high degree by dividing the life span of an option into more stages. This discrete-time approach is mathematically simpler than the PDE method, yet it provides an efficient procedure for valuing options. Copeland and Antikarov (2001) applied Binomial Trees to value real projects and proved that this method is equivalent to the PDE solution. It is easy to use without losing the insights of the PDE model.

Of the three approaches, the Binomial Tree method offers a good balance between insights and complexity.

Real Options Valuation Applied to Forestry

Traditionally, the Faustmann harvest decision approach ignores annual timber price fluctuations and prescribes harvest on the basis of expected prices. Brazee and Mendelsohn (1988) recognized the volatility of timber prices from year to year, and incorporated a stochastic timber price into their work. They concluded that the flexible price harvest policy significantly increases the present value of expected returns over the rigid Faustmann model. Clarke and Reed (1989) and Reed and Clarke (1990) further distinguished the stochastic uncertainty of timber price and the timber growth. Provencher (1995) investigated other factors affecting harvesting decisions, such as profit shocks.

Miller and Voltaire (1983) were amongst the first authors to introduce Real Options into forestry. Morck, Schwartz and Stangeland (1989) used a PDE approach to determine the optimal harvesting rate. Thomson (1992) employed a Binomial Tree to determine land rent endogenously assuming stumpage prices follow the Geometric Brownian Motion (GBM) process.

Plantinga (1998) highlighted the role of option values in influencing the optimal timing of harvests. He treated an option value as a premium over the expected value of a timber stand reflecting the opportunity cost of harvesting now and foregoing the option to delay harvest until information on future stand values is revealed. His work shows that expected timber values are higher with a reservation price policy when timber prices are stationary compared to the

Faustmann model with expected prices. When timber prices are non-stationary, the expected timber values are identical to Faustmann values. In other words, when prices follow a random walk, there is little to no option value. On the other hand, when prices follow a mean reverting process, there is a larger option value.

Gjolberg & Guttormsen (2002) applied the Real Options approach to the tree-cutting problem under the assumption of mean-reverting (rather than random-walk) stumpage prices.

Insley (2002) investigated the role of the timber price process on the rotation length in a single-rotation model. A dynamic programming approach and a general numerical solution technique were used to determine the value of the option to harvest a stand of trees and the optimal cutting time when timber prices follow a known stochastic process. It was concluded that "*option value and optimal cutting time are significantly different under the mean reversion assumption compared to geometric Brownian motion*".

In Insley and Rollins (2005), the authors extended the single-rotation work by Insley (2002) to multiple rotations, and analyzed forest stand value with stochastic timber prices and deterministic wood volume. In their work, it was suggested that, like many commodities such as oil and copper, timber prices should eventually revert to some mean, reflecting long run marginal costs.

Duku-Kaakyire and Nanang (2004) compared a forestry investment using the Faustmann NPV model and the Real Options approach. They investigated four options: an option to delay deforestation, an option to expand the size of the wood processing plant, an option to abandon the processing plant if timber prices fall below a certain level, and an option that included all three of these individual options. This analysis was conducted using the Binomial Tree method. The results show that while the Faustmann analysis rejected investments as unprofitable, the Real Option analysis showed that all four options were highly valuable. It demonstrated the weakness of the Faustmann approach, namely, the lack of managerial flexibility to adjust for shocks, risks and uncertainty.

Manley and Niquidet (2010) compared the Faustmann method with three Real Options valuation methods, namely, the Binomial Option Pricing model, the

Stochastic Dynamic Programming model, and a new approach based on the Black and Scholes (1973) option pricing model called the Abandonment Adjusted Price model. This comparison assumed that the timber price follows a random walk process. It concluded that the increase in forest value over the Faustmann value can be substantial, but only when prices are low and close to the exercise cost, with gains quickly diminishing as price increases. This conclusion is consistent with the conclusion of Plantinga (1998), which is that when prices follow a random walk, there is little to no option value.

Valuations of fixed and flexible rotation ages are commonly compared using different and separate methods: an NPV/LEV model and a Real Options model. In such comparisons, the Real Options models tend to have higher data requirements, employ different assumptions and are much more complex to estimate compared to NPV/LEV. Because of these differences, it may be difficult to isolate the cause of the increased valuation.

In Guthrie (2009), the author applied a single random variable (RV) Binomial Tree method to study the optimal harvest decision of forests in Oregon (USA) using a mean-reverting timber price process. The same Binomial Tree method was able to generate results for Real Options (flexible harvest decision) and NPV/LEV (fixed rotation), for both single and infinite rotations. The work of Guthrie (2009) is useful and can be used to isolate the cause of increased valuation of flexible rotations compared to fixed rotations. For this reason, this method is chosen for use in this thesis, as opposed to other methods identified in this section.

2.2 Carbon Forestry and Climate Change Mitigation

In Englin and Callaway (1993), the authors investigated the use of forests for climate change mitigation purposes. They were the first to integrate the carbon sequestration lifecycle into the Faustmann framework of forest management and develop optimal cutting rules when both timber and carbon sequestration benefits are considered.

Van Kooten, Binkley and Delcourt (1995) further investigated the effect of carbon taxes and subsidies on optimal forest rotation. Their work showed that when carbon sequestration for climate change mitigation purposes is taken into account, the optimal rotation age is no longer the Faustmann age because the rate of net carbon uptake by a forest is proportional to the growth of the forest, rather than the timber volume.

Romero, Ros, Rios and Diaz-Balteiro (1998) approached the timber and carbon problem by examining the trade-offs between the value of harvested timber and the value of carbon sequestration for climate change mitigation purposes.

Sohngen and Mendelsohn (2003) developed a general equilibrium model to show the interaction between carbon and timber prices. A global timber market (pricing) model was used as a carbon sequestration cost function, whereas a separate greenhouse gas model of carbon and the world economy was used to project the carbon price. More recently, Olschewski and Benitez (2009) investigated the optimization of joint timber production and carbon sequestration of afforestation projects covered under the Kyoto Protocol.

Chladna (2007) used Real Options to study the impact of carbon credit payment schemes on the optimal rotation length. The author was the first to provide a detailed (PDE) numerical analysis that employs both stochastic wood prices and stochastic carbon prices. The analysis assumed that the timber price is mean reverting, whereas the carbon price follows a geometric Brownian motion. In the analysis, the carbon price grows exponentially at a rate 3.6%, from zero Euros/ton in the year 2000 to more than 130 Euros/ton in the year 2100. It is unclear whether the exponentially growing carbon price is a realistic assumption, particularly when the timber price is assumed to revert to a long term level (i.e. essentially remaining constant aside from the short term fluctuations). The exponential carbon price may also be a key reason why the approach taken in this work was limited to analysing a single rotation since over multiple rotations, the carbon price would have grown to very high levels, when compared to the mean reverting timber price.

The works highlighted in this section shows the broad range of methods used to analyze carbon forestry. In order to ensure comparability between timber-only and carbon forestry while maintaining consistency in studying fixed and flexible rotations, the method of Guthrie (2009) is adapted to study carbon forestry in this thesis.

2.3 Overview of the New Zealand Emissions Trading Scheme

The Kyoto Protocol is an international climate change agreement that sets binding greenhouse gas (GHG) reduction targets for 37 industrialized countries and the European Community. The collective reduction target amounts to an average of 5% against 1990 emission levels over the five year period of 2008-2012. It covers six greenhouse gases, namely, carbon dioxide ($C0_2$), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). These emissions are categorized under five sectors/sources – energy, industrial processes, agriculture, waste, and solvent (and other product use) (UNFCCC, 1998).

New Zealand’s GHG emissions for 2008, broken down by each sector, are shown in Figure 2. The two major emitting sectors are agriculture and energy. The Land Use, Land Use Change and Forestry (LULUCF) sector is a major source of carbon sinks (i.e. absorb/sequester carbon) (Ministry for the Environment, 2010).

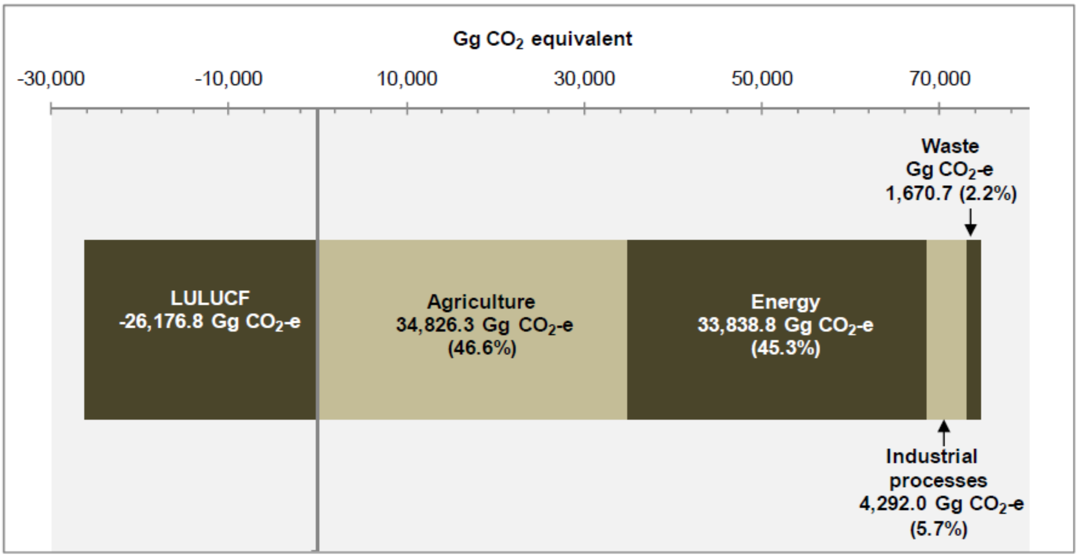


Figure 2: New Zealand’s GHG emissions by sector in 2008.

In order to meet New Zealand's Kyoto Protocol commitments, the government passed cap-and-trade legislation, called the New Zealand Emissions Trading Scheme (NZETS), to create a carbon price and create incentives for businesses and consumers to change behaviour. The NZETS is the world's first economy-wide cap-and-trade system that covers all sectors and all gases. It is internationally linked and reflects international climate change rules (New Zealand Government, 2010).

The NZETS has a transition period between 1st July 2010 and 31st December 2012, during which emitters will be able to buy emission units (carbon credits) from the New Zealand government for a fixed price of $25. In addition, emitters will only have to surrender one emission unit for every two tons of emissions they produce during this period.

For the forestry sector, new forests established on and after 1st January 1990 are eligible to earn carbon credits[6]. Known domestically as post-1989 forests, these forests can earn carbon credits for increases in carbon stocks from 1st January 2008[7]. If the carbon stock in a post-1989 forest decreases (for example, due to harvesting), emission units must be surrendered (i.e. harvest liabilities). These post-1989 forestry NZETS rules have been designed to directly reflect the rules of afforestation and reforestation under Article 3.3 of the Kyoto Protocol (UNFCCC, 1998).

For forest owners, the new revenue stream from carbon credits and harvest liabilities alters the traditional timber-only cash flow business model, and affects the harvesting decision. After receiving the credits, they can be accumulated or immediately sold in domestic and international carbon markets, thereby, generating a new set cash flow for forest owners. Upon harvesting of the post-

---

[6] It is noted here that some owners of pre-1990 forest land are eligible for a free allocation of carbon credits. This type of allocation is a one-off compensation and is not considered in this thesis since the focus here is on new post-1989 forests.

[7] Carbon stock accumulated between 1st January 1990 and 31st December 2007 does not earn any credits, nor does it incur any liabilities.

1989 forests, the proportionate amount of carbon credits must be surrendered by the forest owner. These credits could be purchased from domestic or international carbon markets at the market price for surrendering (Ministry of Agriculture & Forestry, 2010).

2.4 Carbon Forestry in New Zealand

The works of Maclaren et al (2008a), Maclaren et al (2008b), Manley and Maclaren (2009) and Manley and Maclaren (2010) employed the NPV/LEV methodology to analyse the impact of the New Zealand Emissions Trading Scheme (NZETS) on forest management.

Turner et al (2008) employed a combination of NPV/LEV and simulations to model and analyse the management of planted forests for carbon under the NZETS. In Meade et al (2008), results from a simulation method called Bootstrapping Real Options Analysis were compared to results from a NPV (discounted cash flow) calculation.

Guthrie and Kumareswaran (2009) used PDEs to study the impact of carbon credit payment schemes over multiple rotations in New Zealand. Due to the complexity of the PDE method, the timber price was assumed to be stochastic whereas the carbon price is assumed to be constant in order to keep the mathematics tractable.

New Zealand is the only country in the world with a forestry Emissions Trading Scheme. The work of this thesis using the Binomial Tree method will complement existing works and contribute positively to the carbon forestry literature in New Zealand.

CHAPTER 3: THE SINGLE RANDOM VARIABLE (RV) BINOMIAL TREE METHOD

This chapter describes the single random variable (RV) Binomial Tree method used in this thesis, and its application to flexible and fixed harvest decisions.

3.1 Overview of the Binomial Tree Method

Single Random Variable (RV) Price Binomial Tree

The basic parameters of a price Binomial Tree are:

- $X(i,n)$ is the price, where i is the number of downward price moves and n is the time step
- $X(0,0)$ is the present price
- U is the upward price move multiplicative factor
- D is the downward price move multiplicative factor ($D = 1/U$)
- $\theta_U(i,n)$ is the probability of an upward price move
- $\theta_D(i,n)$ is the probability of a downward price move ($\theta_D = 1 - \theta_U$)

An example of the Binomial Tree labeling convention is shown in Figure 3 for $n = 2$. Each $X(i,n)$ node on the Binomial Tree is calculated by applying U and D to $X(i,n)$ starting with $X(0,0)$, such that $X(i,n+1) = X(i,n)U$ and $X(i+1,n+1) = X(i,n)D$.

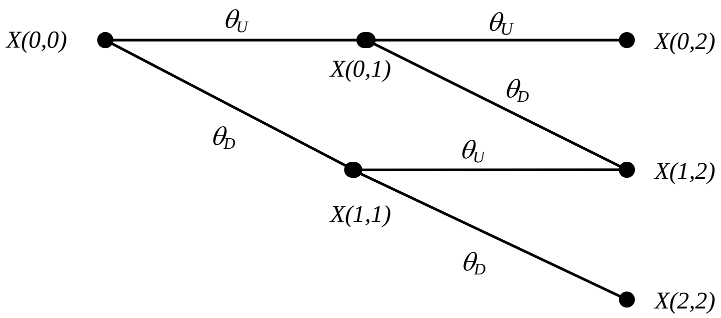


Figure 3: The Binomial Tree labeling convention.

Calibrating the Binomial Tree for a Mean-Reverting Price Process

A mean-reverting price process is assumed. The technique for calibrating the Binomial Tree for a mean reverting price is summarized as follows (Guthrie,2009):

1. Estimating the first-order autoregressive process of the price model

For a mean reverting price series, the logarithm of the price follows a first-order autoregressive process. If p_j denotes the j^{th} observation of the logarithm of the price, then:

$$\begin{aligned} p_{j+1} - p_j &= \alpha_0 + \alpha_1 p_j + u_{j+1} \\ u_{j+1} &\sim N(0,\phi^2) \end{aligned}$$

Changes in p are normally distributed with mean $\alpha_0+\alpha_1 p_j$ and variance ϕ^2, and u_{j+1} is a noise term. α_0, α_1 and ϕ are related to the Ornstein-Uhlenbeck parameters (a, b and σ) by the following equations:

$$\begin{aligned} \alpha_0 &= (1-e^{-a\Delta t})b \\ \alpha_1 &= -(1-e^{-a\Delta t}) \\ \phi^2 &= \frac{\sigma^2}{2a}(1-e^{-2a\Delta t}) \end{aligned}$$

where a = rate of mean reversion, b = long-run level, σ = volatility of the Ornstein-Uhlenbeck process, and Δt = time step size.

2. *Estimating the Ornstein-Uhlenbeck parameters*

An Ordinary Least Squares (OLS) regression of the price data produces estimates of α_0, α_1 and ϕ respectively as:

$$\hat{\alpha}_0 = (1 - e^{-\hat{a}\Delta t_d})\hat{b}$$

$$\hat{\alpha}_1 = -(1 - e^{-\hat{a}\Delta t_d})$$

$$\hat{\phi}^2 = \frac{\hat{\sigma}^2}{2\hat{a}}(1 - e^{-2\hat{a}\Delta t_d})$$

where Δt_d is the time step size of the price data. Solving for estimates of a, b and σ produces:

$$\hat{a} = \frac{-\log(1+\hat{\alpha}_1)}{\Delta t_d}$$

$$\hat{b} = \frac{-\hat{\alpha}_0}{\hat{\alpha}_1}$$

$$\hat{\sigma} = \hat{\phi}\left(\frac{2\log(1+\hat{\alpha}_1)}{\hat{\alpha}_1(2+\hat{\alpha}_1)\Delta t_d}\right)^{1/2}$$

3. *Filling in the Binomial Tree parameters*

From estimates of the Ornstein-Uhlenbeck parameters, the Binomial Tree parameters, namely U, D and $\theta_U(i,n)$, are calculated as:

$$U = e^{\hat{\sigma}\sqrt{\Delta t_m}}$$

$$D = e^{-\hat{\sigma}\sqrt{\Delta t_m}}$$

$$\theta_u(i,n)=\begin{cases} 0 & if\ \frac{1}{2}+\frac{(1-e^{-\hat{a}\Delta t_m})(\hat{b}-\log(X(i,n))}{2\hat{\sigma}\sqrt{\Delta t_m}}\le 0 \\ \frac{1}{2}+\frac{(1-e^{-\hat{a}\Delta t_m})(\hat{b}-\log(X(i,n))}{2\hat{\sigma}\sqrt{\Delta t_m}} & if\ 0<\frac{1}{2}+\frac{(1-e^{-\hat{a}\Delta t_m})(\hat{b}-\log(X(i,n))}{2\hat{\sigma}\sqrt{\Delta t_m}}<1 \\ 1 & if\ \frac{1}{2}+\frac{(1-e^{-\hat{a}\Delta t_m})(\hat{b}-\log(X(i,n))}{2\hat{\sigma}\sqrt{\Delta t_m}}\ge 1 \end{cases}$$

where Δt_m is the time step size of the Binomial Tree.

Single Random Variable Valuation Binomial Tree

Binomial Trees are also used to implement valuations. The probability of an up move (θ_U) and probability of a down move (θ_D) in the price Binomial Tree are applied to the valuation Binomial Tree, as shown in Figure 4 for $n = 2$. Each node is labeled *V(i,n)*, representing valuation at time step *n*, with *i* number of down moves in the price.

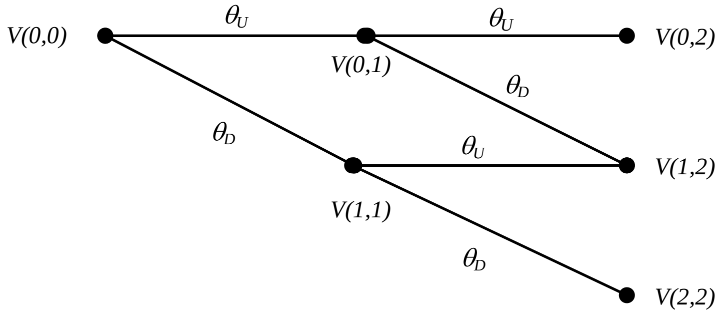


Figure 4: Single random variable valuation Binomial Tree.

In contrast to the price Binomial Tree which is calculated forward using *X(0,0)*, *U* and *D*, the valuation Binomial Tree is calculated backwards (in reverse) starting from the terminal (last) time step, *N*, and the corresponding terminal nodes *V(i,N)*.

Discount rates are added to the valuation calculations to reflect the time value of money. For example, valuation at node *V(0,1)* is:

$$V(0,1) = \frac{\theta_U V(0,2)}{R_f} + \frac{\theta_D V(1,2)}{R_f}$$

where $R_f = (1 + discount\ rate)$. This valuation process traverses backwards systematically until it ends at *V(0,0)*.

<u>Capital Asset Pricing Model (CAPM)</u>

In addition to the discount rate, the Capital Asset Pricing Model (CAPM) can be used to further reflect a market risk premium into the valuation. A market risk premium is the expected differential return of the stock market over as risk-free asset, such as a Treasury bond (Fernandez, 2004). It is the minimum amount of money by which the expected return on a risky market portfolio must exceed the known return on a risk-free asset, in order to induce an investor to accept compensation for the risk.

Through a so-called Risk Neutral probability, the market risk premium is factored into the valuation Binomial tree's probabilities of an upward and downward price move. A Market Risk Premium Adjustment (MRP_{Adj}) is subtracted from the θ_U to produce the Risk Neutral probability Π_U (Guthrie, 2009):

$$\begin{aligned} \Pi_U &= \theta_U - MRP_{Adj} \\ \Pi_D &= 1 - \Pi_U \end{aligned}$$

The MRP_{Adj} is obtained by regressing price changes on stock market returns on an index such as the NZX 50 Total Returns Index (Guthrie, 2009).

Separating the market risk premium from the risk-free asset return (discount rate) is a standard practice under the CAPM approach. However, in conventional NPV/LEV forestry valuations, risk is not modeled separately and is typically factored in implicitly by using a high discount rate.

It is noted here that valuation using Binomial Tree could also be performed without the CAPM element (i.e. using θ_U and θ_D instead of Π_U and Π_D). In such a case, the appropriate level of risk premium is simply incorporated by choosing a higher factor rate (R_f).

3.2 Application to a Flexible Harvest Decision (Real Options)

When calculating the valuation (backwards), a decision on whether to harvest or not to harvest is re-evaluated at each and every node. If the present value of the cash flows from harvest at each node is more than the present value of the expected future cash flows (i.e. cash flows from not harvesting), then the optimal decision is to harvest, and the valuation at the node equals the cash flow from harvest. If the present value of the expected future cash flows (i.e. those from not harvesting) is more than the present value of the cash flows from harvesting, then, the optimal decision is not to harvest, and the valuation at the node equals the present value of the corresponding expected future cash flows. That is:

$$V(i,n) = \max\left\{ \begin{aligned} & (1-T)((X(i,n)-H)Q(n\Delta t_m)) + B, \\ & (1-T)(-M_T) + \frac{\Pi_u(i,n)V(i,n+1) + \Pi_D(i,n)V(i+1,n+1)}{R_f} \end{aligned} \right\}$$

where T is the tax rate, H is the harvesting cost, Q(n) is the timber volume at time step n, B is the value of the bare land that remains after the harvest (“Bareland value”), and M_T is the maintenance cost of the forest. The first argument of the max function represents the cash flow from harvesting, whereas the second argument represents the cash flow from not harvesting.

As mentioned previously, this process traverses backwards from $n = N$ to $n = 0$, ending with $V(0,0)$. The Binomial Tree valuation is implemented backwards recursively over multiple iterations. Each iteration represents one harvest and replant rotation. During the calculation for the first iteration, the Bareland value is assumed to be zero. At the end of the first iteration, a Bareland value is estimated by deducting the cost of (re-)planting the forest from *V(0,0)*:

$$B = V(0,0) - (1-T)G$$

where *G* is the cost of (re-)planting the forest. This first iteration Bareland value is the valuation for a single rotation forest with flexible harvest (i.e. Real Options valuation for single rotation).

To calculate the value for an infinite rotation forest, this first iteration Bareland value is then fed into the second iteration (i.e. during the second iteration of valuation calculations, *B* in the *V(i,n)* function is no longer zero). After this process is repeated for a certain amount of iterations (e.g. 10 iterations), the Bareland value converges to a steady state value (i.e. it no longer changes with subsequent iterations). This converged Bareland value is the valuation for an infinite rotation forest with flexible harvest (i.e. Real Options valuation for infinite rotation).

3.3 Application to a Fixed Harvest Decision (Fixed Rotation NPV/LEV)

To apply this valuation method to a fixed harvest, the same process is used with one modification. The harvest decision is fixed (i.e. pre-decided regardless of the price) at the node where *t* = fixed harvest age (i.e. use node *t* as the terminal node instead of *N* where *t* < *N*). All nodes on the valuation Binomial Tree to the right side of *t* (i.e. all nodes between *t+1* and *N*) are ignored (i.e. truncated) and the backward traverse starts from node *t* (instead of node *N* as for the case of flexible rotation forest).

During each node traverse, unlike the flexible harvest case, there is no re-evaluation of a harvest decision (i.e. no harvest decision reconsidered at subsequent nodes) because there is already a fixed (i.e. pre-decided regardless of price) harvest decision at node t (= fixed harvest age). As such, the valuation for each node from *n* = *(t – 1)* to *n* = *0* is:

$$V(i,n) = (1-T)(-M_T) + \frac{\Pi_u(i,n)V(i,n+1) + \Pi_D(i,n)V(i+1,n+1)}{R_f}$$

This is the only modification required to compute the fixed harvest results. The value of B after the first iteration is the single rotation NPV. After a certain number of iterations (e.g. 10 iterations), B converges to the infinite rotation LEV.

