Modeling a Dynamic Forest Sector in a General Equilibrium Framework

Xiaohui Tian
The Ohio State University
tian.41@osu.edu

Brent Sohngen
The Ohio State University
sohngen.1@osu.edu

Ronald Sands
Economic Research Service, U.S. Department of Agriculture
rsands@ers.usda.gov

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's

2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4-6, 2013

Modeling a Dynamic Forest Sector in a General Equilibrium Framework

Xiaohui Tian[a], Brent Sohngen[a] and Ronald Sands[b]
[a] Ohio State University
[b] Economic Research Service, U.S. Department of Agriculture[1]

In this study, we develop a dynamic forest sector in a Computable General Equilibrium (CGE) model. There are several reasons why it is important to model a dynamic forest sector in a general equilibrium context. One key reason lies in the role of forestry in the global carbon cycle. On one hand, deforestation is considered the second largest source of greenhouse gas emissions (IPCC, 2000); on the other, forests might be a significant component in climate change mitigation. It is estimated that forestry can potentially sequester one third of global carbon abatement, with two thirds of carbon gains coming from tropical forests (Sohngen and Mendelsohn, 2003). More appealingly, most of these gains can be achieved at costs that are competitive with other abatement options (Richards and Stokes, 2004). This could have important implications for future carbon prices. However, most of these analyses are done in a partial equilibrium framework of the forestry sector, and they ignore the impacts of climate change policy in forestry on other economic activities.

Another reason is the potential impact of forestry on energy prices due to the increasing role of woody biomass in energy use. Especially in Europe and the U.S., there are many legislative efforts which promote biomass energy as a renewable source for electricity. With further technology innovation, it is estimated the demand for woody biomass will increase globally in the future. Thus, forests might have important implications on future energy prices and therefore other sectors of the economy. To tackle these issues, we use a general equilibrium model where the economy-wide effects of biomass technology or policy changes can be modeled.

A third reason stems from the importance of land use analysis in integrated assessment modeling (IAM). Integrated assessment models have become the standard tool used to analyze the implications of climate change and climate change policies on the economy. They link atmospheric models to other components of the earth system via economic, physical or biological connections. The economic and biological link on the land use side in these models has been under-developed for years, despite mounting evidence that land use has played and continues to play a critical role in the global

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[1] The views expressed are those of the authors, and should not be attributed to the Economic Research Service or USDA.

carbon cycle. The limitations in this component of integrated assessment modeling trace directly to the inability of these models to account for the dynamics of forest management. This work addresses this gap in the literature by showing how a dynamic forestry sector can be integrated into an intertemporal general equilibrium model. These techniques can then be used more broadly by the economic modeling community. The model we propose here represents forestry land use and land use changes in two aspects. First, the model introduces a land-based age-specific forest sector, and the land heterogeneity has productivity and carbon capture implications. Second, we introduce land competition between agriculture and forestland indirectly via a rising cost land supply function. Land use decisions are endogenously made so that forestland can be converted to alternative uses or new land can be incorporated into timber production.

Despite the importance of introducing the forestry sector into a general equilibrium framework, modeling the forestry sector in a general equilibrium context remains an extremely difficult task due to the complex dynamics inherent in forestry management. It takes several decades to grow new forests. Perhaps more so than other land use sectors, investments in forest are based on expectations about future markets and climate change policies. The harvest and management decisions are also dynamic. With user costs, any changes in harvesting have implications for the future, so decisions are made in an intertemporal context. While it might be enough to use a static or a recursively dynamic model for agriculture, the dynamic nature of forestry sector requires an intertemporal frameworks which allows forward-looking behavior. In addition, prices should be endogenous. Many simple dynamic models hold prices as fixed and thus cannot adequately reflect market fluctuations. Finally, growth rates of forests are nonlinear and vary substantially across vintages. This requires substantial computational effort from CGE modelers.

We illustrate how to introduce a dynamic forestry sector into a CGE model with perfect foresight in all sectors. The forestry sector is land-based and embodies different age classes. On the production side, there are three general sectors which produce heterogeneous final goods. Forestry products serve as intermediate inputs to the general sectors. The forest production sector is endowed with forestland and forest inventory on the land, which is exogenous. The forest sector maximizes profits by choosing optimal rotation ages and adjusting forestland. In order to capture land competition between forests and agriculture, we impose a rising land rent cost to forestland. Homogenous consumers purchase goods from the general sectors. Both consumers and producers have an infinite planning horizon.