CHAPTER 4: TIMBER FORESTRY VALUATION USING THE SINGLE RANDOM VARIABLE (RV) BINOMIAL TREE METHOD

In this chapter, the Binomial Tree method used by Guthrie (2009) is applied to analyze radiata pine timber forests in New Zealand. Optimal valuation results of fixed and flexible harvest decisions, for single and infinite rotations, are generated. Further valuation results for a constant timber price are produced and compared with the result obtained via a standard NPV/LEV calculation using an Excel spreadsheet. The Binomial Tree method and the NPV/LEV calculations are shown to produce the same result when the timber price is constant.

4.1 Data Used And Assumptions Made

Timber Volume

For this work, the timber volume function was sourced from the R300 Radiata Pine Calculator model by Future Forests Research Limited (2010), which is based on Kimberley et al (2005). Figure 5 plots the timber volume function, generated using default values of the Calculator: site index of 28.3 meters, with 850 stems planted per ha.

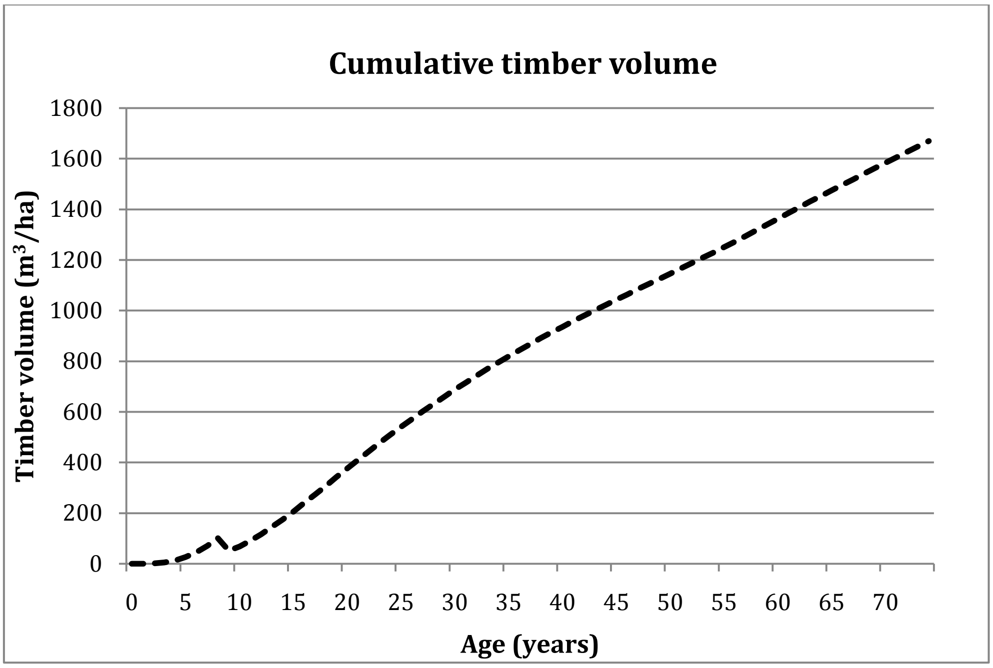


Figure 5: Timber volume function based on the R300 Radiata Pine Calculator.

Timber Price

Figure 6 shows the New Zealand Ministry of Agriculture and Forestry radiata pine price data for various log grades (Horgan, 2010).

Table 1 shows the yield by log grade for trees of various ages. The average log grade yield is used as the weighting for aggregating the log prices in Figure 6 into a single proxy timber price series. This is further adjusted with the Consumer Price Index (CPI) from Statistics New Zealand (2010) to result in the CPI-adjusted timber price series as shown in Figure 7.

Log Grade	**Yield by Timber Age (years)**										**Average Yield**
	25	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	
Pruned	33%	31%	28%	27%	25%	24%	24%	23%	23%	22%	26%
S1	1%	4%	7%	8%	10%	11%	14%	17%	20%	22%	11%
S2	14%	16%	16%	16%	16%	16%	16%	16%	16%	14%	16%
L1&L2	11%	16%	20%	21%	22%	24%	24%	25%	25%	26%	22%
S3&L3	26%	20%	18%	17%	15%	14%	13%	11%	9%	8%	15%
Pulp	14%	13%	11%	11%	10%	10%	9%	8%	8%	7%	10%

Table 1: Log grade yield of various timber ages.

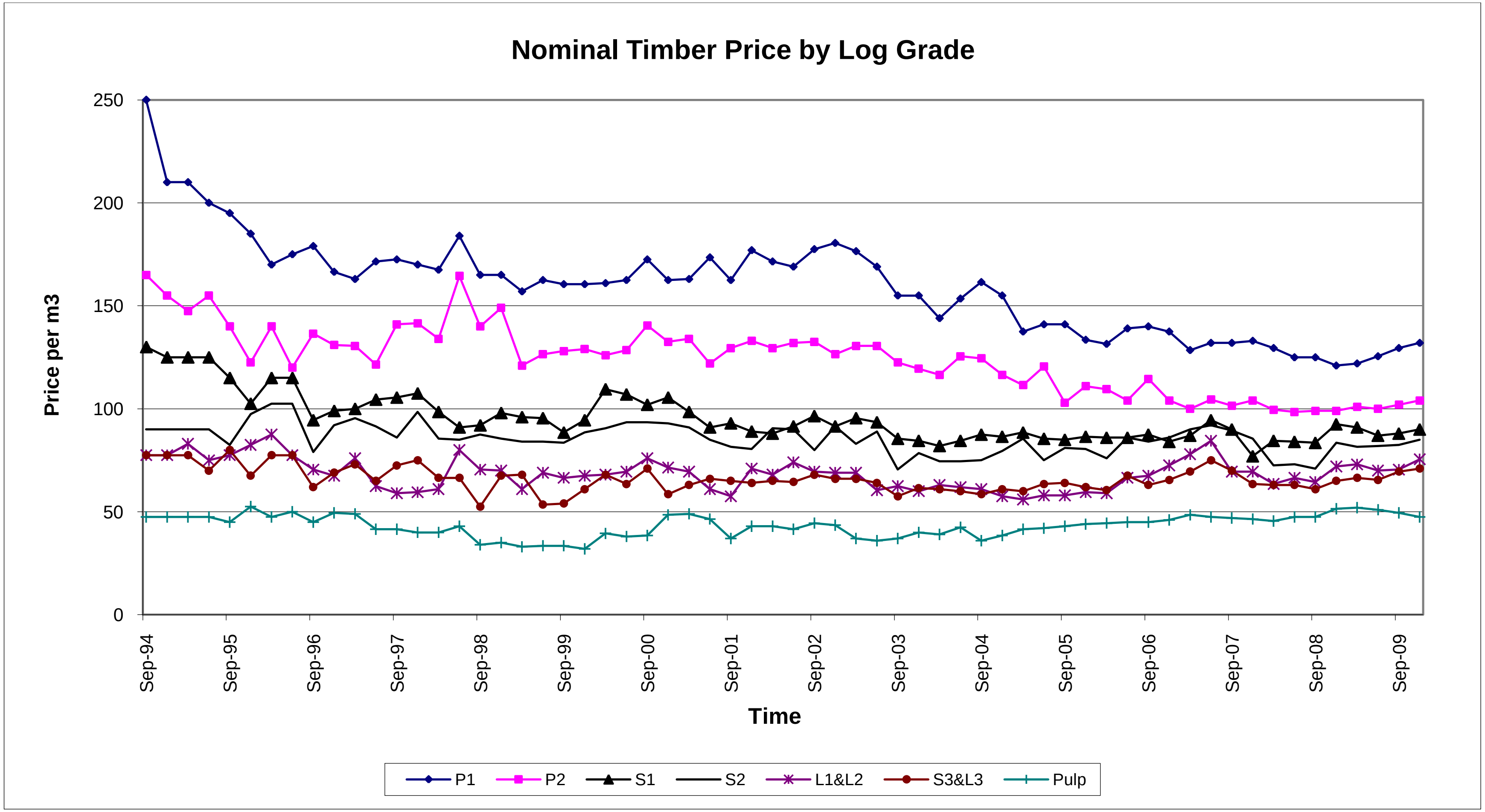


Figure 6: Ministry of Agriculture and Forestry radiata pine price data.

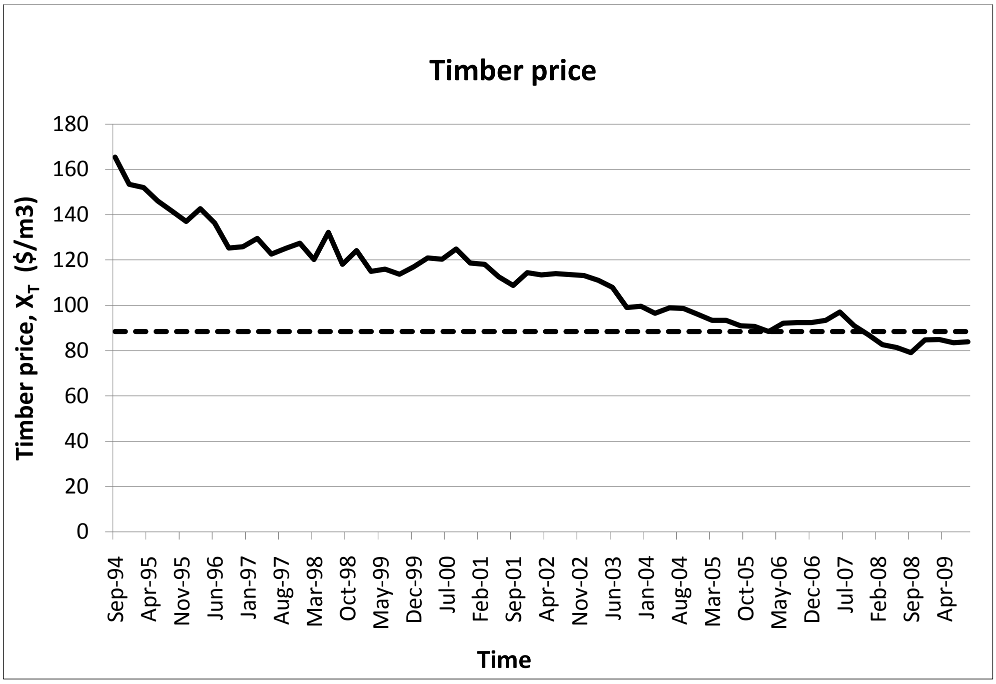


Figure 7: CPI-adjusted proxy timber price series, with the long run price shown as a dashed line.

The timber price is assumed to be a mean reverting process. An Ordinary Least Squares (OLS) regression of the proxy timber price series using the methodology described in section 3.1 produces:

$$\hat{a} = 0.216006$$

$$\hat{b} = 4.482340$$

$$\hat{\sigma} = 0.080705$$

From these values, U and D are estimated to be 1.0236 and 0.9770 respectively, which are used to calculate $X(i,n)$ and θ_U of the price Binomial Tree. The long run timber price is $e^{\hat{b}} = \$88.44$ which is shown in Figure 7 as a dashed line.

Market Risk Premium (MRP)

In Franks et al (2010), the authors recommended an MRP range between 5% and 5.7% for New Zealand. Here, a Market Risk Premium (MRP) of 5.5% is assumed, and MRP_{Adj} is estimated from regression of price changes on stock market returns (NZX 50) as -0.0008, which is used to calculate Π_U and Π_D of the valuation Binomial Tree.

Costs and Cash Flow

Forest management costs are assumed to be:

- Planting costs, G = \$1,251/ha
- Pruning costs = \$473/ha (age 6), \$674/ha (age 7), \$684/ha (age 8)
- Thinning costs = \$370/ha (age 9)
- Forest maintenance costs, M_T = \$50/ha/year
- Harvesting cost (clearfell logging), H_T = \$40/m^3

These costs are based on Turner et al (2008) and the R300 Radiata Pine Calculator (Future Forests Research Limited, 2010). The overall cash flow of carbon forestry (per hectare) is summarized in Table 2.

	Years											
	0	**1**	**2**	**. .**	**5**	**6**	**7**	**8**	**9**	**10**	**. .**	**Harvest year**
Planting costs	(1251)											
Pruning costs						(473)	(674)	(684)				
Thinning costs									(370)			
Maintenance costs, M_T	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	
Timber revenue, X_TQ_T												\$
Harvest costs, H_TQ_T												(\$)

Table 2: Cash flow of timber forestry (per hectare).

Tax and Discount Rate

The tax rate, T, is assumed to be 28%.

Term deposit investment is assumed to be the risk free asset for the CAPM approach, with a return rate of 4%. With this assumption, the cash flow discount rate is 4%, such that $R_f = 1.04$.

In the survey by Manley (2010), the discount rates used by forest valuers in New Zealand range from 7 to 9 percent. In section 4.3, a sensitivity analysis is performed using discount rates from 3% to 9%, with an MRP of 5.5%. This implies that a 5.5% risk premium is factored into the analysis, over and above the risk-free rate of at least 3% (to a maximum of 9%). Although it is difficult to make a direct and equal comparison, the "effective" discount rate covered in the thesis is much wider and less conservative, ranging from 8.5% (= 3% + 5.5%) to 14.5% (= 9% + 5.5%).

Infinite Rotation

Results for rotation ages of up to 75 years are generated. 21 harvest-and-replant cycles are used to represent infinite rotation. For example, for a 30 year rotation age, the approximated infinite rotation is 21 x 30 = 630 years. For a 75 year rotation age, the approximated infinite rotation is 21 x 75 = 1575 years.

4.2 Results for Binomial Tree Method (Mean Reverting Timber Price)

Binomial Tree Method with Fixed Harvest (Mean Reverting Price)

Figure 8 shows the results for fixed harvest cases of single and infinite rotations, with Figure 9 zooming into the maxima points between ages 24 and 35. For a single rotation with fixed harvest, the optimal rotation age is 31 years, with an NPV valuation of $4,494. For an infinite rotation with fixed harvest, the optimal rotation age is 27 years (i.e. the Faustmann rotation age), with an LEV valuation of $6,628.

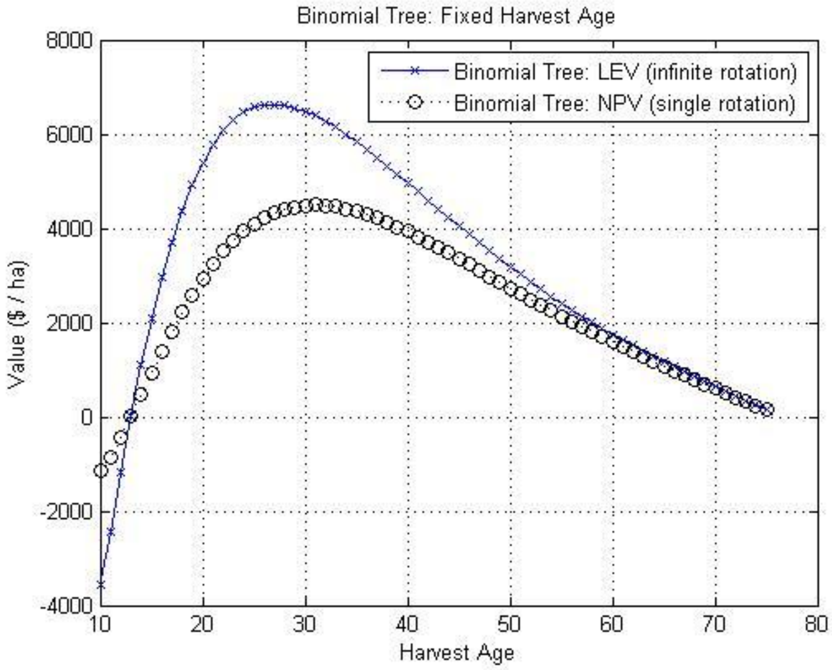


Figure 8: Results for fixed harvest cases of single and infinite rotations.

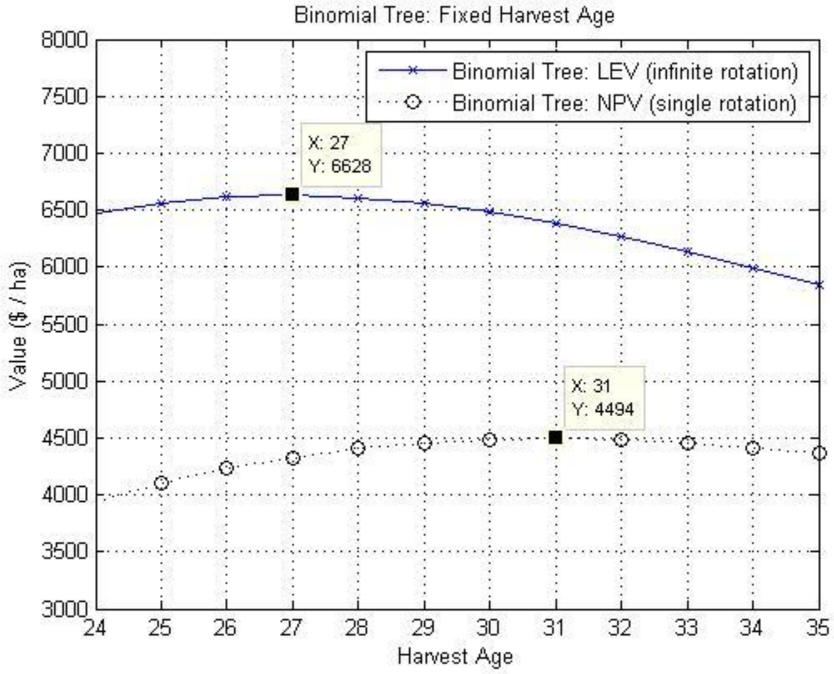


Figure 9: Enlargement on the maxima points of Figure 8.

Binomial Tree Method with Flexible Harvest (Mean Reverting Price)

Figure 10 shows the results for flexible harvest cases of single and infinite rotations. For a single rotation, the optimal valuation is the Bareland value after one iteration, is $5,785. For an infinite rotation, the Bareland value converges to $8,185 after about 10 harvest-and-replant cycles.

Compared to the case of a fixed harvest, allowing a flexible harvest results in 29% and 23% higher valuations for single and infinite rotations, respectively.

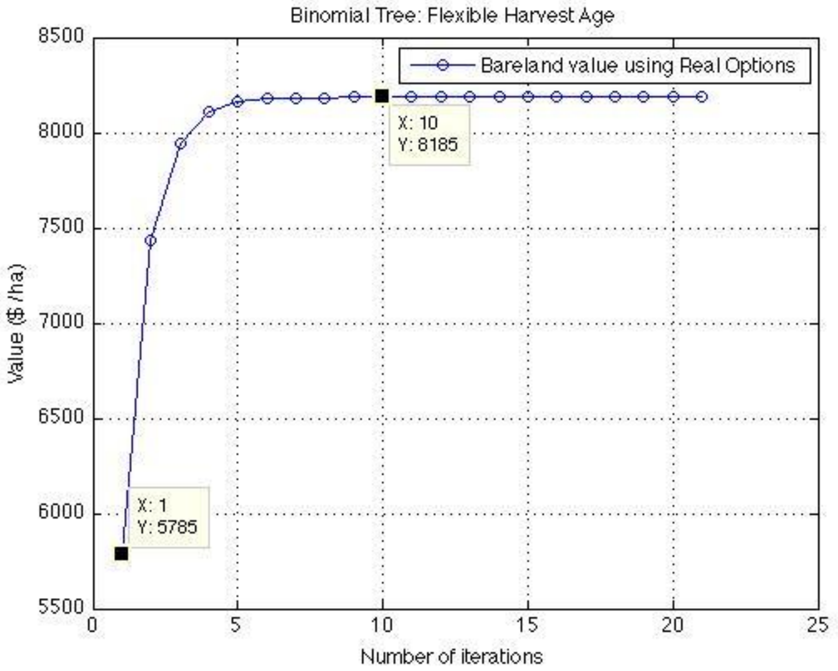


Figure 10: Results for flexible harvest cases for single and infinite rotations.

Figures 11 and 12 show the optimal harvest thresholds for single and infinite rotations, respectively. In each graph, the area above the dotted line shows the range of timber prices that favour a harvest decision for a given forest age. As a example in Figure 11, the threshold for a 25 year old single rotation forest is $83.90 such that if the timber price at that time (age 25) is above this threshold, it would be optimal to harvest, whereas if the timber price at that time (age 25) is below this threshold, it would not be optimal to harvest (and the optimal decision would be to defer harvest).

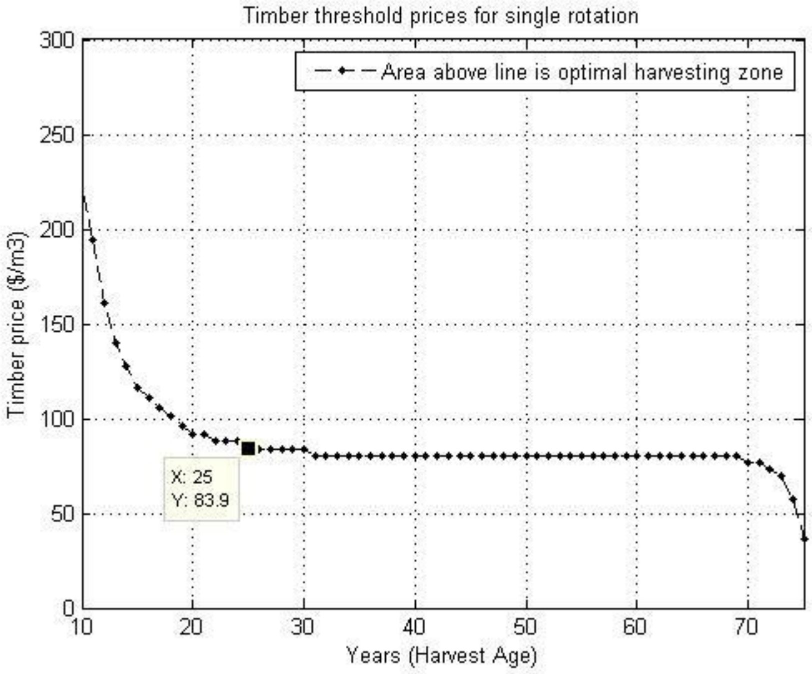


Figure 11: Optimal harvest threshold for single rotation.

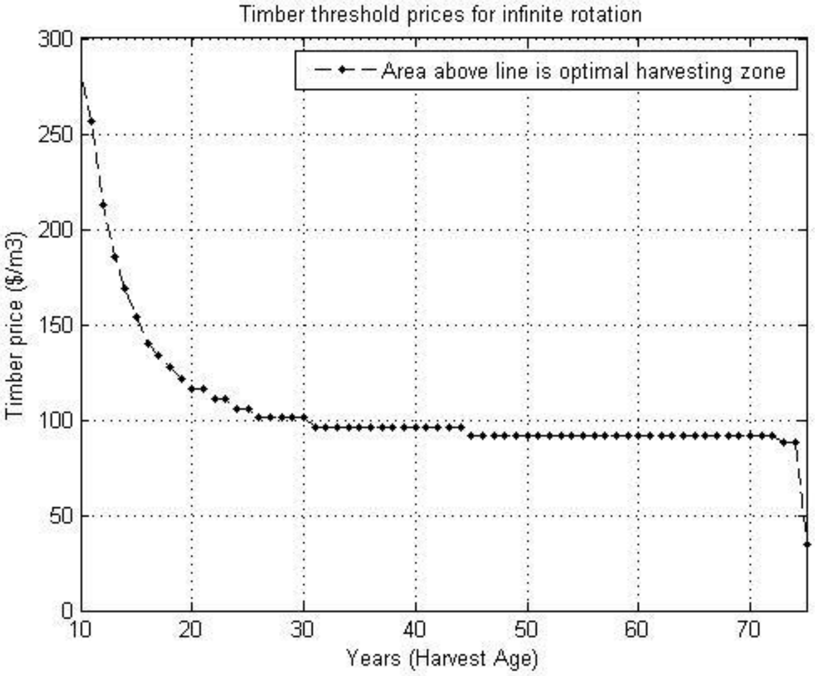


Figure 12: Optimal harvest threshold for infinite rotation.

4.3 Discount Rate Sensitivity Analysis for Valuation

Figure 13 shows the single rotation valuation for fixed harvest at various discount rates. The corresponding valuation for infinite rotation is shown in Figure 14. As the discount rate increases from 3.0% to 8.0%, the optimal single rotation age decreases from 36 years to 22 years. For infinite rotation, the optimal rotation age falls from 29 to 22 years. At a discount rate of 8.0%, the valuations for single and infinite rotation are $482 and $590.60, respectively, which are barely profitable.

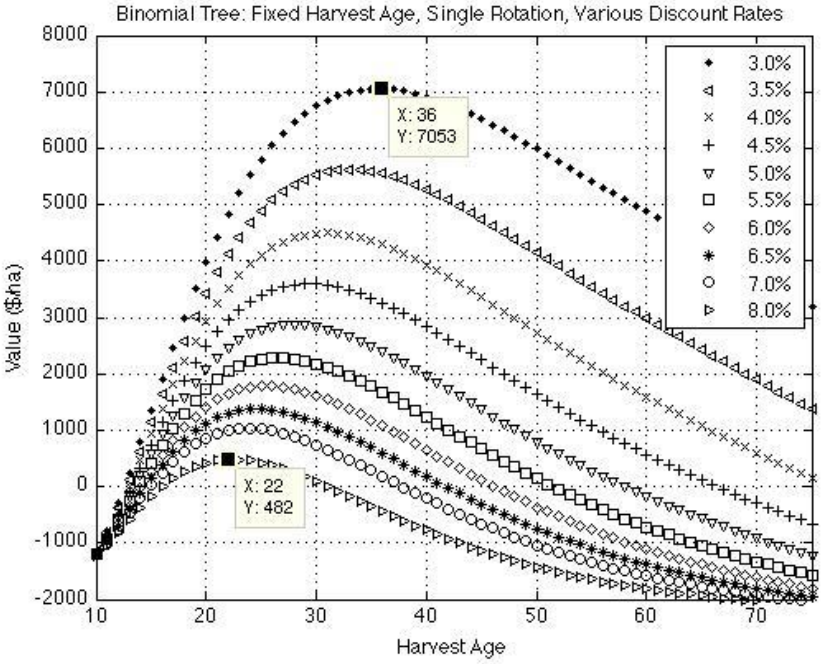


Figure 13: Single rotation valuation for fixed harvest at various discount rates.

Figure 15 shows the single and infinite rotation valuations for flexible harvest. For single rotation, the valuation falls from $9,233 to $763.30 as the discount rate rises from 3.0% to 8.0%. For infinite rotation, the valuation decreases from $14,200 to $926.90.

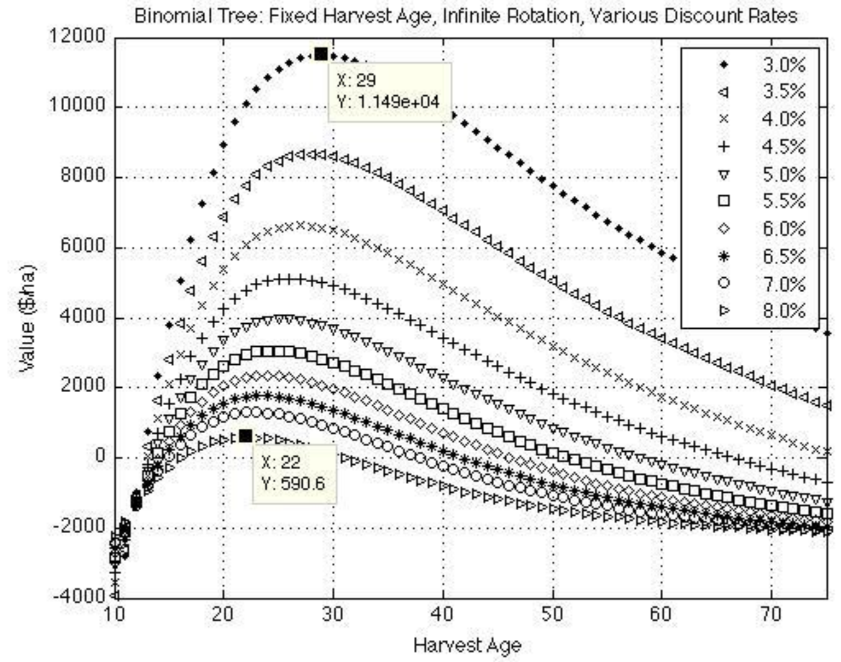


Figure 14: Infinite rotation valuation for fixed harvest at various discount rates.

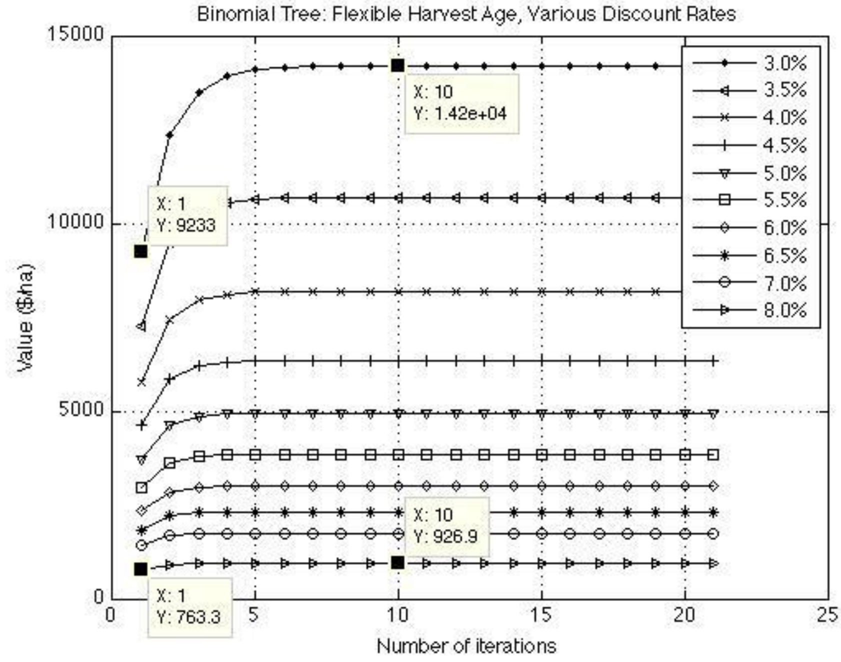


Figure 15: Single and infinite rotation valuations for flexible harvest at various discount rates.

Figure 16 plots the maxima points of Figure 13 (i.e. single rotation NPVs) for various discount rates and compares it to the single rotation valuations for flexible harvest (i.e. minima points from Figure 15).

Figure 17 plots the corresponding comparisons for infinite rotation.

In both graphs, all the valuations decrease exponentially as discount rates increase. The flexible harvest valuations are also always greater than the fixed harvest valuations. For fixed harvest, the optimal rotation ages decline at an almost linear fashion as the discount rate increases.

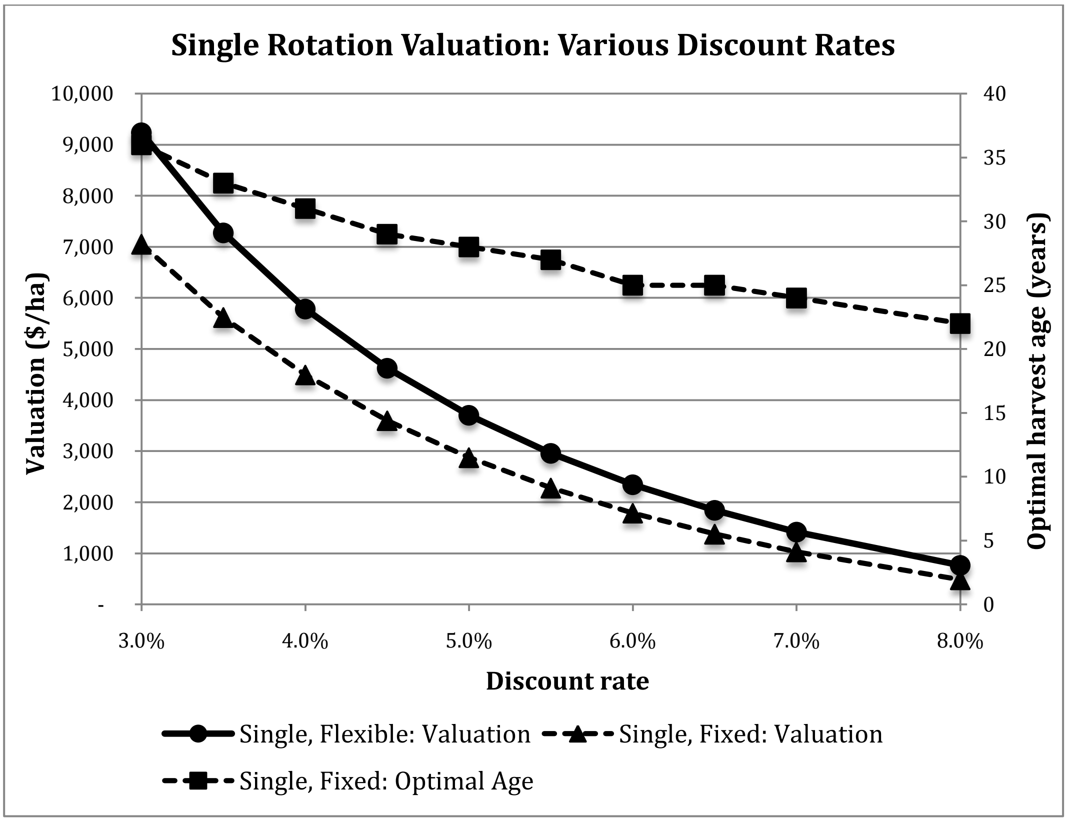


Figure 16: Comparing the single rotation valuations for fixed harvest (NPV) and flexible harvest (Real Options) at various discount rates.

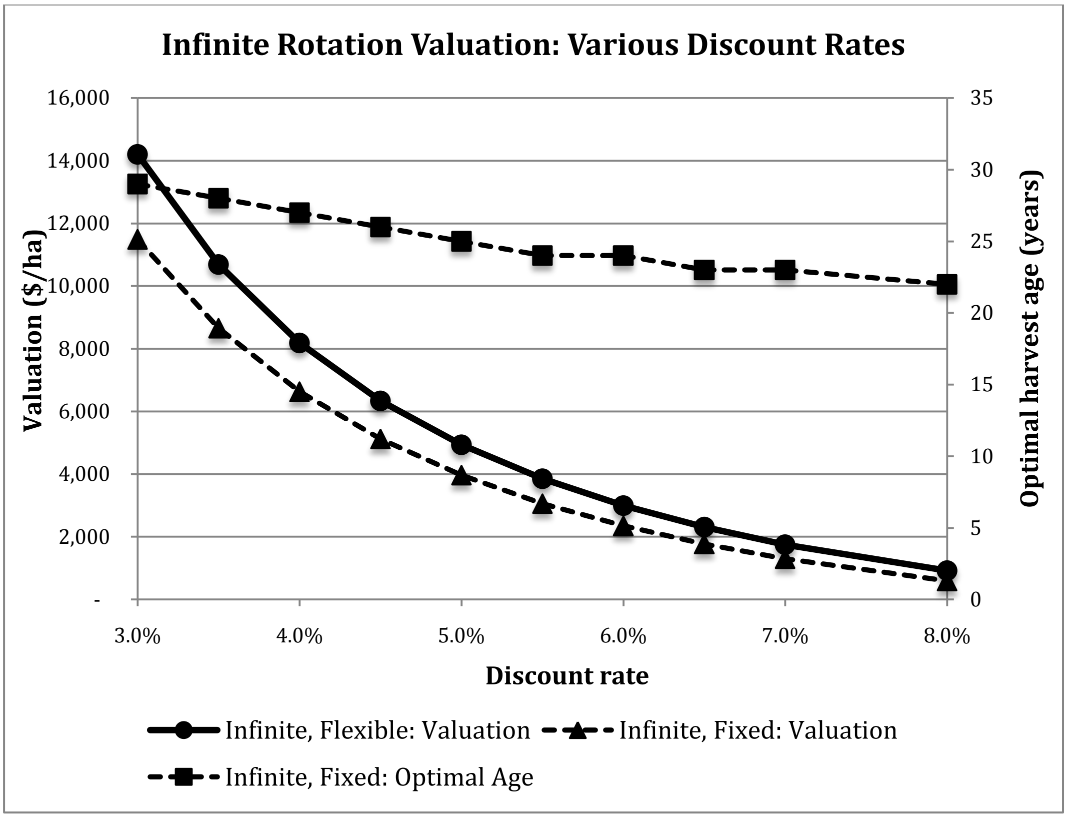


Figure 17: Comparing infinite rotation valuations for fixed harvest (LEV) and flexible harvest (Real Options) at various discount rates.

4.4 Results for Binomial Tree Method (Constant Timber Price)

If the volatility of the mean reverting price process is zero, then, the price becomes constant. In this section, the volatility of the price process is set equal to zero, and results from the Binomial Tree valuation are presented using a constant timber price, assumed to be the long run timber price value of $88.44. Here, the discount rate of 4.0% is assumed, as per section 4.2.

Binomial Tree Method with Fixed Harvest (Constant Price)

Figures 18 and 19 show the NPV and LEV results obtained from the Binomial Tree valuation with fixed harvest at a constant price. For single rotation, the optimal age is 31 with a valuation of $4,368. For infinite rotation, the optimal age is 27 with a valuation of $6,443.

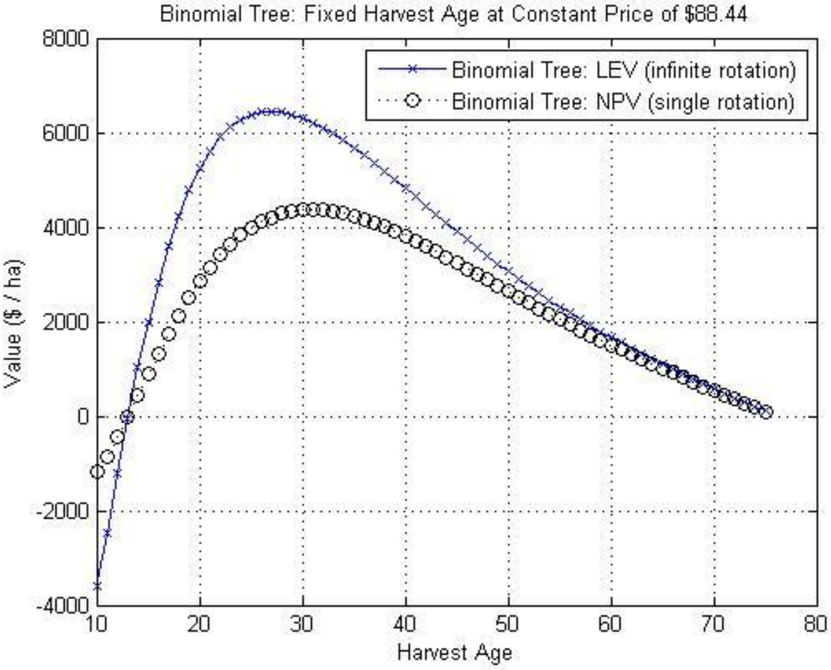


Figure 18: Results for fixed harvest cases of single and infinite rotations at a constant price.

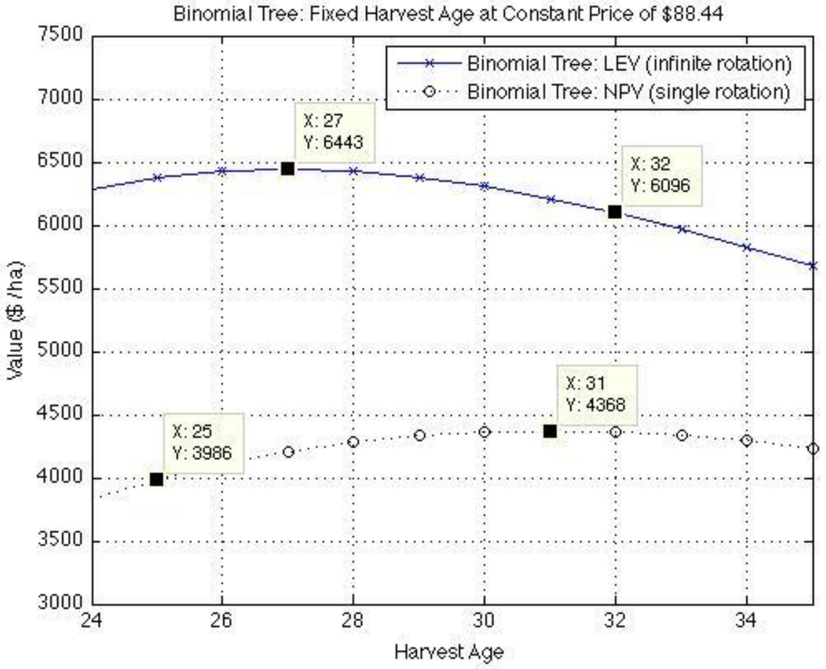


Figure 19: Enlargement on the maxima points of Figure 18.

Binomial Tree Method with Flexible Harvest (Constant Price)

Figure 20 shows the results obtained from the Binomial Tree valuation with flexible harvest at a constant price. The single and infinite rotation valuations are $4,368 and $6,443 respectively. These are identical values to the maximum NPV and maximum LEV values of Figure 19.

These results show and confirm that when prices are constant, fixed harvest valuation (NPV and LEV) produces the same result as flexible harvest valuation (Real Options). This is because when the price is constant, there is no flexibility because prices do not rise/fall, and therefore, there is no additional value from delaying harvest. The optimal flexible harvest decision produces the same results as the optimal fixed harvest decision, which are the NPV and LEV values.

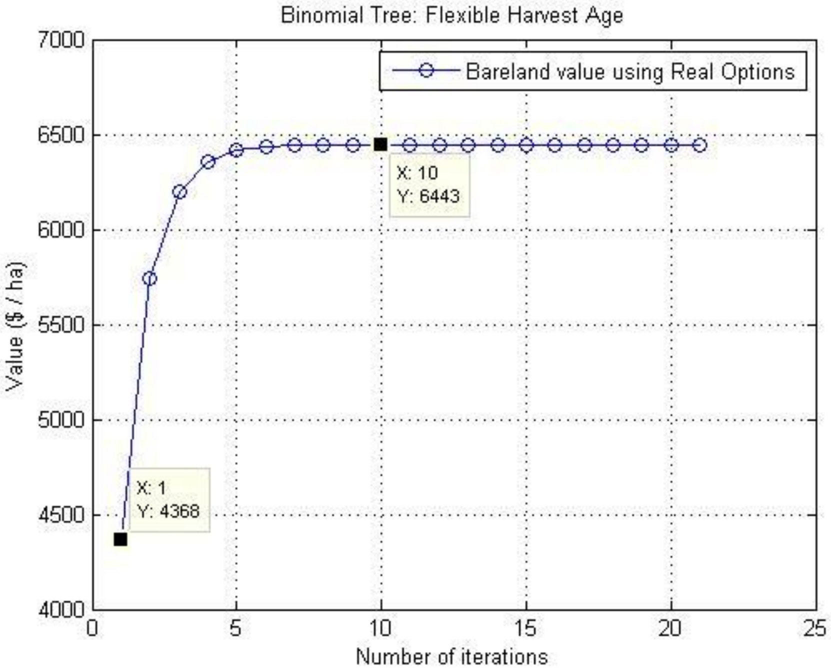


Figure 20: Results for Binomial Tree valuation with flexible harvest at a constant price.

4.5 Results for Standard NPV and LEV at a Constant Price

In this section, results for fixed harvest at a constant price are generated using the standard Excel spreadsheet NPV and LEV calculation. A discount rate of 4.0% is assumed. Table 3 shows the results of the calculations. For single rotation, the optimal age (i.e. highest NPV) is 31 years with an NPV of $4,368, whereas for infinite rotation, the optimal age (i.e. highest LEV) is 27 years with an LEV of $6,443.

Harvest Age	NPV	LEV
25 years	$3,986	$6,379
26 years	$4,111	$6,430
27 years	$4,208	**$6,443**
28 years	$4,282	$6,424
29 years	$4,331	$6,376
30 years	$4,360	$6,303
31 years	**$4,368**	$6,209
32 years	$4,358	$6,096
33 years	$4,332	$5,968
34 years	$4,291	$5,827
35 years	$4,237	$5,675

$$LEV_n = NPV_n \frac{R_f^{\,n}}{R_f^{\,n} - 1}$$

where *n* is the harvest age

Table 3: Results for fixed harvest at a constant price using the standard Excel spreadsheet NPV and LEV calculation.

What is worth noting here is that the valuations in the NPV and LEV columns of Table 3 are identical to each of the values generated from the Binomial Tree valuation in Figure 19. To illustrate this, four data points in Figure 19 are highlighted: $3,986 at 25 years, $4,368 at 31 years, $6,443 at 27 years and $6,096 at 32 years. These points are equal to the respective points in Table 3, and thus, confirm that both methods are equivalent when prices are constant.

4.6 Conclusions

For a mean-reverting price process, it is shown in this chapter that flexible harvest (Real Options) results in higher valuations for both single and infinite rotations when compared to fixed harvest (NPV/LEV). This is because flexible harvest takes advantage of price fluctuations by deferring harvest when prices are low and accelerating it when they are high, thereby, generating the higher valuation.

When the price is constant, both fixed harvest and flexible harvest produce the same valuations. This is because when prices do not rise or fall, there is no additional value from delaying harvest. Under such a circumstance, the optimal flexible harvest decision produces the same valuation results as the optimal fixed harvest decision, which is equal to the NPV and LEV values. It is further confirmed that the Binomial Tree method is equivalent to the standard NPV/LEV method when the price is constant.

The Binomial Tree method is a relatively simple way to implement Real Options analysis. NPV and LEV results can also be produced using this same model, data, and assumptions, allowing for differences in valuations to be attributed solely to the fixed versus flexible decision, rather than differences in model sophistication, data requirement or assumptions employed. For flexible harvest, the Binomial Tree method also produces the price thresholds for optimal harvesting, which is a useful tool for forest owners in making an optimal harvest/no-harvest decision given a timber price at a certain age. The results offer useful insights, allowing forest owners to take into account contemporary pricing information to make a potentially better investment decision.

CHAPTER 5: CARBON FORESTRY VALUATION USING THE SINGLE RV BINOMIAL TREE METHOD

In this chapter, the single random variable (RV) Binomial Tree method is used to analyze carbon forestry under the NZETS. Two models are considered. Model I uses a stochastic (mean-reverting) timber price with a constant carbon price, whereas Model II uses a stochastic (mean reverting) carbon price with a constant timber price. Only results for infinite rotations are presented. It is shown that carbon forestry generates a significantly higher return compared to traditional timber-only forestry. Both models provide forest owners with price thresholds for optimal harvest that can be compared with actual timber and carbon prices in every year in order to guide the optimal harvest decision.

5.1 Real Options Valuation Functions

The Binomial Tree method employed in this chapter is the same as that of chapter 3. However, there are now two prices in the model – timber price and carbon price. Because the Binomial Tree has only one random variable (RV) in the presence of two stochastic prices, only one price can be modeled stochastically whereas the other is assumed to be constant. Here, the case of stochastic timber price with constant carbon price is designated as Model I, whereas the case of stochastic carbon price with constant timber price is designated Model II.

For Model I (stochastic timber), the Real Options valuation function is:

$$V(i,n)=\max\left\{\begin{array}{l}(1-T)\left([X_T(i,n)-H_T]Q_T(n)-X_C Q_C(n-1)-M_C\right)+B, \\ \\ (1-T)\left(-M_T-M_C+X_C[Q_C(n)-Q_C(n-1)]\right) \\ +\dfrac{\Pi_u(i,n)V(i,n+1)+\Pi_D(i,n)V(i+1,n+1)}{R_f}\end{array}\right\}$$

where T is the tax rate, $X_T(i,n)$ is the price at time step n, H_T is the harvesting cost, $Q_T(n)$ is the timber volume at time step n, X_C is the constant carbon price, $Q_C(n-1)$ is the carbon stock at time step $(n-1)$, M_C is the NZETS compliance cost, B is the Bareland value and M_T is the maintenance cost of the forest. The first (shorter) term of the max function represents the cash flow from harvesting, whereas the second (longer) term represents the cash flow from not harvesting.

For Model II (stochastic carbon), the corresponding valuation function is:

$$V(i,n)=\max\left\{\begin{array}{l}(1-T)([X_T-H_T]Q_T(n)-X_C(i,n)Q_C(n-1)-M_C)+B,\\ \\ (1-T)(-M_T-M_C+X_C(i,n)[Q_C(n)-Q_C(n-1)])\\ +\dfrac{\Pi_u(i,n)V(i,n+1)+\Pi_D(i,n)V(i+1,n+1)}{R_f}\end{array}\right\}$$

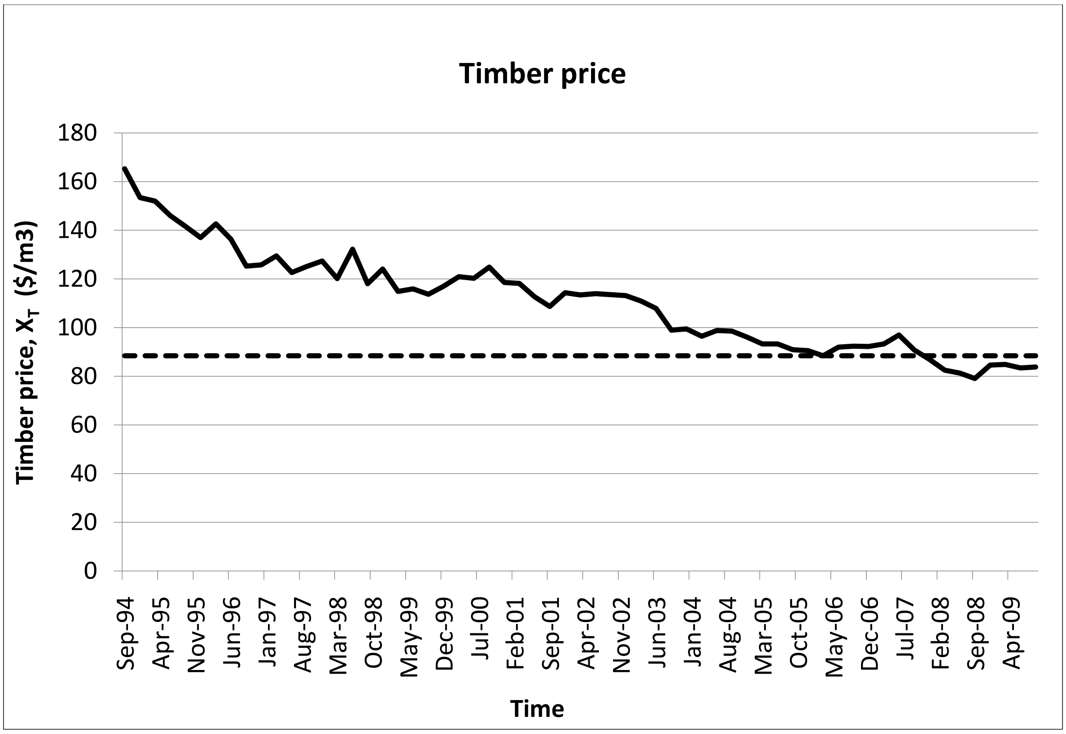
where X_T is the constant timber price and $X_C(i,n)$ is the carbon price at time step n.

5.2 Data Used and Assumptions Made

Timber and Carbon Prices

The timber price used here is as per chapter 4, reproduced in Figure 21 for convenience. The carbon price data is shown in Figure 21, sourced from the New Zealand Treasury (Treasury, 2010), adjusted with the Consumer Price Index (CPI) from Statistics New Zealand (2010). The carbon price data is the same data used to calculate New Zealand's net position under the Kyoto Protocol, and it provides a common reference point for analyzing the effects of the NZETS.

Like the timber price, the carbon price is also assumed to be a mean reverting process.



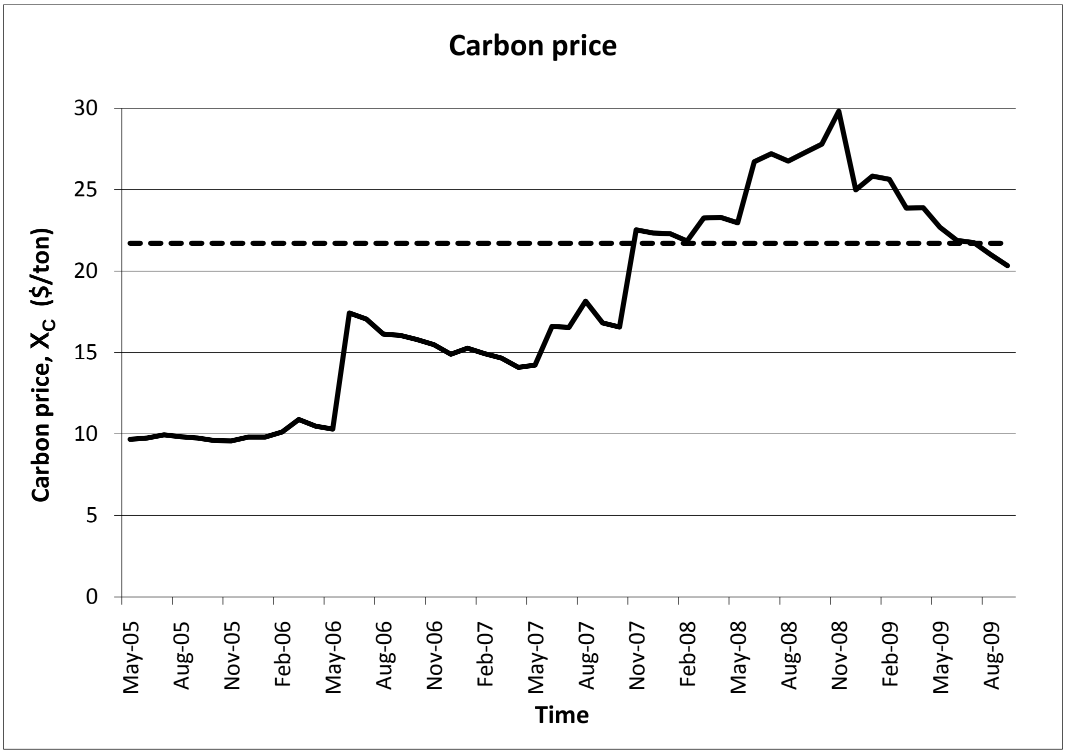


Figure 21: Timber and carbon prices, CPI adjusted, with long run prices shown as dashed lines.

Ordinary Least Squares (OLS) regression is applied individually to each of the timber and carbon price series, using the same procedures described in section 3.1, resulting in the following parameters:

$$Timber\ \ price\ \ series\ \ (as\ \ per\ chapter\ \ 4)$$

$$\hat{a}_T = 0.216006$$

$$\hat{b}_T = 4.482340$$

$$\hat{\sigma}_T = 0.080705$$

$$U_T = 1.0236$$

$$D_T = 0.9770$$

$$e^{\hat{b}_T} = NZ\$88.44\ \ (long\ \ run\ timber\ \ price)$$

$$Carbon\ price\ series$$

$$\hat{a}_C = 0.703590$$

$$\hat{b}_C = 3.078332$$

$$\hat{\sigma}_C = 0.346650$$

$$U_C = 1.1052$$

$$D_C = 0.9048$$

$$e^{\hat{b}_C} = NZ\$21.72\ \ (long\ run\ carbon\ price)$$

These parameters are used to calculate $X(i,n)$ and θ_U of the respective price Binomial Trees. The long run prices are also shown in Figure 21 (dashed line).

Market Risk Premium

A Market Risk Premium (MRP) of 5.5% is assumed, and MRP_{Adj} is estimated to be -0.0008 (as per chapter 4) and 0.0015 for Models I and II respectively.

Timber Volume and Carbon Stock

The cumulative timber volume and carbon stock functions up to 75 years of age are sourced from the R300 Radiata Pine Calculator model from Future Forests Research Limited (2010), as plotted in Figure 22.

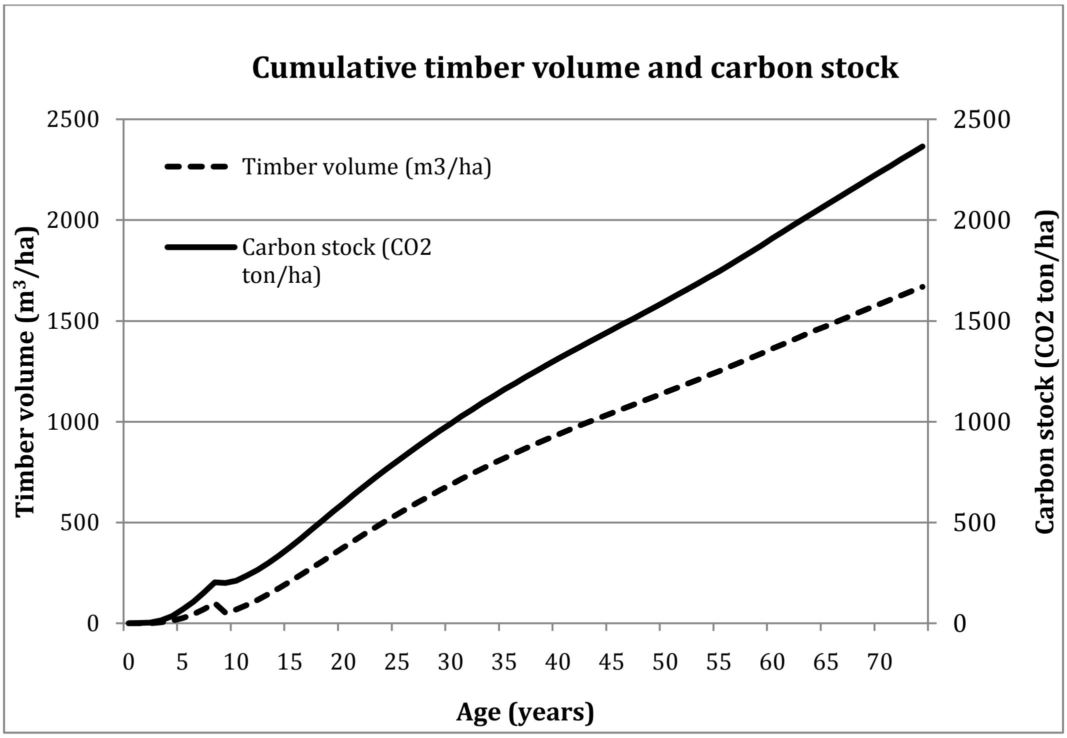


Figure 22: Cumulative timber volume and carbon stock functions.

The annual carbon stock change is shown in Figure 23. This represents the amount of carbon sequestered, and therefore carbon credits received, every year throughout the life of the forest. It is assumed that carbon credits received every year are sold during the same year, thereby, generating annual carbon revenues.

When the forest is harvested, the carbon stock in the forest decreases sharply before it gradually increases again upon subsequent replanting. Figure 24 shows the cumulative carbon stock profile of a 75 year fixed rotation forest, over multiple harvest-replant rotations. The sharp decrease represents the amount of harvest liabilities that needs to be paid at the time of harvest, as per forestry rules in the NZETS.

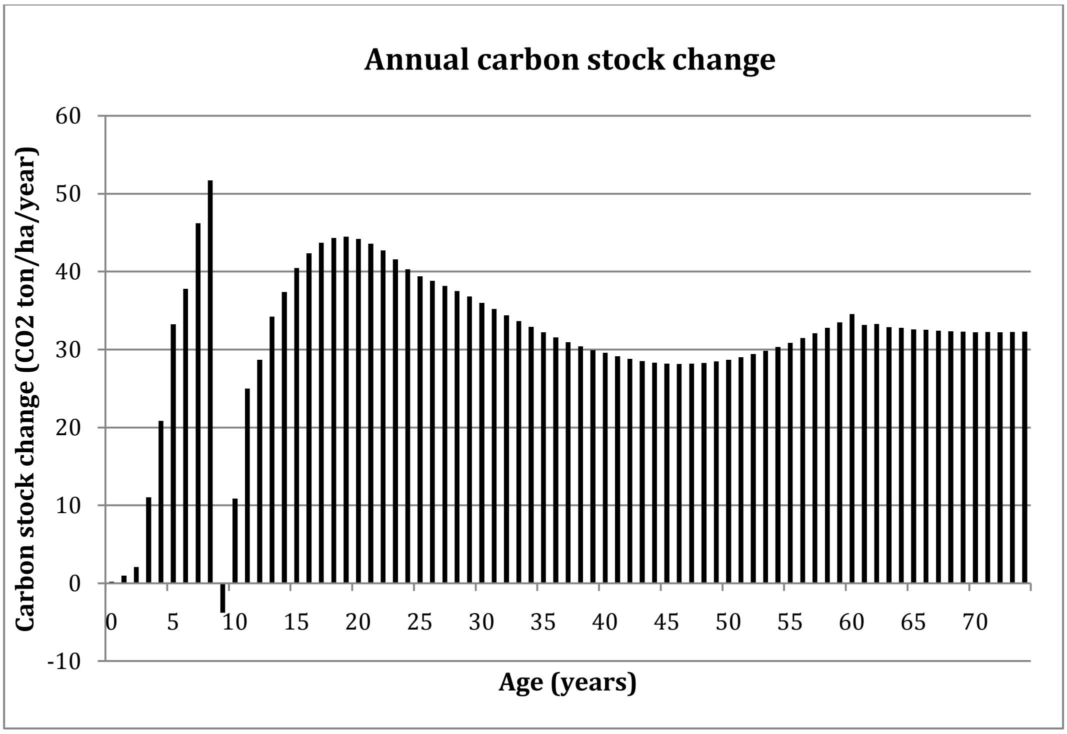


Figure 23: Annual carbon stock change.

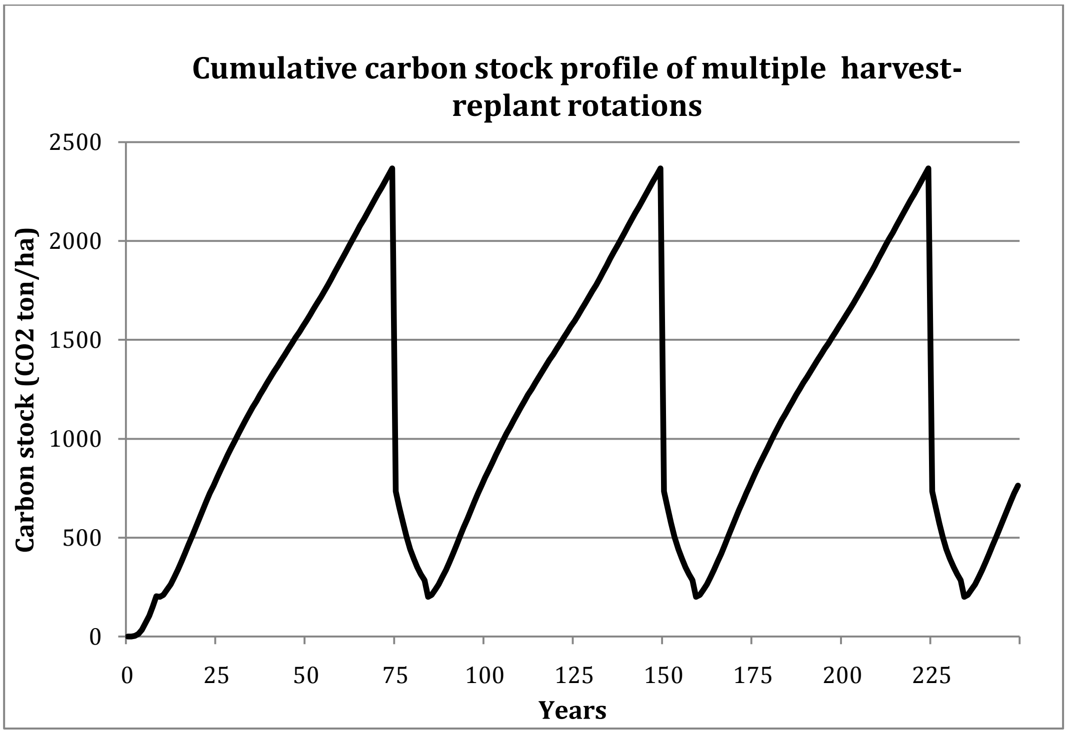


Figure 24: Cumulative carbon stock profile of a 75 year fixed rotation forest, over multiple harvest-replant rotations.

Modeling Carbon Stock Profile Over Multiple Rotations

When a forest is first planted on a new piece of bareland, the land is assumed to be clear, without any pre-existing stumps, branches and roots. At harvest, all the carbon stored in the timber (which is removed away from the forest land) is considered by the NZETS to be emitted, creating a harvest emissions liability, whereby equivalent amounts of carbon credits must be surrendered for this decrease in carbon stocks.

After the first rotation harvest, the land is replanted with a new set of trees (i.e. second rotation). During this second rotation period, not all the carbon from the first rotation is removed. There is leftover carbon stock from the first rotation, such as stumps, branches and roots, which remains on site. This leftover carbon stock breaks down slowly, as the new second rotation forest grows (Ministry of Agriculture and Forestry, 2011). This is the reason why the carbon stock for the second and subsequent rotations, as shown in Figure 24, does not start from zero as in the case of the first rotation.

The amount of leftover carbon from harvesting varies depending on the age of the forest. An older forest will have larger stumps and other leftovers after it is harvested, whereas, a younger forest will have less leftovers after harvest. For example, a first rotation age of 33 years would retain about 240 tons of leftover carbon stock per hectare after harvesting – see Figure 25. This leftover carbon is sometimes known as the "safe" level of carbon following harvest.

The "gain" from leftover carbon after the first rotation, since a majority of this leftover carbon stock would have decayed during the second rotation. Upon harvest of the second rotation, there will be leftover carbon stock from the second rotation as trees of the third rotation trees grow.

Figure 26 shows the estimated carbon stock of the first rotation and the second rotation, starting from year 33 onwards, which is the year of harvesting the first rotation. The graph shows the leftover carbon stock from the first rotation decaying slowly during the second rotation. The growth in carbon stock from the new second rotation trees is also shown. The bold solid line is the combined carbon stock of the leftovers from the first rotation and the new second rotation trees.

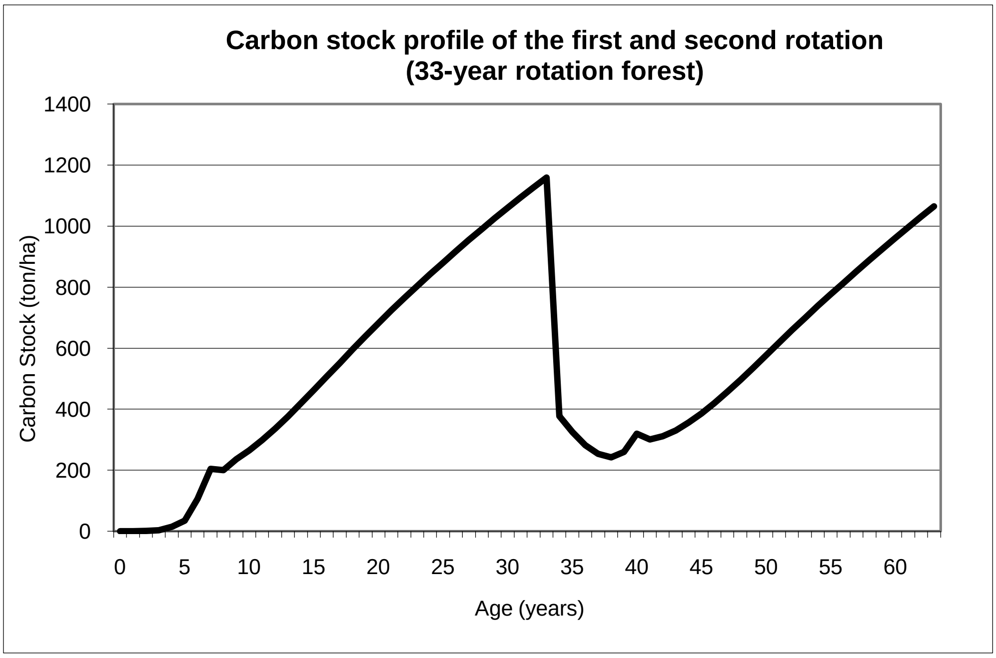


Figure 25: Carbon stock profile of the first and second rotation of a 33-year rotation forest.

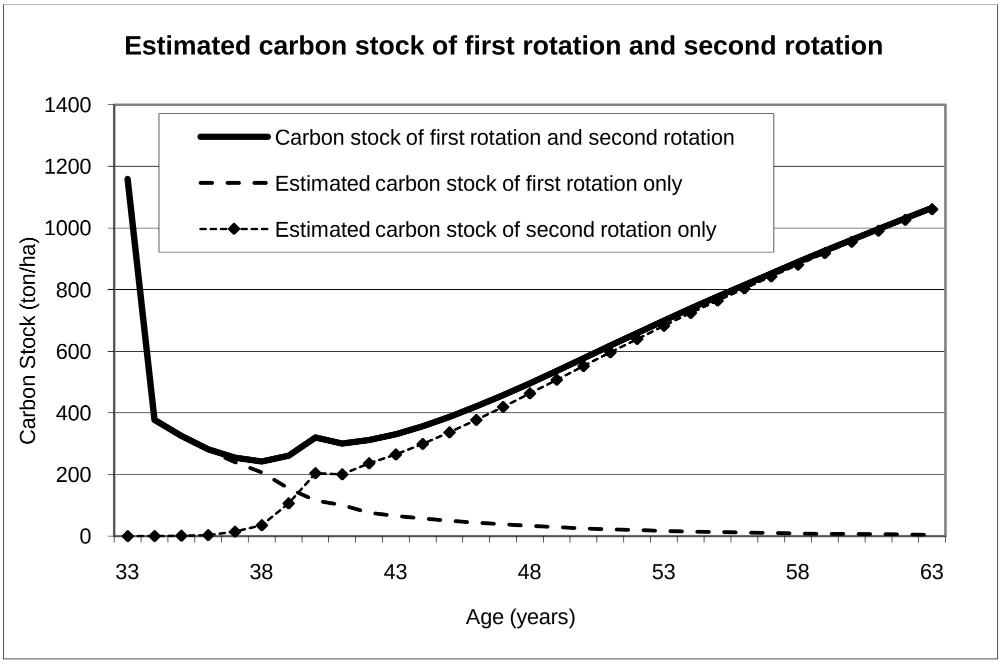


Figure 26: Estimated carbon stock of first rotation and second rotation.

From one perspective, the leftover carbon stock from the first rotation is considered to be the "safe" level because the gradual emission of this carbon stock is offset by the carbon stock growth of trees from the second rotation.

From another perspective, the leftover carbon stock from the first rotation can be considered as a liability inherited by the second rotation, because carbon stock growth of trees from the second rotation is being used to repay emission liabilities of the leftover carbon stock from the first rotation. This means that part of the carbon stock growth of the new trees cannot be claimed as new carbon credits.

Such inheritance of liabilities would continue for subsequent rotations. If land ownership were to change hands at the end of a rotation harvest, then, the new owner would essentially inherit the carbon liabilities of the leftovers, unless the previous owner includes compensations for these liabilities as part of the sale. Such liabilities/compensations can be rather significant. At a carbon price of $20 per ton, a 240 ton carbon stock leftover implies a liability of $4,800 per hectare.

The work in this thesis assumes that carbon credits from the first rotation are completed repaid back at the time of harvest. This allows for revenues, costs and liabilities from the first rotation to be contained within the first rotation period, instead of spilling over to affect the second rotation. The emission liabilities of the leftovers from the first rotation are included in the cash flow and valuation of the first rotation. Such a treatment allows for new trees from the second rotation to earn new credits as they grow. This approach of treating the carbon liabilities is a more conservative approach towards managing the carbon liabilities, compared to the rules of the NZETS.

In Figure 26, it was shown that the leftover carbon stock from the first rotation decays slowly, till around year 61. This slow decay over a long period of time complicates the valuation analysis. In order to simplify the valuation, it is assumed that the leftover carbon stock decays to zero within 10 years of harvest. Figure 27 shows the estimated decay rate of the first rotation compared to the modeled decay rate.

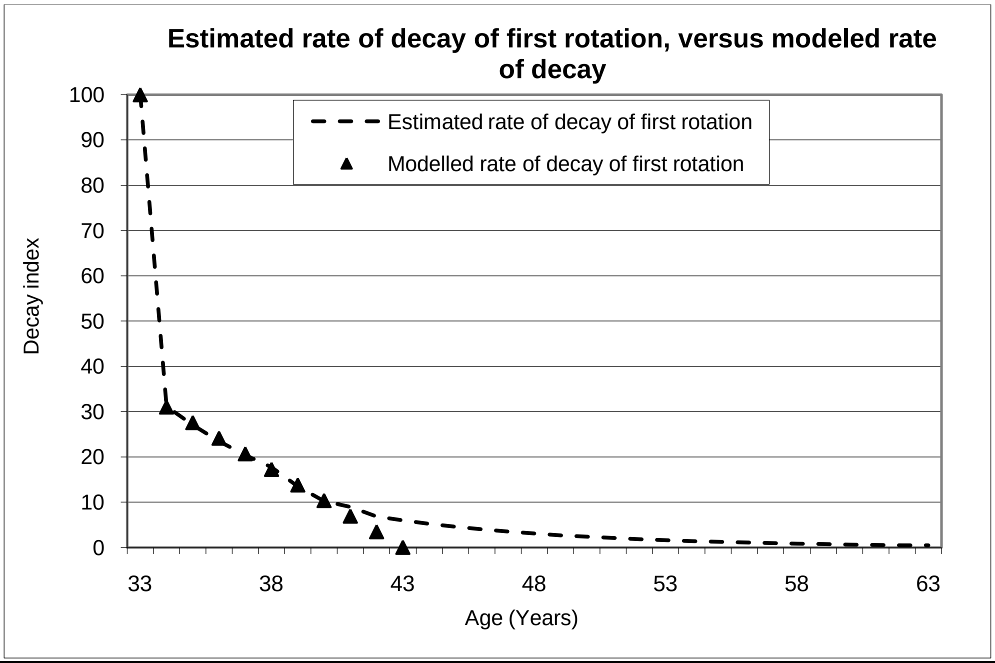


Figure 27: Estimated rate of decay of the first rotation compared to the modeled rate of decay.

Using this modeled decay rate, carbon liabilities from the leftover carbon stock are assumed to repaid at the time of harvest, at the contemporary carbon price, discounted to the net present value (i.e. the present value of the carbon liabilities at the time of harvest). This is how the liabilities of the leftover carbon stock is included in the valuation in the same rotation age period.

Costs and Cash Flow

Costs are as per chapter 4, with an additional NZETS compliance cost, M_C, amounting to $60/ha/year. The overall cash flow of carbon forestry (per hectare) is summarized in Table 4.

	Years											
	0	**1**	**2**	**. .**	**5**	**6**	**7**	**8**	**9**	**10**	**. .**	**Harvest year**
Planting costs	(1251)											
Pruning costs						(473)	(674)	(684)				
Thinning costs									(370)			
Maintenance costs, M_T	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	
NZETS compliance costs, M_C	(60)	(60)	(60)	(60)	(60)	(60)	(60)	(60)	(60)	(60)	(60)	(60)
Timber revenue, X_TQ_T												$
Harvest costs, H_TQ_T												($)
Carbon revenue, $X_C\Delta Q_C$	$	$	$	$	$	$	$	$	$	$	$	$
Carbon liability, X_CQ_C												($)

Table 4: Cash flow of carbon forestry (per hectare).

Tax and Discount Rate

As per chapter 4, the tax rate, T, is assumed to be 28% and the discount rate is assumed to be 4%, such that $R_f = 1.04$.

5.3 Results for Model I (Stochastic Timber, Constant Carbon)

In this section, carbon forestry valuation results are presented for the case of stochastic timber price and constant carbon price. Fixed harvest results are compared with flexible harvest results.

Results for Various Carbon Prices With a Stochastic Timber Price

The case of fixed harvest with a $0 carbon price generates a valuation of $5,503 with an optimal rotation age of 27 years, as shown in Figure 28. For the case of flexible with a $0 carbon price, the valuation is higher at $7,060 as shown in Figure 26. It is noted here that the case of $0 carbon price is considered as timber-only forestry. Both the valuations here are slightly lower than that those in section 4.2 (i.e. $6,628 of Figure 9 and $8,185 of Figure 10, respectively) due to the additional inclusion of NZETS compliance costs ($60 per year) in this section.

From Figure 28, the valuation of fixed harvest carbon forestry increases from $5,503 to $7,493, $11,060 and $21,000 as the carbon price increases from $0 to $10, $25 and $50, respectively. It is also worth noting that as the carbon price increases, the shape of the valuation graphs evolve from a Faustmann-type "parabolic" profile to an "exponential" profile, due to the effects of the annual carbon revenue on the valuation. At a $50 carbon price, the graph trends towards significantly delaying harvest. That is, if the allowable harvest age is extended beyond 75 years, the rotation length is likely to increase beyond 75 years as well.

For flexible harvest carbon forestry, the valuations at the corresponding carbon price points are shown in Figure 29. As the carbon price increases from $0 to $50, the valuations rise from $7,060 to $21,920.

In summary, the presence of a non-zero constant carbon price in both cases of fixed and flexible harvest significantly increases their valuations.

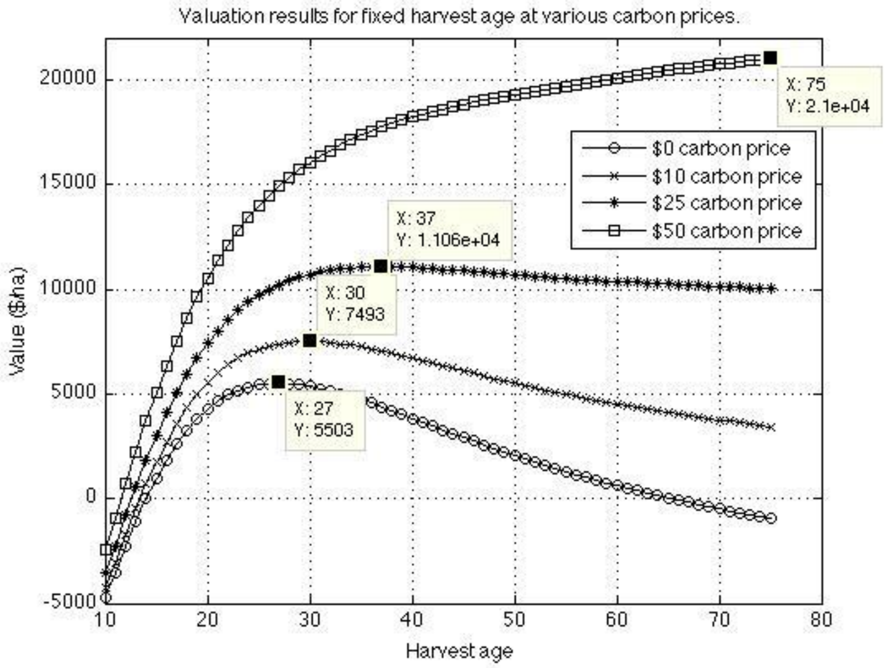


Figure 28: Valuation for fixed harvest carbon forestry at various carbon prices.

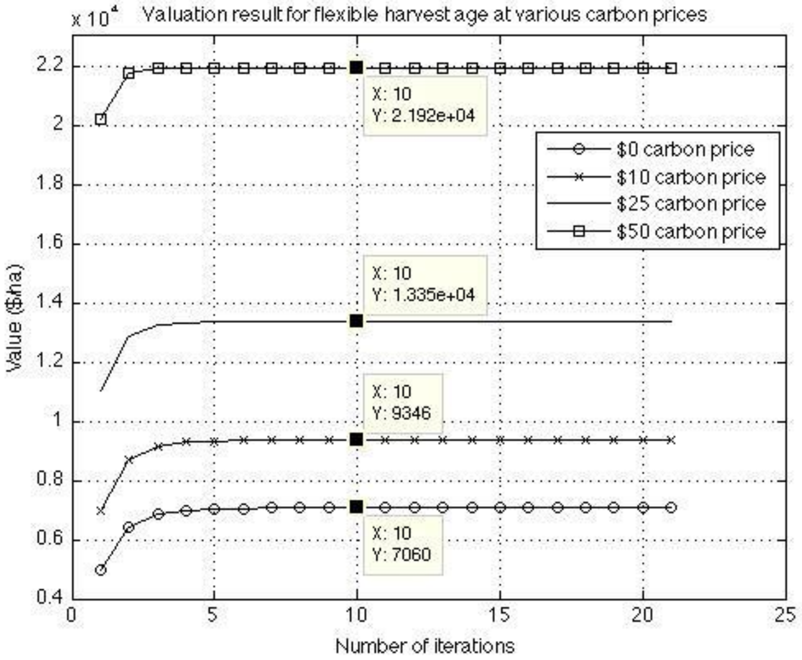


Figure 29: Valuation for flexible harvest carbon forestry at various carbon prices.

It is worth noting that at a $50 carbon price, the $21,000 valuation for fixed harvest is quite close to the $21,920 valuation for flexible harvest. Indeed, at an extreme carbon price of $150, valuations are virtually the same at $64,900 and $64,920, respectively (not plotted in the graphs here). It can be concluded that when the carbon price is sufficiently high, the choice of fixed harvest versus flexible harvest is one and the same.

Figure 30 shows the timber price thresholds for optimal flexible harvest at various constant carbon prices. The area above the dotted lines shows the timber prices that favour a harvest decision for a given forest age. As an example, with a $0 carbon price, the timber price threshold for a 30 year old timber forest is $101.10 such that if the timber price is above this threshold when the forest reaches age 30, it would be optimal to harvest. If the timber price is below this threshold when the forest reaches age 30, it would not be optimal to harvest, and the optimal decision would be to defer harvest until the price is above the threshold for the respective age.

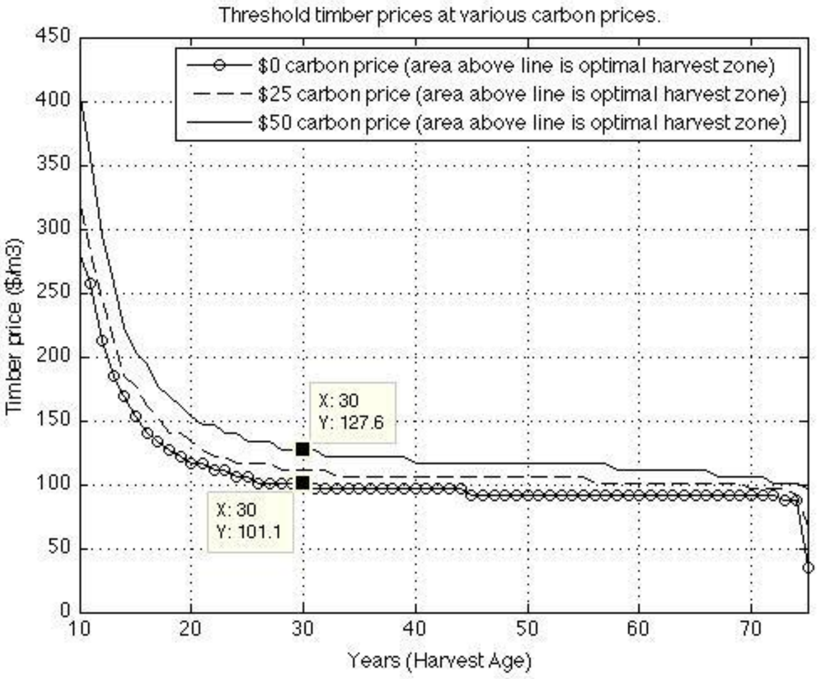


Figure 30: Timber price thresholds for optimal flexible harvest of carbon forestry at various carbon prices.

As the carbon price increases from $0 to $50, the timber price threshold also rises. For example, at age 30, the timber price threshold for the case of $50 carbon price is $127.60 at age 30. The higher the constant carbon price, the higher is the timber price threshold floor. It is so because a higher carbon price incurs a higher harvest liability (cost), thereby requiring a higher timber price (revenue) to absorb the harvest liability. It means that as the carbon price increases, there is a greater likelihood of deferring harvest, thereby keeping carbon sequestered in the forest.

5.4 Discount Rate Sensitivity Analysis for Valuation

Figure 31 shows the fixed harvest valuations at a $25 constant carbon price for various discount rates. As the discount rate increases from 3.0% to 8.0%, the valuation decreases from $16,430 to $3,439. The optimal rotation age also decreases from 39 years to 34 years.

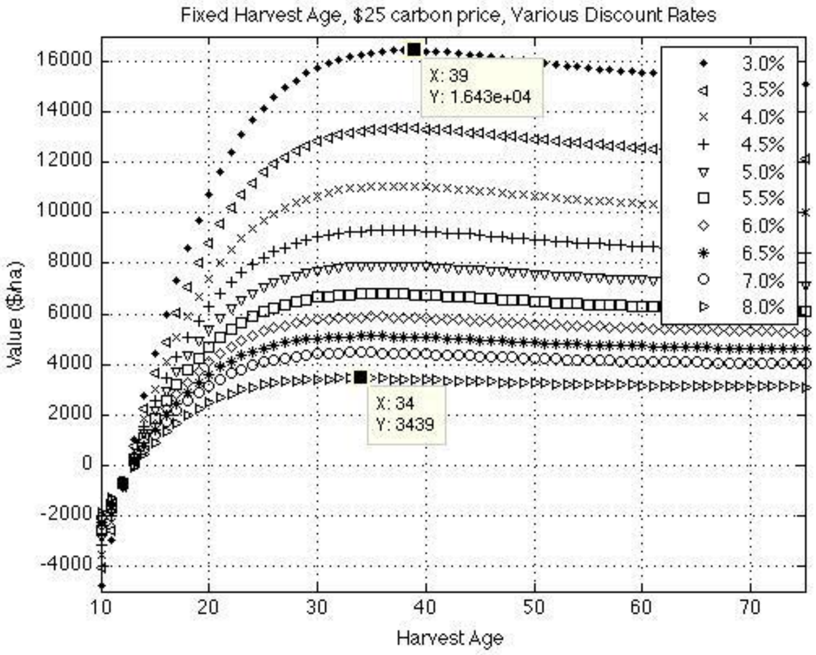


Figure 31: Fixed harvest valuations at $25 constant carbon price for various discount rates.

Figure 32 shows the flexible harvest valuations at a \$25 constant carbon price for various discount rates. As expected, the valuation falls from \$20,230 to \$3,969 as the discount rate rises from 3.0% to 8.0%.

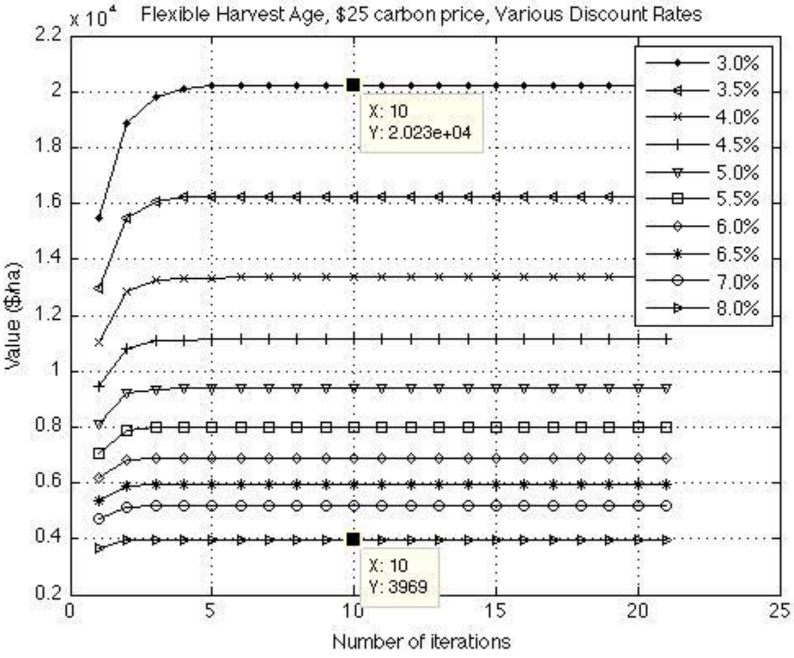


Figure 32: Flexible harvest valuations at \$25 constant carbon price for various discount rates.

Figure 33 plots the maxima points of Figure 31 (i.e. infinite rotation LEVs) for various discount rates and compares it to the corresponding valuations for flexible harvest from Figure 32. Similar to the trends observed for timber forestry in section 4.3, all valuations decrease exponentially with increasing discount rates. Likewise, the valuations for flexible harvest are always greater than those for fixed harvest. The fixed harvest optimal rotation ages also declines at an almost linear manner with increasing discount rates.

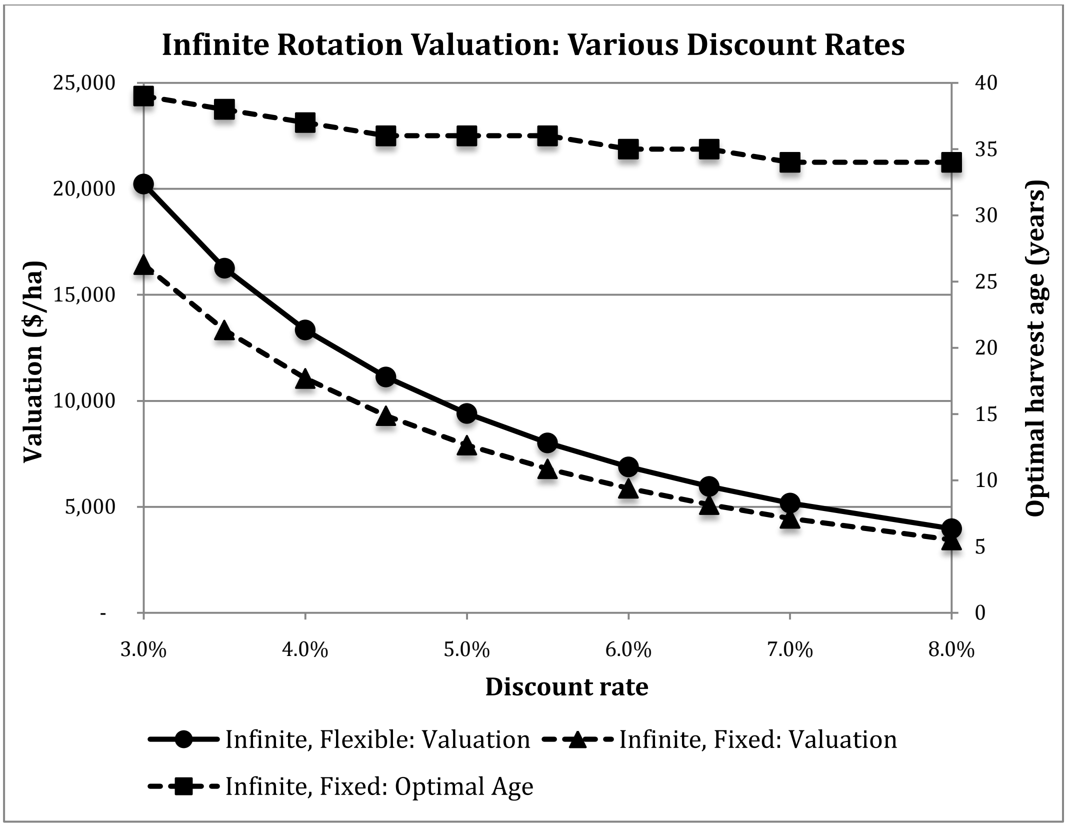


Figure 33: Comparing valuations for fixed harvest (LEV) and flexible harvest (Real Options) at $25 constant carbon price for various discount rates.

5.5 Results for Model II (Stochastic Carbon, Constant Timber)

Figure 34 shows the fixed harvest carbon forestry valuation results for Model II, at various constant timber price levels. Valuation increases with increasing timber prices, while the optimal rotation age reduces.

Figure 35 shows the flexible harvest carbon forestry valuation results for Model II, at various constant timber price levels. As expected, higher timber prices generate higher revenues (cash flows), and therefore, result in higher valuations.

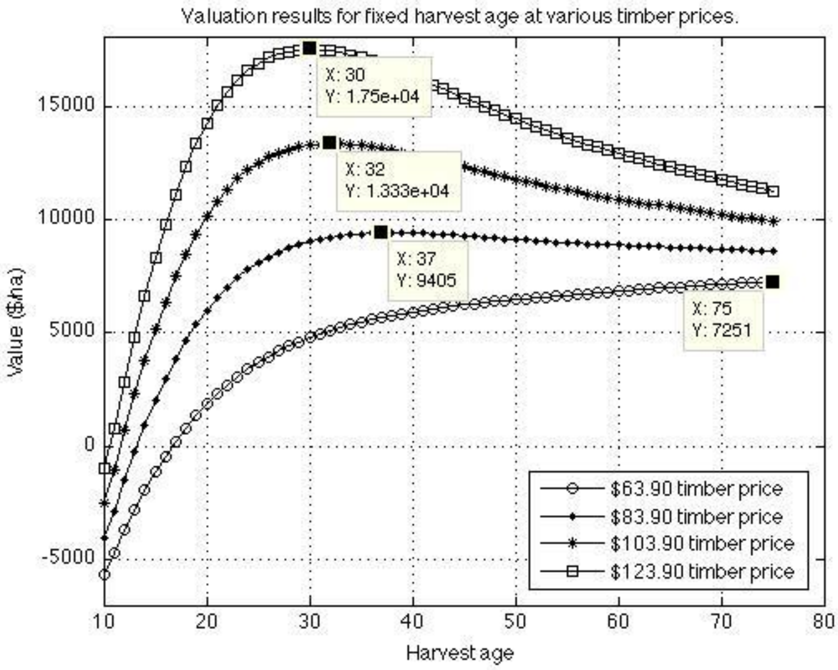


Figure 34: Fixed harvest valuation results using Model II at various constant timber price levels.

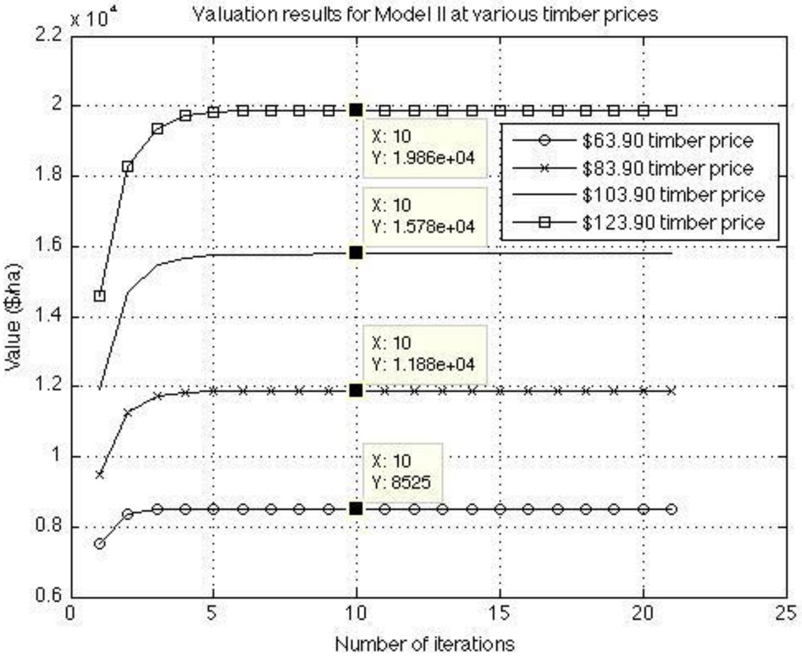


Figure 35: Real Options (flexible harvest) valuation results using Model II at various constant timber price levels.

Figure 36 shows the optimal carbon price thresholds that would trigger an optimal harvest decision in any given year, at various constant timber price levels. The area *below* each line (i.e. carbon price ceiling) is the optimal harvest zone. The graph shows year 40 as an example of an optimal harvest threshold. At a constant timber price of $63.90, the carbon price needs to be a maximum of $11.16 in order to trigger an optimal harvest. However, at a constant timber price of $123.90, the carbon price ceiling threshold is raised to $16.66, allowing for a larger optimal harvest zone. The higher the constant timber price, the higher is the carbon price threshold ceiling. A higher timber price (revenue) allows for better absorption of the carbon harvest liabilities (cost), thereby raising the carbon price threshold ceiling.

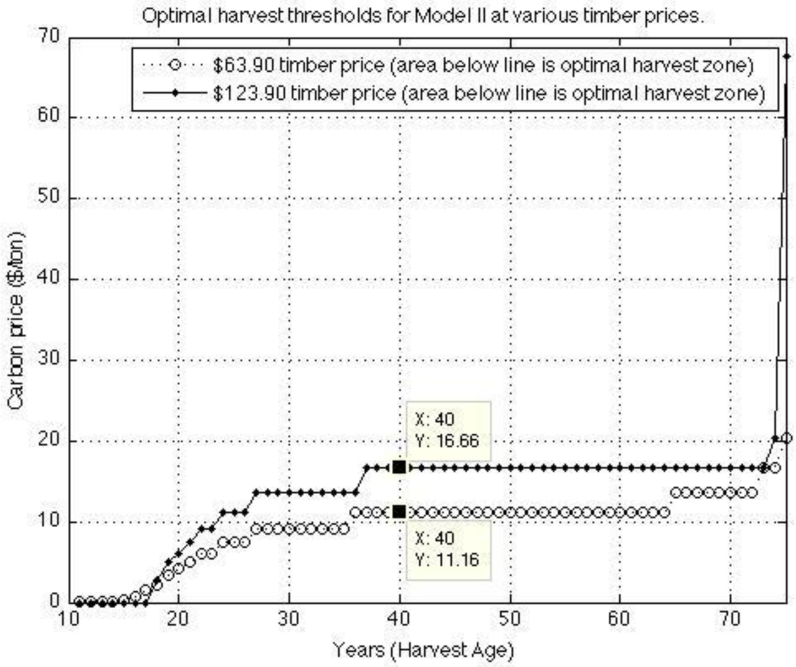


Figure 36: Optimal carbon price thresholds using Model II at various constant timber price levels.

5.6 Results for Special Cases of Models I and II Using Long Run Values as the Constant Prices

In this section, results for two special cases are presented. Model I (stochastic timber price with a constant carbon price) is analyzed using a constant carbon price which, instead of using an arbitrary carbon price, is set equal to the long run level of the carbon price series of Figure 21 ($21.72). The second special case is Model II (stochastic carbon price with a constant timber price). The analysis in this case considers a constant timber price set equal to the long run level of the timber price series of Figure 21 ($88.44). In both cases, the model is asked to find the solution for long run price levels.

Model I with constant carbon price equal to the long run carbon price

The Real Options valuation is computed to be $12,410 (diagram not shown here). Figure 37 shows the Model I optimal harvest threshold for the case of a constant carbon price set equal to the long run value of $21.72.

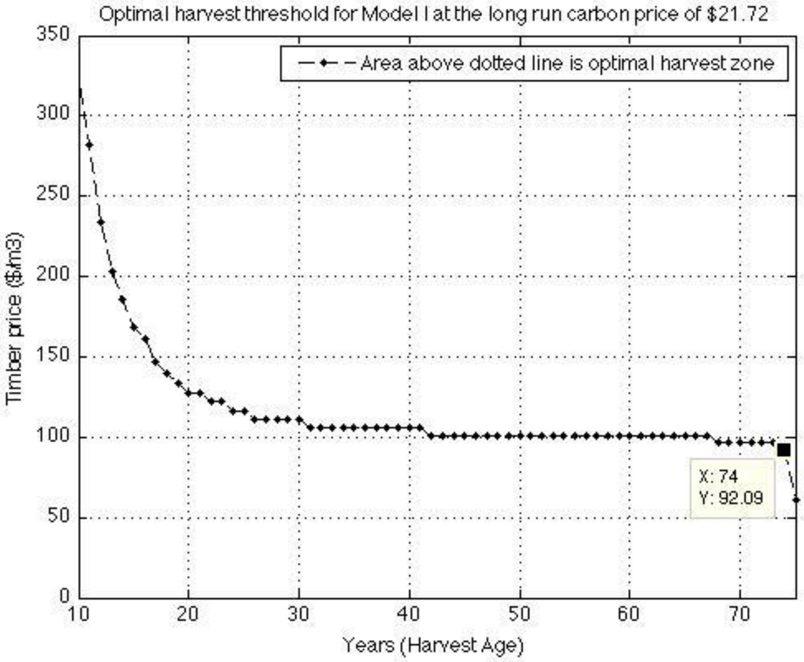


Figure 37: Model I optimal harvest threshold for the case of a constant carbon price which equals to the long run value of $21.72.

Model II with constant timber price equal to the long run timber price

The Real Options valuation is computed to be $12,740 (diagram not shown here). Figure 38 shows the Model II optimal harvest threshold for the case of a constant timber price, which equals to the long run value of $88.44.

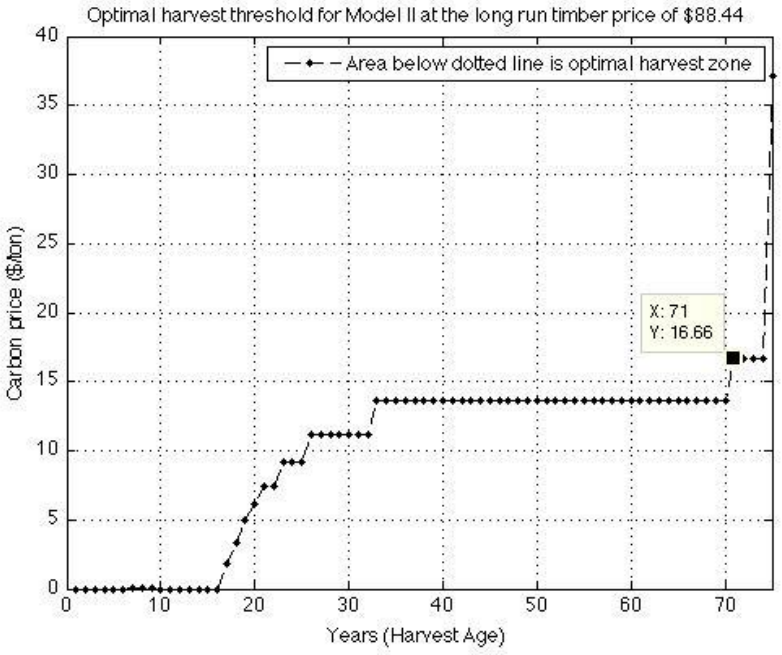


Figure 38: Model II optimal harvest threshold for the case of a constant timber price which equals to the long run value of $88.44.

Complementary Results of Models I and II

The optimal harvest thresholds of the two special cases can be used in a complementary manner to estimate and determine the optimal harvest decisions and behaviours. The timber price threshold graph of Figure 37 shows that the *minimum* timber price that will trigger an optimal harvest decision is $92.09, at a forest age of 74 years. The carbon price threshold graph of Figure 38 shows that the *maximum* price ceiling of the carbon price that will trigger an optimal harvest decision is $16.66, at age 71. What is interesting is that the long run levels of the state variables ($88.44 for timber and $21.72 for carbon) are *below* the harvest threshold in the case of Model I ($92.09) and *above* the harvest threshold in the case of Model II ($16.66), respectively.

In both cases, if the state variable always stayed at its long run level, then, harvest would not occur and would be delayed until the last possible date (i.e. until the biological growth limit of the trees is reach, which is assumed to be 75 years here due to lack of tree growth data beyond this age).

The insight here is that price volatilities matters. Even though the thresholds are above/below the long run levels, harvest is still expected to occur before the last possible date because the state variable fluctuates *around* its long run level (i.e. even though the timber price threshold that triggers harvest is above the long run timber price, it will not always be above the short run timber price). It is this volatility that is the source of the option value in the forest (and the value in performing Real Options analysis). A forest owner under the NZETS has the option to delay harvest, allowing him/her to exploit the price volatilities.

Given the wide window of technically feasible harvest dates (of up to 75 years), the owner can afford to wait until the timber/carbon price takes one of its deviations from the long run level and harvest when it happens. This wait is feasible because the increase in harvest payoff may well dominate the cost of waiting.

The optimal harvest thresholds are useful tools for forest owners and managers. For example, they can be used to produce the data summarized in Figures 37 and 38, which provide reference thresholds that can be compared with actual timber and carbon prices in every year in order to make the optimal harvest decision. For policy makers, the information in these graphs can be an insightful decision making tool that can be continuously updated with recent and latest prices in order to estimate the forest land use/management behavior due to economic incentives created by timber and carbon prices.

5.7 Conclusions

From results presented in this chapter, it is concluded that by creating a price on carbon via the New Zealand Emissions Trading Scheme, carbon forestry provides a significantly higher bareland valuation compared to traditional timber-only forestry. This higher return comes with the cash flow advantages of annual revenues from the sale of carbon credits. Even at a modest carbon price of $10, which is approximately half of the current carbon price, the value of bareland employed in new post-1989 forestry increases significantly. Such bareland land planted with new forests will become more valuable, and some land not currently used for this purpose will likely switch land use. This indicates that the NZETS provides a strong economic incentive to forest owners to plant new forests.

The increased returns will also very likely cause a shift in forest management behaviour by simply deferring harvest. As carbon prices increase over time, it will become even more economically attractive to do so. This effect will contribute positively towards climate change mitigation in New Zealand.

CHAPTER 6: CARBON FORESTRY VALUATION USING THE DOUBLE RV BINOMIAL TREE METHOD

By the nature of its constraints, a single RV Binomial Tree used in chapter 5 can only handle one stochastic price at a given time while holding the other price constant. It is unable to simultaneously model both timber and carbon prices stochastically. In this chapter, a double RV Binomial Tree is developed to model both timber and carbon stochastic prices endogenously, allowing for a joint optimization of the harvest decision. It is assumed that timber and carbon prices are independent. Results are also presented and discussed.

6.1 Overview of the Double RV Binomial Tree

Let X^T = the timber price, X^C = the carbon price, θ^T = probability of the timber price process and θ^C = probability of the carbon price process. For the case of n = 1, the single RV price Binomial Trees for timber and carbon are shown below in Figure 39.

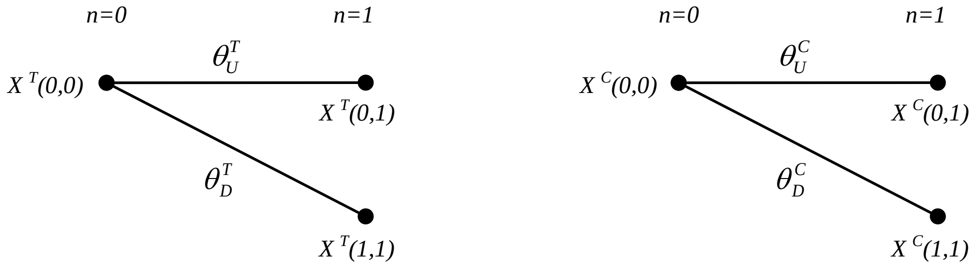


Figure 39: Single RV price Binomial Trees for timber (left) and carbon (right).

These single RV price Binomial Trees can be combined to construct a double RV price Binomial Tree as shown in Figure 40, where each node consists of a pair of timber and carbon prices.

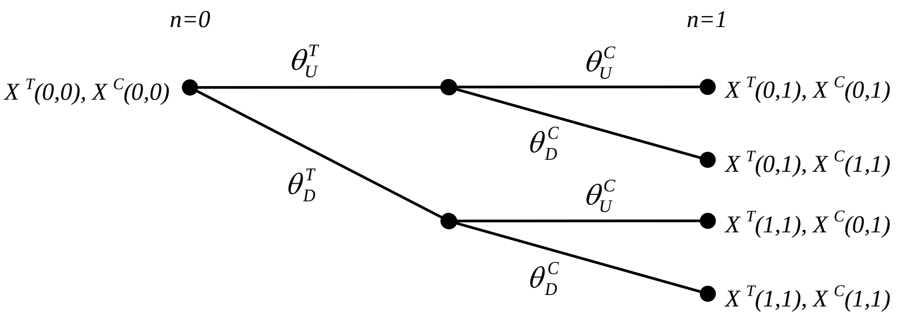


Figure 40: Double RV price Binomial Tree for timber and carbon.

For a single RV Binomial Tree, the number of nodes increases with *n* at the rate of *(n+1)*, whereas for a double RV Binomial Tree, the number of nodes increases with *n* at the rate of $(n+1)^2$. This increase adds to the computation complexity of the double RV Binomial Tree method.

The corresponding double RV valuation Binomial Tree is shown in Figure 41.

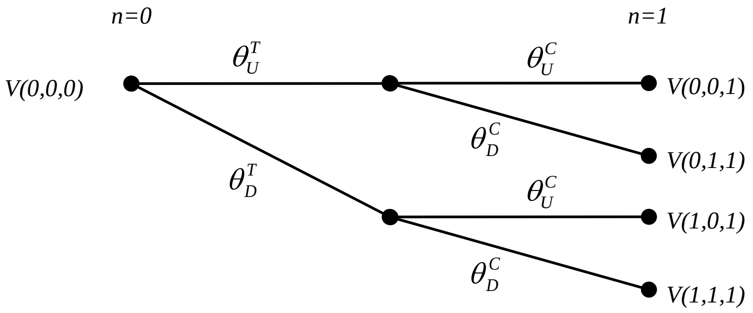


Figure 41: Double RV valuation Binomial Tree for timber and carbon.

In the same way as the case for single RV, the valuation process traverses backwards systematically, starting from the terminal (last) nodes *V(i,j,N)* until it ends at *V(0,0,0)*. For N = 1, the valuation is:

$$V(0,0,0) = \frac{\theta_U^T \theta_U^C V(0,0,1)}{R_f} + \frac{\theta_U^T \theta_D^C V(0,1,1)}{R_f} + \frac{\theta_D^T \theta_U^C V(1,0,1)}{R_f} + \frac{\theta_D^T \theta_D^C V(1,1,1)}{R_f}$$

6.2 Real Options Valuation Function

For the double RV Binomial Tree, the Real Options valuation function is:

$$V(i,j,n) = \max \left\{ \begin{array}{l} (1-T)\left([X^T(i,n) - H^T]Q^T(n) - X^C(j,n)Q^C(n-1) - M^C\right) + B, \\ \\ (1-T)\left(-M^T - M^C + X^C(j,n)[Q^C(n) - Q^C(n-1)]\right) \\ + \dfrac{\Pi_U^T(i,n)\Pi_U^C(j,n)V(i,j,n+1)}{R_f} \\ + \dfrac{\Pi_U^T(i,n)\Pi_D^C(j,n)V(i,j+1,n+1)}{R_f} \\ + \dfrac{\Pi_D^T(i,n)\Pi_U^C(j,n)V(i+1,j,n+1)}{R_f} \\ + \dfrac{\Pi_D^T(i,n)\Pi_D^C(j,n)V(i+1,j+1,n+1)}{R_f} \end{array} \right\}$$

where T is the tax rate, $X^T(i,n)$ is the price at time step n, H^T is the timber harvesting cost, $Q^T(n)$ is the timber volume at time step n, $X^C(j,n)$ is the carbon price at time step n, $Q^C(n-1)$ is the carbon stock at time step n-1, M^C is the NZETS compliance cost, B is the bareland value, M^T is the maintenance cost of the forest, Π^T is the risk neutral probability for the timber price, and Π^C is the risk neutral probability for the carbon price. The first (shorter) term of the max function represents the cash flow from harvesting, whereas the second (longer) term represents the cash flow from not harvesting.

6.3 Data Used and Assumptions Made

Data used and assumptions made in this chapter are identical to those of chapter 5.

6.4 Results for the Double RV Binomial Tree Method

Valuation Results for Fixed and Flexible Harvest Infinite Rotation Forests

Figure 42 shows the fixed harvest valuation for new post-1989 carbon forestry under the NZETS using the double RV Binomial Tree method. The valuation amounts to $10,420, with an optimal rotation age of 36 years.

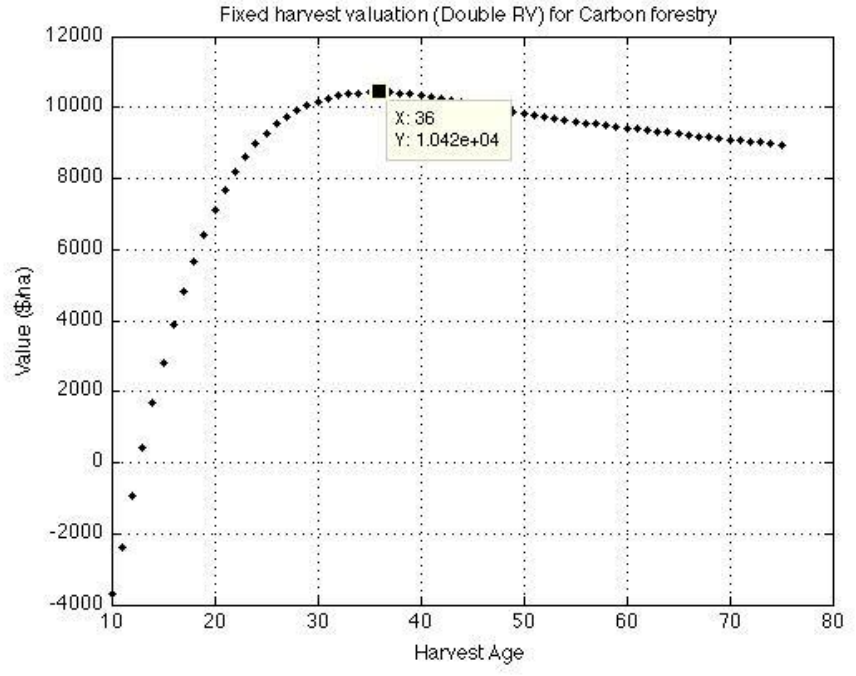


Figure 42: Fixed harvest valuation for new post-1989 carbon forestry under the NZETS using the double RV Binomial Tree method.

Figure 43 shows the Real Options (flexible harvest) valuation for new post-1989 carbon forestry under the NZETS using the double RV Binomial Tree method. The valuation amounts to $14,040, which is about 35% higher than the fixed harvest valuation, and almost double the $7,060 for timber-only forestry in section 5.3.

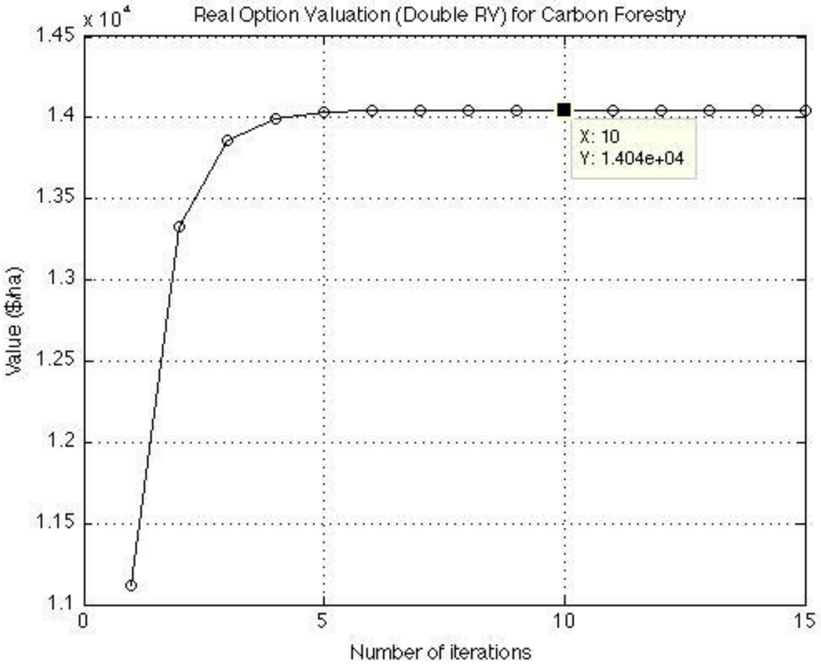


Figure 43: Real Options (flexible harvest) valuation for new post-1989 carbon forestry under the NZETS using the double RV Binomial Tree method.

Timber-Carbon Price Thresholds for Optimal Harvest Decisions

The timber price is a key driver of revenue during harvest, and as such, the higher the timber price, the more attractive is the harvest decision to the owner, at any given age. On the other hand, the carbon price is a key driver of cost during harvest (even though it is a source of revenue annually prior to harvest). Due to the large harvest liabilities (i.e. paying back all the carbon credits for harvesting), a lower carbon price will make harvest more attractive to the owner. If the carbon price is high, then, the timber price will need to be much higher in order to trigger an optimal harvest decision (in order to "offset" the harvest liabilities). For any given forest age, these timber-carbon price thresholds for optimal harvest decisions can be generated by the double RV Binomial Tree method.

Figures 44, 45, 46 and 47 show a select range of timber-carbon price thresholds from ages 12 to 75 years (maximum biological limit for tree growth). The horizontal axis represents the carbon price, whereas the vertical axis is the timber price. The shaded areas are the optimal harvest price zones, whereas non-shaded areas are no-harvest zones). It is noted here that the threshold for age 75 years in Figure 47 is for a forced harvest decision (rather than the optimal harvest decision) since 75 years is the assumed maximum biological limit for tree growth, at which point harvest must take place.

For young age forests, the thresholds (shaded zones) take place at very high timber prices and very low carbon prices. This is because of the low timber volume in the young forests, resulting in the need for the combination of a very high timber price (revenue) and a very low carbon price (cost) in order to trigger an optimal harvest decision. As the forest age increases, there is more timber volume in the forests, and the timber-carbon price threshold lowers, evident by the enlarged optimal harvest zones. For example, at age 15 (in Figure 44), the combination of \$120 timber price and \$15 carbon price is in the no-harvest zone. However, at age 40 (in Figure 45), this price combination is well within the optimal harvest price zone.

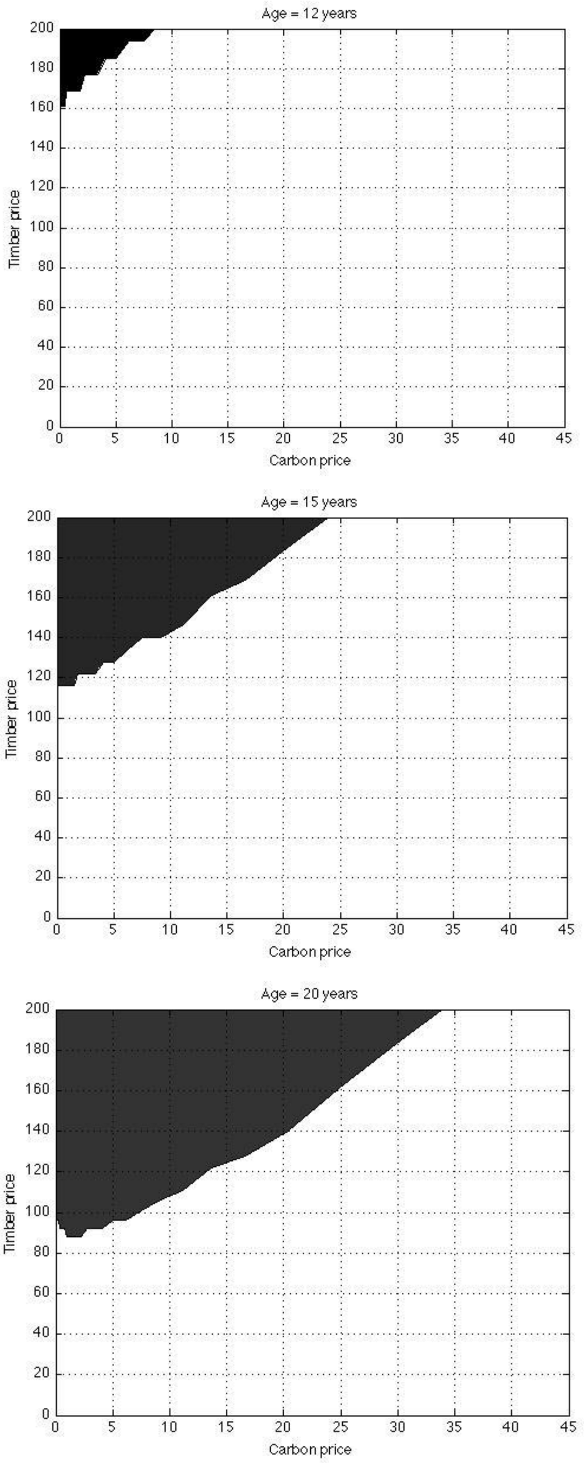


Figure 44: Timber-carbon price thresholds (double RV) for optimal harvest decisions for forest ages 12, 15 and 20 years[8].

---

[8] The shaded area in each graph is the optimal harvest zone, whereas the non-shaded area is the no-harvest zones.

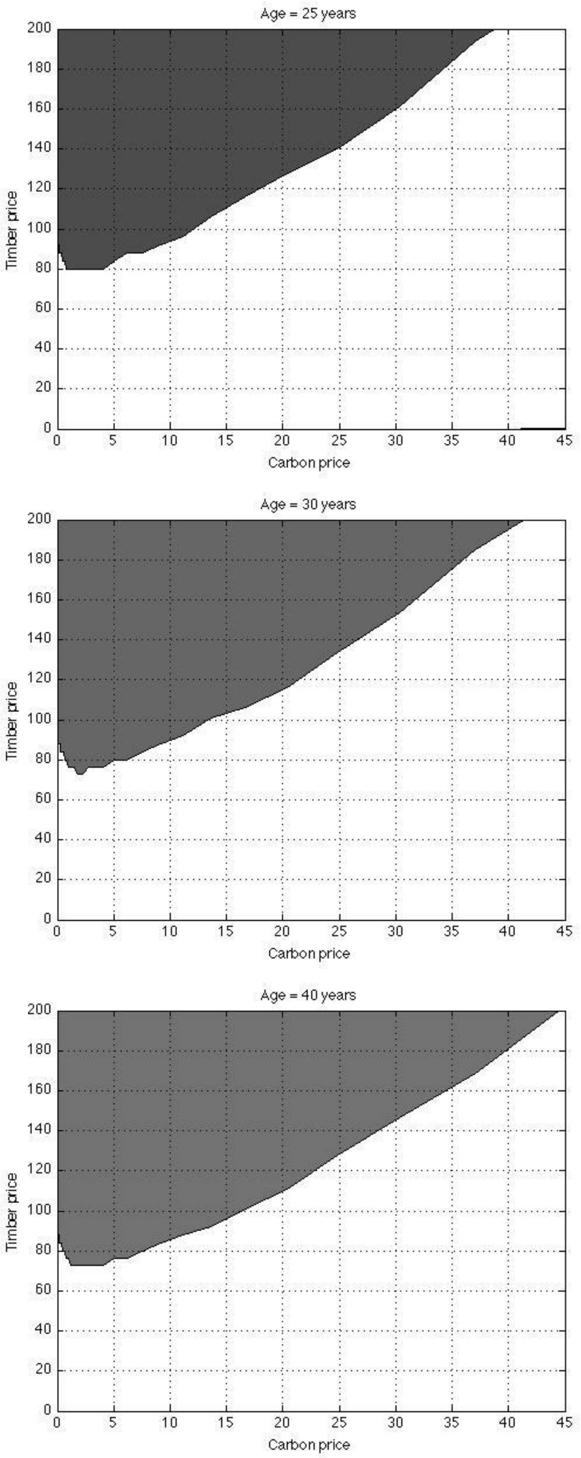


Figure 45: Timber-carbon price thresholds (double RV) for optimal harvest decisions for forest ages 25, 30 and 40 years[9].

---

[9] The shaded area in each graph is the optimal harvest zone, whereas the non-shaded area is the no-harvest zones.

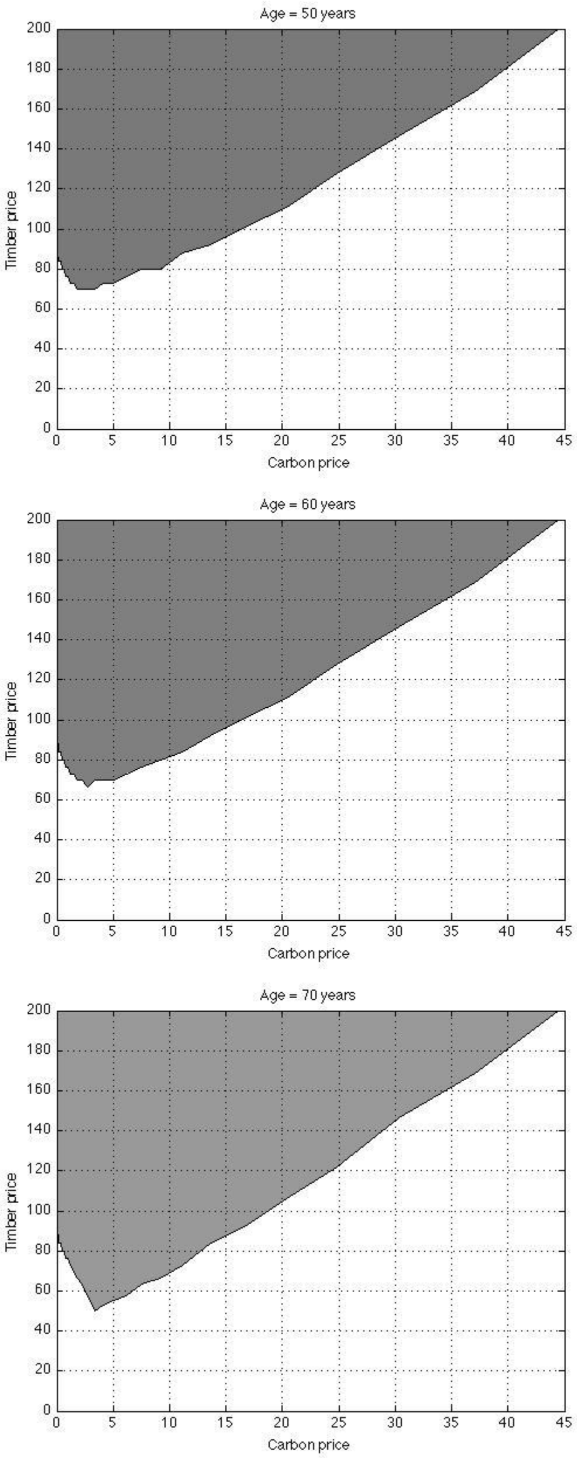


Figure 46: Timber-carbon price thresholds (double RV) for optimal harvest decisions for forest ages 50, 60 and 70 years[10].

---

[10] The shaded area in each graph is the optimal harvest zone, whereas the non-shaded area is the no-harvest zones.

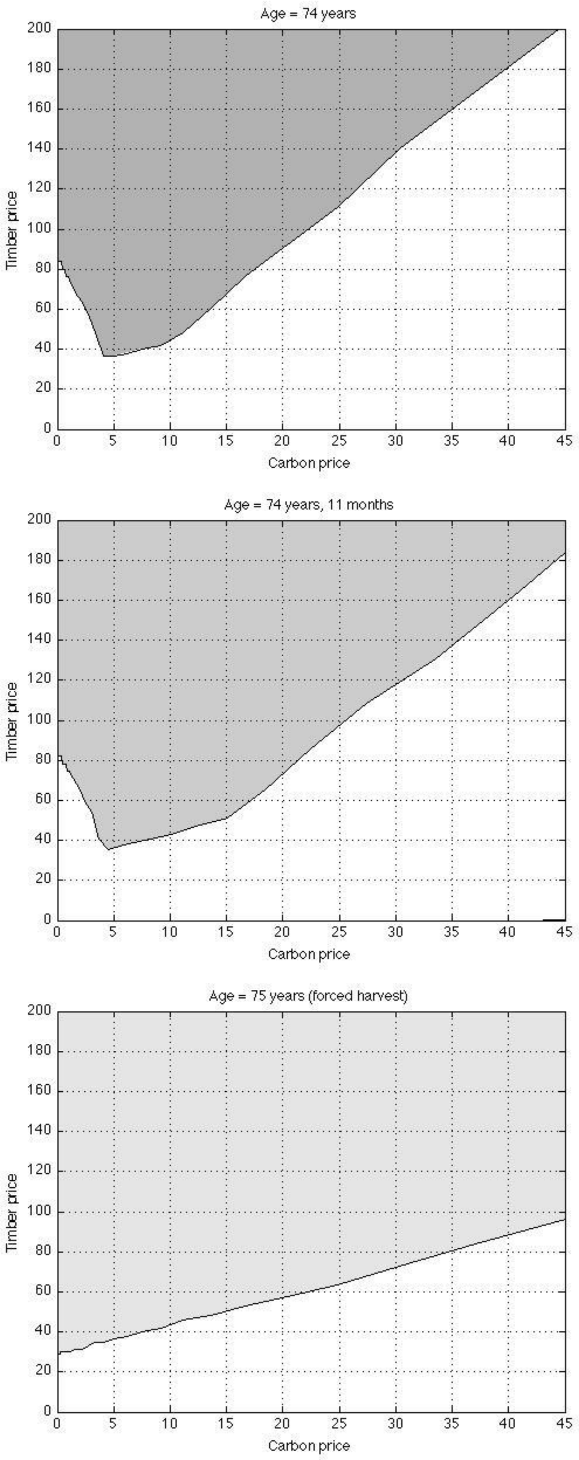


Figure 47: Timber-carbon price thresholds (double RV) for optimal harvest decisions for forest ages 74 years, 74 years 11 months and 75 years[11].

---

[11] The shaded area in each graph is the optimal harvest zone, whereas the non-shaded area is the no-harvest zones. Note that the graph for age 75 years is for a forced harvest thresholds (rather than the optimal harvest threshold) due to maximum tree age.

In Figure 48, the timber-carbon price thresholds are stacked together into a single graph to show the trend of enlarged optimal harvest zones with increasing forest age. As the forest age increases, the threshold boundaries become more and more like a "V" shape. This is due to the cascading effects of the valuation process, which traverses backwards starting from the terminal age of 75 with a forced, non-optimal harvest decision.

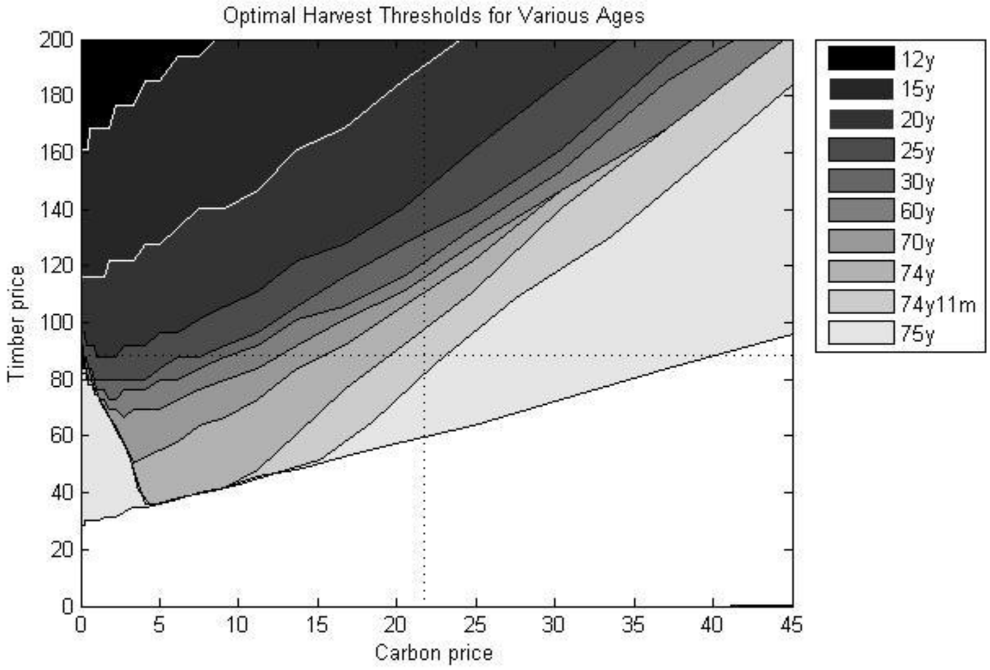


Figure 48: Timber-carbon price thresholds (double RV) for optimal harvest decisions for forest ages 12 to 75 years, stacked into a single graph[12].

The long run prices for carbon (NZ$21.72) and timber (NZ$88.44) are also plotted in Figure 48, as vertical and horizontal dotted lines, respectively. These dotted lines divide the graph into 4 quadrants:

- Top-Left quadrant: High timber price, and low carbon price

---

[12] The shaded areas are optimal harvest zones for the respective ages.

- Top-Right quadrant: High timber price, and high carbon price
- Bottom-Left quadrant: Low timber price, and low carbon price
- Bottom-Right quadrant: High timber price, and high carbon price

The Top-Left quadrant represents the best pricing conditions for an optimal harvest (i.e. high revenue from timber, and low cost of harvest liabilities), whereas, the Bottom-Right quadrant represents the worst pricing conditions (i.e. low revenue from timber, and high cost of harvest liabilities).

6.5 Conclusions

The double RV Binomial Tree method developed in this chapter overcomes the limitation of the single RV Binomial Tree method employed in chapter 5 to analyse carbon forestry under the NZETS. Results from this improved method reinforce the conclusions that the NZETS is expected to be an effective policy in increasing carbon sequestration in the forestry sector, contributing positively towards climate change mitigation in New Zealand.

Given the wide window of technically feasible harvest dates (of up to 75 years), the forest owner can afford to wait for the optimal combination of timber and carbon prices, and harvest when it happens. The optimal harvest price thresholds generated from the double RV Binomial Tree method are also very useful tools for both forest owners and policy makers.

Forestry has a long investment cycle. It is therefore absolutely crucial for the New Zealand government to provide and maintain policy certainty to the forestry sector in order to encourage carbon forestry investments. This certainty can be provided by ensuring that the NZETS remains in place for the foreseeable decades ahead.

CHAPTER 7: IMPLICATIONS AND CONCLUSIONS

In this chapter, key findings are summarized. A scenario analysis of potential implications to carbon stock management in New Zealand is presented. Areas for future research are also identified.

7.1 Summary of Key Findings

Research questions posed in chapter 1 are answered in a summary below:

1) *How does the NZETS affect the bareland valuation of new post-1989 forests?*

- Based on the results in this thesis, it is concluded that the NZETS increases the bareland valuation of new carbon forestry compared to new timber-only forestry. This is consistent with the NPV/LEV analysis of Maclaren et al (2008a, 2008b), where it was found that "*revenue from annual sales of carbon units greatly increases the profitability of all species and regimes*".

2) *How do analytical methodologies and assumptions of flexible versus fixed harvest ages affect bareland value?*

- The Real Options valuation methodology is able to generate bareland valuations for both fixed (NPV/LEV) and flexible harvest ages, while incorporating stochastic price processes.
- A higher bareland valuation is attained if a flexible rotation age (as opposed to a fixed rotation age) is adopted in order to take advantage of price fluctuations.

3) *To what extent will a carbon price affect harvesting decisions?*

- NPV/LEV and Real Options results of this research show that a carbon price will most likely lengthen the forest rotation age from 27 years to longer rotation ages, even up to 75 years old. This is consistent with the NPV/LEV work of Maclaren et al (2008a, 2008b) where it was concluded that "*as the carbon price increases, there is a general lengthening of optimum rotation age"*. It is also consistent with the Markov Decision Process model analysis of Turner et al (2008), which came to a similar conclusion that "*carbon-price risk increases the length of the average optimal rotation, due to forest owners' best decision being to delay harvest when the carbon price is high"*.

4) What is the optimal harvesting decision for new post-1989 forests in New Zealand?

- For carbon forestry, it is optimal to harvest when timber price (revenue) is high and carbon price (costs) is low. The optimal harvest decision thresholds, particularly those generated by the double RV Binomial Tree method in chapter 6, help forest owners to decide when to harvest.

5) What are the impacts of these effects on New Zealand?

- The lengthening of the forest rotation age contributes positively towards climate change mitigation in New Zealand, because as long as a forest is not harvested, it keeps on sequestering carbon every year (up to its biological growth limit), at a rate highlighted in Figure 49 (reproduced from section 5.2).

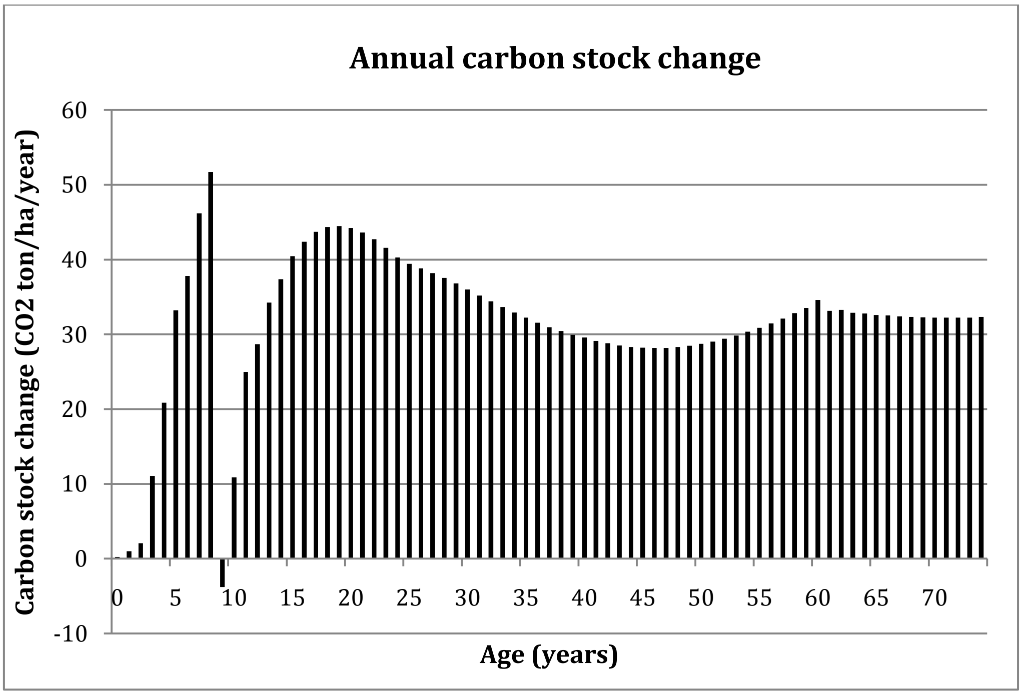


Figure 49: Annual carbon stock change of a radiata pine forest.

7.2 Scenario Analysis of Potential Implications for Carbon Stock Management in New Zealand

The Ministry for the Environment periodically publishes a projection of New Zealand's Land Use, Land Use Change and Forestry (LULUCF). This publication shows New Zealand net position for the LULUCF sector under the Kyoto Protocol, for the short term period between 2008 and 2012. The most recent report was produced in April 2011 (Ministry for the Environment, 2011).

In this section, a scenario analysis is conducted to investigate the potential implications of lengthening forest rotation, effected by the NZETS, on a longer term horizon beyond 2012.

Figure 50 shows the rate of new forest plantings between 1990 and 2008 (Horgan, 2007).

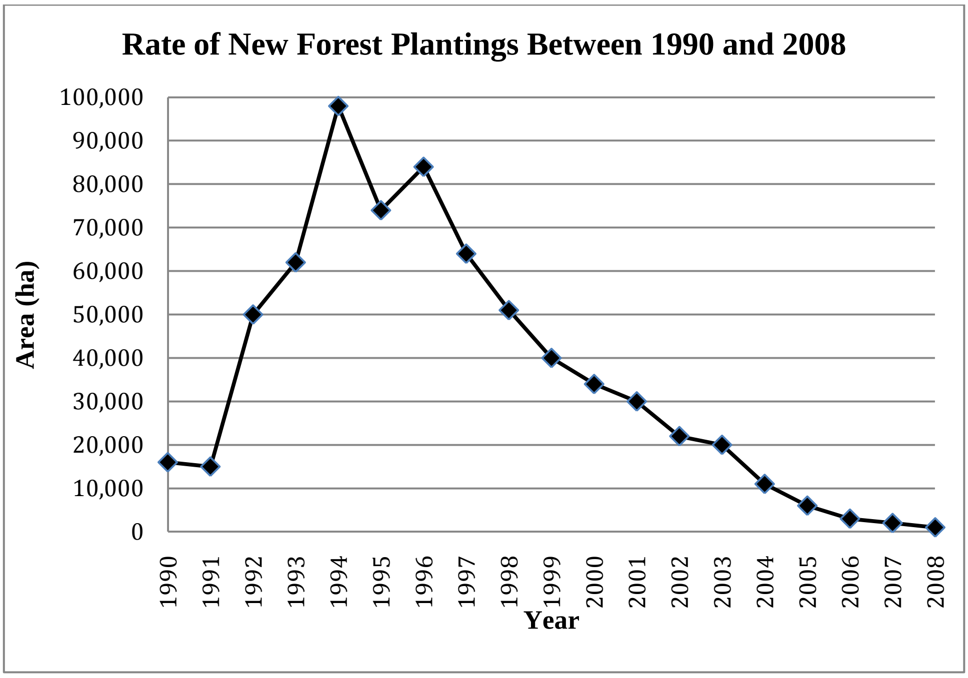


Figure 50: Rate of new forest plantings between 1990 and 2008.

Assumptions Made in the Scenario Analysis

In order to simplify the scenario analysis, only radiata pine post-1989 forests[13] are considered – all other forest species are excluded. It is assumed that an average of 89%[14] of all the new forest plantings in each year between 1990 and 2008 in Figure 50 are radiata pine forests. All radiata pine forests are also assumed to have characteristics that are identical to the forest modelled in chapters 5 and 6.

Based on these assumptions, the entire post-1989 radiata pine forests in New Zealand is broken down into 19 uniform age classes, each planted in every year between 1990 and 2008 as per Figure 50.

Five scenarios of rotation age lengthening are analysed: 27, 30, 37, 50 and 75 years. In each of these scenarios, all the radiata pine forests are assumed to be harvested at the same age, at the rotation length being analysed in the respective scenarios. For example, under the 30 year rotation age scenario, all 13,350[15] hectares of radiata pine forests planted in 1991 are assumed to be harvested in the year 2021, and all 44,500[16] hectares of radiata pine forests planted in 1992 are assumed to be harvested in the year 2022, and so forth. This simplistic assumption is consistent with the approach taken by Manley and Maclaren (2009) where scenarios for 28 year, 32 year and 40 year rotations were projected[17].

The five scenarios are not intended to be a detailed and accurate projection/forecast such as the New Zealand Wood Availability Forecasts 2010-2040 (Ministry of Agriculture and Forestry, 2010). They are intended to show a

---

[13] Pre-1990 forests are not included in this scenario analysis.

[14] Based on data from Ministry of Agriculture and Forestry (2009), 89% of all post-1989 forests are Radiata Pine forests.

[15] 15,000 hectares x 0.89 = 13,350 hectares.

[16] 50,000 hectares x 0.89 = 44,500 hectares.

[17] This refers to Figure 10 of Manley and Maclaren (2009). It is noted here Manley and Maclaren (2009) plotted carbon stock (i.e. the cumulative carbon stock of New Zealand's Kyoto plantations), whereas in this section, the annual carbon stock change (i.e. the amount by which carbon stock increases or decreases every year) is plotted.

hypothetical and potential effect of lengthening the rotation age on the carbon stock in New Zealand. The work here takes the projection to a more extreme level, by considering the hypothetical and potential effect of lengthening the rotation age to 50 and 75 years, which was not previously considered in Manley and Maclaren (2009).

Results of the Scenario Analysis

Figure 51 shows the projected annual carbon stock change of post-1989 radiata pine carbon forests, for the scenarios of 27, 30 and 37 year rotation ages, between the time horizon of 2008 and 2100. The positive value range of the vertical axis represents the net annual carbon sequestration, whereas the negative value range represents the net annual carbon emissions (i.e. carbon liabilities due to harvesting).

A section of Figure 51 is magnified in the Figure 52 to show the horizontal axis zero crossings (marked by circles). In the near term, lengthening of rotation age prolongs the duration that annual carbon stock change of carbon forests remains in the positive territory. A 27 year rotation crosses zero at around 2021, a 30 year rotation crosses zero at around 2023, and a 30 year rotation crosses zero at around 2030.

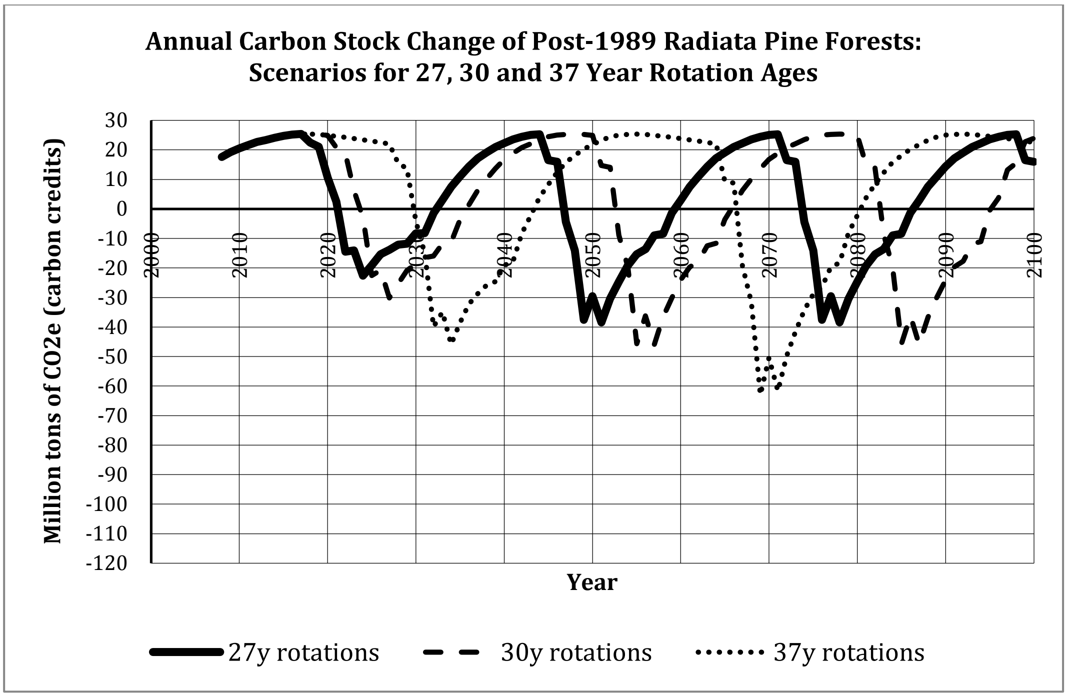


Figure 51: Scenarios of annual carbon stock change of New Zealand's post-1989 radiata pine carbon forests, for rotation ages 27, 30 and 37 years, between the time horizon of 2008 and 2100.

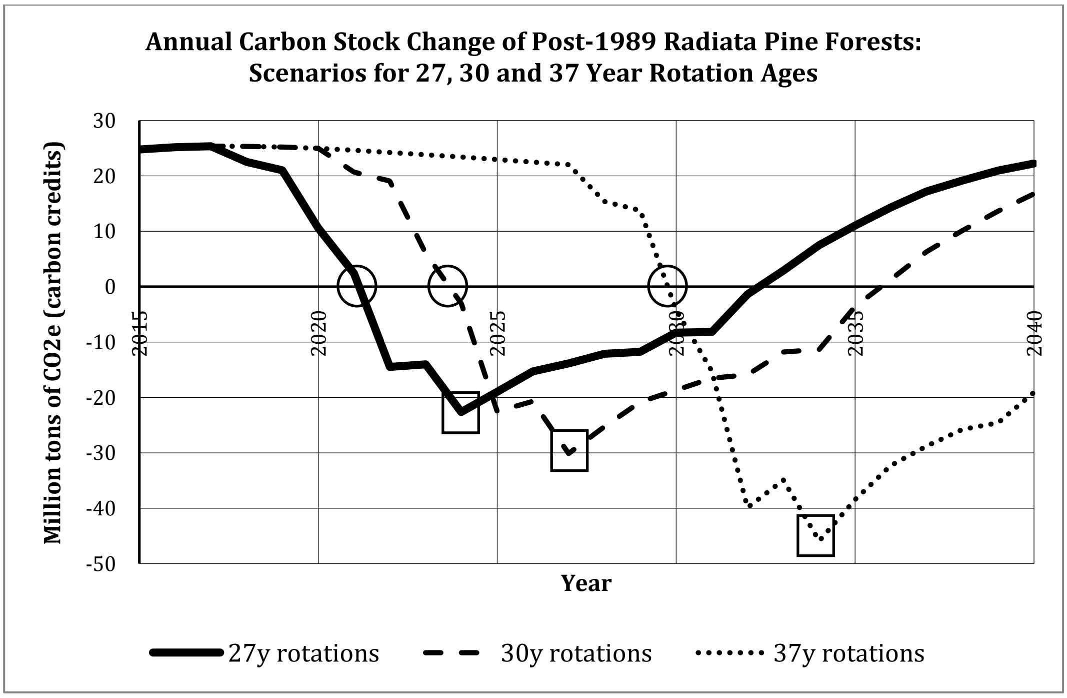


Figure 52: Magnification of Figure 51 to show the zero crossings (marked by circles) and minima points (marked by squares).

Lengthening the rotation age also results in more forest growth (i.e. a 37 year old forest has more timber than a 27 year old forest), which results in a higher accumulation of total carbon stock. This implies that when forests are harvested, because of their lengthened growth period, the magnitude of harvest liabilities is higher. For New Zealand's carbon forests, the (peak) harvest liability minima are marked by squares in Figure 52. The minima point for 27 year rotations is about -22 million tons (occurring in the year 2024), whereas the respective minima for 30 and 37 year rotations are about -30 million tons (occurring in the year 2027) and -45 million tons (occurring in the year 2034).

Both the effects of extended sequestration and higher magnitude of harvest liabilities are significantly amplified if the rotation age extends beyond 37 years to 50 or 75 years, as shown in Figure 53. For 50 year rotation scenario, the forest keeps on sequestering carbon and only crosses zero in 2042, with a minimum point of approximately -70 million tons in 2047. For 75 year rotations, the zero crossing happens in 2067, with a much larger minimum of approximately -118 million tons in 2072.

To illustrate the monetary value of such potential harvest liabilities, a $20 carbon price would mean that a harvest liability of -$1.4 billion[18] in the year 2047 for the 50 year rotation scenario. For the extreme 75 year scenario, a harvest liability of -$2.36 billion[19] would be incurred in the year 2072.

For further comparison of the order of magnitude, New Zealand's 2008 GHG emissions are only approximately -75 million tons (Ministry for the Environment, 2010). This emission is of a similar order of magnitude to the potential harvest liabilities due to extending rotation lengths. As such, the lengthening of rotation age for short and medium term carbon sequestration benefits has potentially major long term implications to the overall carbon stock balance in New Zealand.

---

[18] -70 million tons x $20 per ton = -$1.4 billion.

[19] -118 million tons x $20 per ton = -$2.36 billion.

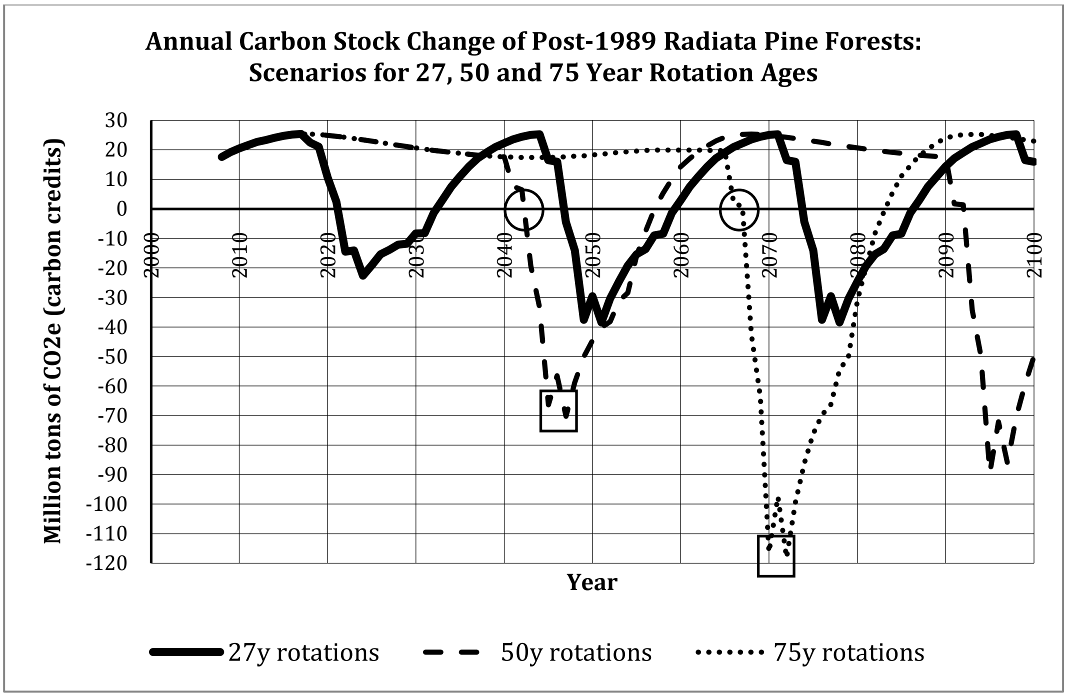


Figure 53: Scenarios of annual carbon stock change of New Zealand's post-1989 radiata pine carbon forests, for rotation ages 27, 50 and 75 years, between the time horizon of 2008 and 2100[20].

Potential Implications

It would be crucial for forest owners and the government to manage New Zealand's overall carbon stock with care, particularly the potentially massive harvest liabilities. Analogous to the financial and banking system, the government may need to put in place necessary regulatory measures and contingencies in order to ensure the stability of the carbon market in New Zealand in future.

It is also important to recognize that while climate change mitigation via carbon forestry offsets is an effective solution, it is only a temporary one. Sooner or later, the forests will have to be harvested, and when that happens, the carbon will be re-emitted back into the atmosphere and the carbon credits will have to be repaid back (i.e. harvest liabilities).

---

[20] Zero crossings are marked by circles, and minima points are marked by squares.

The silver lining is that carbon forestry buys time in order to allow for innovative technological solutions to GHG emissions (such as low-emission/hybrid/electric vehicles and clean electricity) to be developed and deployed widely in a cost effective manner.

7.3 Limitations of this Research and Potential Areas for Future Work

Weighting of Log Grades

Table 1 (reproduced here) shows how log grade volume percentages changes with timber age. Percentages for ages 25 to 70 were averaged to provide weights in the development of a proxy log price series. This averaging is a major simplification in the development of the (proxy) timber price series. Use and development of an improved weighting is one area for future research.

Log Grade	**Yield by Timber Age (years)**										**Average Yield**
	25	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	
Pruned	33%	31%	28%	27%	25%	24%	24%	23%	23%	22%	26%
S1	1%	4%	7%	8%	10%	11%	14%	17%	20%	22%	11%
S2	14%	16%	16%	16%	16%	16%	16%	16%	16%	14%	16%
L1&L2	11%	16%	20%	21%	22%	24%	24%	25%	25%	26%	22%
S3&L3	26%	20%	18%	17%	15%	14%	13%	11%	9%	8%	15%
Pulp	14%	13%	11%	11%	10%	10%	9%	8%	8%	7%	10%

Table 1: Log grade yield of various timber ages.

Time Window of Price Data

The survey of Manley (2010) on "discount rates used for forest valuation" pointed out that "*the majority of valuers use current prices for the short-term with long-term prices (e.g. after 5 years) predicted using average prices of the last 12 or 20 quarters*". In this research, the time window used is 1994 to 2009, as depicted in Figure 7, reproduced here as Figure 54. It is observed that for the time window of 1994 to 2005, the price appears to be trending on a declining mean. Taking into account the survey findings from Manley (2010), it may be useful for future work to revisit the time window of historical data used for estimating the mean reverting price parameters.

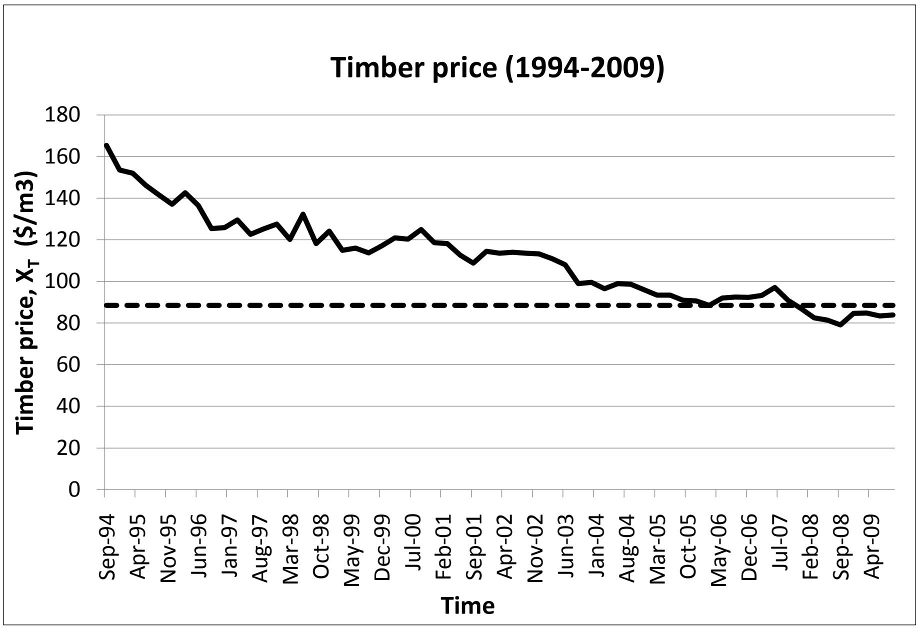


Figure 54: Timber price data from 1994-2009 used in this research.

Figure 55 shows recent timber price data from 2002 to 2011. This price trend is more oscillatory, which exhibits a stronger mean reverting characteristic, especially for the most recent 20 quarters (5 years).

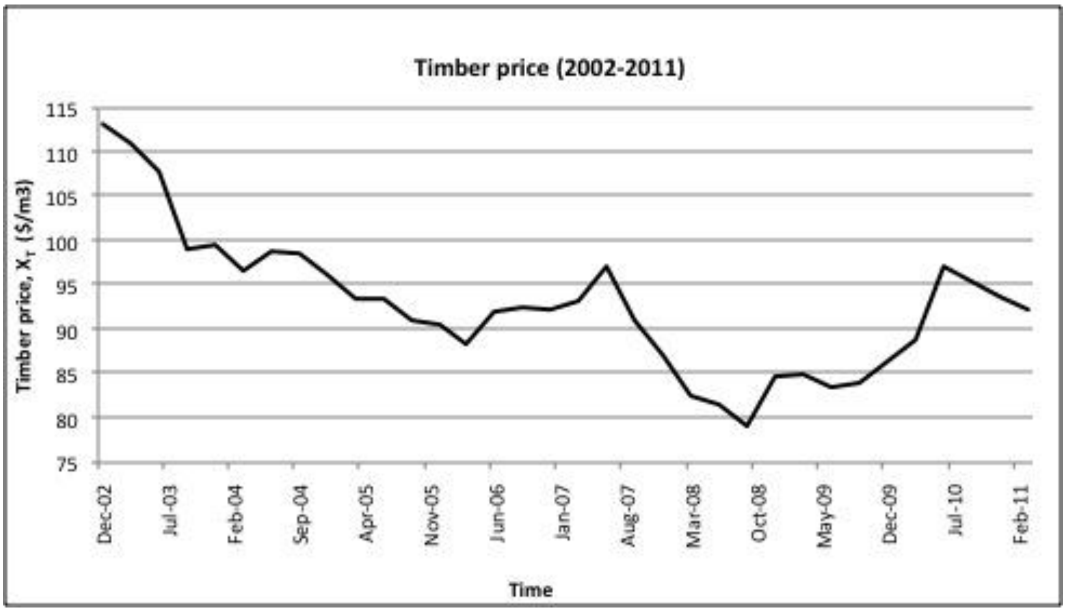


Figure 55: Timber price data from 2002 to 2011.

Incidentally, the original Climate Change Response Act was passed in November 2002, leading to the Climate Change Response (Emissions Trading) Amendment Act being passed in September 2008. It is possible that the Act passed in 2002 may have contributed (among other factors) to a structural and permanent change in the timber price model. For future work, it may be useful to use historical prices from late 2002 onwards (after the passing of the 2002 Act), and omit price data prior to that.

Price Process (Mean Reverting versus Random Walk)

A major assumption made throughout the work of this research is that both the timber price and the carbon prices follow a mean reverting process. This is a critical assumption because a different price process (such as a random walk process) is likely to produce quite different results. Such effects have previously been highlighted, for example, by Binkley et al. (2001) and Niquidet and Manley (2007):

> "*When prices follow a random walk, the current price is the best predictor of future prices so the gains from adaptive management are either very small or zero. Conversely, if prices can be considered as random draws from a distribution around a stationary mean or exhibit mean reversion, the potential gains from following a reserve pricing strategy are significant*".

An interesting area for future research is to employ a random walk price process, and compare it with the mean reverting process from this research.

Supply and Demand of Carbon Credits in New Zealand

Another potential area for further study is the supply of carbon credits in the New Zealand carbon market over the next few decades. Key elements of the supply include the post-1989 carbon forests already planted between 1990 and 2008 (as discussed in the previous section) and also new forests expected/projected to be planted every year from 2009 onwards. It would also be interesting to study the demand for carbon credits in New Zealand. Projections of future GHG emissions over the next few decades could be further analyzed. In combination, a better understanding of both the supply and demand for carbon credits could pave the way for studying the supply-demand equilibrium levels.

Other Areas

Additional areas for future research include:

- Studying the effect of decreasing harvest cost with age
- Analysing the bareland valuations under various different forest management regimes (stocking, pruning and thinning)

REFERENCES

Binkley, C.S., Washburn, C., Aronow, M.E., Fritzinger, T. (2001). “Modeling future price uncertainty”, Hancock Timberland Investor, first quarter 2001. http://www.htrg.com/pdf/htio1q1.pdf

Black, F., and Scholes, M. (1973). "The Pricing of Options and Corporate Liabilities", Journal of Political Economy, 81 (3), pp. 637–654.

Brazee, R.J., and Mendelsohn, R. (1988) Timber harvesting with fluctuating prices. Forest Science 34(2):359-372.

Chladna, Z. (2007), “Determination of optimal rotation period under stochastic wood and carbon prices”, Forest Policy and Economics, 9, pp. 1031-1045.

Clarke, H.R., and Reed, W.J. (1989) The tree cutting problem in a stochastic environment: the case of age dependent growth. Journal of Economic Dynamics and Control 13(4):569-595.

Copeland, T.E. and Antikarov, V. (2001). "Real Options: A Practitioner's Guide", 2001, W.W. Norton & Company

Cox, J.C., Ross, S.A. and Rubinstein, M. (1979). "Option Pricing: A Simplified Approach", Journal of Financial Economics, 7 (1979), pp. 229-263.

Dixit, A.K. and Pindyck, S., (1995). “The Options Approach to Capital Investment”, Harvard Business Review, vol. 73, pp. 105-115

Duku-Kaakyire, A., and Nanang, D.M. (2004). “Application of Real Options Theory to Forestry Investment Analysis”. Forest Policy and Economics. Volume 6, Number 6, pp. 539-552

Englin, J. and Callaway J. (1993). "Global Climate Change and Optimal Forest Management", Natural Resources Modelling, 7(3), pp.191-202.

Esa-Jussi, V. (2006). "An Early Contribution of Martin Faustmann to Natural Resource Economics", Journal of Forest Economics, 12 (2006), pp.131-144.

Faustmann, M. (1849). "On the Determination of the Value Which Forest Land and Immature Stands Possess for Forestry", English edition edited by M. Gane, Oxford Institute Paper 42, 1968, entitled "Martin Faustmann and the Evolution of Discounted Cash Flow”.

Fernandez, P. (2004). “Market Risk Premium – Required, Historical and Expected”, Working Paper No. 574, IESE Business School, University of Navarra

Franks, J., Lally, M., and Myers, S (2010). “Recommendation to the New Zealand Commerce Commission on whether or not it should change its previous estimate of tea-adjusted market risk premium as a result of the recent global financial crisis”, 14 April 2010, paragraph 17, pp.6.

Future Forests Research Limited (2010), “Radiata Pine Calculator, Version 3.0”, New Zealand.

Gamba, A. (2003). "Real Options Valuation: A Monte Carlo Approach", Working Paper Series 2002/03, Faculty of Management, University of Calgary, Canada.

Gjolberg, O., and Guttormsen, A.G. (2002). “Real Options in the Forest: What If Prices Are Mean-Reverting?”, Forest Policy Economics, 4, pp.13–20

Guthrie, G. (2009) “Real Options in Theory and Practice”. Oxford University Press, USA, pp. 263-284, 347-360.

Guthrie, G., and Kumareswaran, D. (2009). “Carbon Subsidies, Taxes and Optimal Forest Management”. Environmental and Resource Economics 43(2), 275-293.

Horgan, G. (2007) “Financial Returns and Forestry Planting Rates”, Ministry of Agriculture and Forestry, New Zealand.

Horgan, G. (2010). “Indicative New Zealand Radiata Pine Log Prices”, Ministry of Agriculture and Forestry, New Zealand.

http://www.maf.govt.nz/forestry/statistics/logprices/

Insley, M.C. (2002). “A Real Options Approach to the Valuation of a Forestry Investment”, Journal of Environmental Economics and Management, 44, pp. 471–492.

Insley, M.C., and Rollins, K. (2005). “On Solving The Multirotational Timber Harvesting Problem with Stochastic Prices: A Linear Complementarity Formulation”, American Journal of Agricultural Economics, 87, 3, pp. 735-755.

Kimberley, M., West, G., Dean, M., and Knowles, L. (2005). “The 300 Index — a volume productivity index for radiata pine”, New Zealand Journal of Forestry 50 (2), 13–18.

Maclaren, P., Manley, B., and Final Year School of Forestry Students (2008a). “Impact of the ETS on Forest Management”, report produced for MAF Policy under CC MAF POL_2008-10.

Maclaren, P., Manley, B., and Final Year School of Forestry Students (2008b). “Impact of the New Zealand Emissions Trading Scheme on Forest Management”, New Zealand Journal of Forestry, 53(3): 3339.

Manley, B.R. (2010). “Discount rates used for forest valuation - Results of 2009 survey”, New Zealand Journal of Forestry 54(4): 19-23.

Manley, B., and Maclaren, P. (2009). “Modelling the impact of carbon trading legislation on New Zealand’s plantation estate”, New Zealand Journal of Forestry, 54(1): 39-44.

Manley, B., and Maclaren P. (2010). “Impact of carbon trading on forest management in New Zealand”, Forest Policy and Economics. doi:10.1016/j.forpol.2010.01.001

Manley, B., and Niquidet, K. (2010). “What Is The Relevance Of Option Pricing for Forest Valuation in New Zealand?”, Forest Policy and Economics, Elsevier, vol. 12(4), pages 299-307.

Meade, R., Fiuza, G., and Lu, A. (2008). “Forest and Forest Land Valuation: How to Value Forests and Forest Land to Include Carbon Costs and Benefits”, report prepared for the New Zealand Ministry of Agriculture and Forestry.

Merton, R.C. (1973). "Theory of Rational Option Pricing", Bell Journal of Economics and Management Science 4 (1), pp. 141–183

Miller, R.A. and Voltaire, K. (1983). "A Stochastic Analysis of the Tree Paradigm", Journal of Economic Dynamics and Control 6: 371-386

Ministry of Agriculture and Forestry (2009). “National Exotic Forest Description”, 1st April 2009, New Zealand. http://www.maf.govt.nz

Ministry of Agriculture and Forestry (2010). “New Zealand Wood Availability Forecasts 2010-2040”, March 2010, New Zealand. http://www.maf.govt.nz

Ministry of Agriculture and Forestry (2011). “Introduction to Forestry in the Emissions Trading Scheme”, May 2011, New Zealand.

http://www.maf.govt.nz/forestry/forestry-in-the-ets

Ministry for the Environment (2010). “New Zealand’s Greenhouse Gas Inventory 1990-2008”, New Zealand.

http://www.mfe.govt.nz/publications/climate/greenhouse-gas-inventory-2010/index.html

Ministry for the Environment (2011). “Land Use, Land-use Change and Forestry Sector - Greenhouse Gas Emission Projections for the First Commitment Period of the Kyoto Protocol from LULUCF Activities under Article 3.3: Results, Data and Methodology, 2011 Report, New Zelaand.

http://www.mfe.govt.nz/publications/climate/lulucf-2011/index.html

Morck, R., Schwartz, E., and Stangeland, D. (1989). "The valuation of Forestry Resources Under Stochastic Prices and Inventories", Journal of Financial and Quantitative Analysis, 24 (2), pp.473-487.

Myers, S.C. (1977). "Determinants of Corporate Borrowing", Journal of Financial Economics, vol 5, 147-175.

New Zealand Government (2010). “Climate Change Information – New Zealand”, New Zealand. http://www.climatechange.govt.nz

Niquidet, K., and Manley, B. (2007). “Price dynamics in the New Zealand Log Market”, New Zealand Journal of Forestry, 52(3): 4-9.

Olschewski, R., and Benitez, P. C. (2009), “Optimizing Joint Production of Timber and Carbon Sequestration of Afforestation Projects”, Journal of Forest Economics, pp. 1-12

Pindyck, R.S. (1993). “Investment of Uncertain Cost,” Journal of Financial Economics, Aug, 34, pp. 53 – 76.

Plantinga, A.J. (1998). The optimal timber rotation: An option value approach. Forest Science, 44, pp.192–202.

Provencher, B. (1995). “Structural Estimation of the Stochastic Dynamic Decision Problems of Resource Users: An Application to the Timber Harvest Decision”, Journal of Environmental and Economics and Management, 29, pp. 321-338.

Reed, W.J. and Clarke, H.R. (1990). “Harvest Decisions and Asset Valuation for Biological Resources Exhibiting Size-Dependent Stochastic Growth, International Economic Review, 31 (1), pp. 147-169.

Reuer, J.J. and Tong, T.W. (2007). "Real Options in Strategic Management", Advances in Strategic Management, vol 24, 2007, Elsevier

Romero, C., Ros, V. and Daz-Balteiro, L. (1998). "Optimal Forest Rotation Age When Carbon Captured is Considered: Theory and Applications", Journal of the Operational Research Society, 49(2), pp.121-131.

Schwartz, E.S. and Trigeorgis, L. (2004). "Real Options and Investment Under Uncertainty - Classical Readings and Recent Contributions", MIT Press, USA.

Sohngen, B. and Mendelsohn, R. (2003). "An Optimal Control Model of Forest Carbon Sequestration", American Journal of Agricultural Economics, 85(2), pp. 448-457.

Statistics New Zealand (2010). "Consumer Price Index". http://www.stats.govt.nz/methods_and_services/information-releases/consumers-price-index.aspx

Tee, J., Scarpa, R., Marsh, D., and Guthrie, G. (2010). "A Binomial Tree Approach to Valuing Fixed Rotation Forests and Flexible Rotation Forests Under a Mean Reverting Timber Price Process", New Zealand Agricultural and Resource Economics Society (NZARES) Conference, 26th-27th August 2010, Nelson, New Zealand.

Tee, J., Scarpa, R., Marsh, D., and Guthrie, G. (2011a). "Climate Change Mitigation Policy: The Effect of the New Zealand Emissions Trading Scheme on New Radiata Pine Forest Plantations in New Zealand", Australian Agricultural and Resource Economics Society (AARES) Conference, 8th-11th February 2011, Melbourne, Australia.

Tee, J., Scarpa, R., Marsh, D., and Guthrie, G. (2011b). "Real Options Analysis of Afforestation and Reforestation (Article 3.3 of the Kyoto Protocol) Under the New Zealand Emissions Trading Scheme", paper accepted for presentation at the 18th Annual Conference of the European Association of Environmental and Resource Economists (EAERE), 29 June- 2 July 2011, Rome, Italy

Treasury (2010). “New Zealand Position Under the Kyoto Protocol”, New Zealand Government. http://www.treasury.govt.nz/government/kyotoposition

Thomson T.A. (1992). “Optimal Forest Rotation When Stumpage Prices Follow a Diffusion Process”, Land Economics, 68, 3, pp. 329-342

Turner, J.A., West, G., Dungey, H., Wakelin, S., Maclaren, P., Adams, T. and Silcock, P. (2008). “Managing New Zealand Planted Forests for Carbon: A Review of Selected Management Scenarios and Identification of Knowledge Gaps," Contract No.CC MAF POL_2009_09 (108-1), Scion Ltd, New Zealand.

United Nations Framework Convention on Climate Change (UNFCCC) (1998). “Kyoto Protocol To The United Nations Framework Convention on Climate Change”, 1998. http://unfccc.int/resource/docs/convkp/kpeng.pdf

Van Kooten, C.G., Binkley, C.S., and Delcourt, G. (1995). “Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services”. American Journal of Agriculture Economics, 77, 2, pp. 365–374

World Resources Institute (2011). Climate Analysis Indicators Tool (CAIT) Version 8.0, Washington, DC, USA.http://cait.wri.org