To overcome the intrinsic difficulties in solving a dynamic and nonlinear model, we also propose a new algorithm. The fundamental structure of this algorithm involves solving a minimization of distance from the solution to the optimality conditions, so the problem is transformed to a constrained nonlinear optimization problem. This method increases the probability of convergence of the global optimum and thus is more efficient than solving a system of equations. The model is closed for the moment. With the baseline calibrated, various carbon policy and growth scenarios are compared and discussed.

Several important relationships can be analyzed with the forward-looking forest sector. First, prices of forestry products reflect both the marginal costs in the forest sector and its marginal product as an intermediate input to the general sector. Thus, forestry management is determined simultaneously with all sectors. Second, the model is capable of capturing both long-run and short-run effects of policies since both age class adjustments and land use changes are endogenously determined.

1. Review of Literature

While a number of general equilibrium models are in use today, only a few incorporate the land use framework and none of them represent the dynamics of forestry in a comprehensive way (Sohngen et al., 2008). The first attempt of modeling land use in general equilibrium is the FARM model (Darwin et al., 1995). However, the model focused mainly on agriculture, and forestry land use was not studied. Despite the difficulty in introducing forestry into a CGE model, significant efforts have been made among a few studies. In general, there are two ways to introduce the dynamics of forestry management. One way is to link a general equilibrium model with a partial equilibrium model and solve the general equilibrium model based on the results from partial equilibrium which is more capable in capturing the intertemporal dynamics of the forestry sector (e.g. Golub et al., 2008; Hertel, 2009). The other way is to relax the conditions of intertemporal dynamics and apply steady-state conditions, i.e. fixed rotation ages so that the model circumvents the short run adjustments in forestry. The model is greatly simplified in this way. Its strength can also be considered as a major weakness of this approach. Several major efforts in existing studies are summarized here.

Ahammad and Mi (2005) model alternative land uses using the ABARE's global trade and environment model (GTEM). GTEM is a multi-sector, multi-region, recursive dynamic CGE model of the world economy. Agriculture and forest sectors are nested together in a CES production function as primary factors for the energy sector. They explicitly model different age class of forests and allow forests to shift from one age class to another. However, the model does not allow land conversion between agriculture and forests. Actually, the land class structure in the model is only used for various agriculture activities. Forests are not land based but considered as a natural resource. The harvest decision is not endogenous and neither is carbon sequestration. The model harvests a fixed proportion of forests each year. Therefore, this model is not optimizing the forest sector. The implications of policy change for optimal rotation are not captured in the model.

Sohngen and Mendelsohn (2003) develop an optimal control forestry model to explore the role of carbon sequestration of forests in global climate change mitigation. Though this is a partial equilibrium analysis, it established a methodology to link a dynamic forestry model with an integrated assessment model of carbon and the world economy (DICE). The models are solved simultaneously in an iterative process. The DICE model provides the rental rate path to the forestry model and the forest model takes this path to solve for the cost and level of carbon sequestration under an optimal strategy. The iterative process stops when the two models converge to the same level of carbon sequestration and carbon price path. The sequestration supply curve is obtained to show how carbon sequestration should coordinate with overall carbon mitigation programs. Both the short-run and long-run surplus in the forest sector are optimized and the inter-temperate dynamics are fully captured in the forestry model. This study sets up the partial equilibrium foundation for subsequent CGE studies. A weakness of this study is that the linkage between the forestry sector and other parts of the economy is ignored.

Golub et al. (2008) use a recursive dynamic CGE model to investigate long-run land use change at the global scale due to changes of consumption patterns in agriculture and forestry products; they rely on the global timber market model presented by Sohngen and Mendelsohn (2007) to capture the dynamics of forestry resource. Three steps are conducted to create the soft link between the general equilibrium model and forestry sector model. The general equilibrium model first runs for 100 years to establish the baseline path for economy, including the aggregate demand for forestry products. Second, based on the demand path, the forest model runs to generate the price path of forest products. Finally, they recalibrate the general equilibrium model so that the baseline hits the same price path. This price path represents changes in the value of forests product over time and reflects forward-looking behavior in the forestry sector. However, the general equilibrium model, including the forest sector in the model, does not involve forward-looking behavior. The results of the model are still highly dependent on the calibration, which is the major limitation of this approach.

Hertel (2009) uses a similar approach to Golub et al. (2008), but uses a comparative-static general equilibrium model to address different questions. Specifically, the paper examines the mitigation potential for land based emissions under different carbon prices. The general equilibrium model is calibrated to mimic the responses of the forestry model in different regions. The innovation of this study is that it differentiates mitigation at the extensive margin (more land) from the intensive margin (more carbon in existing forests). They find that altering the optimal rotation age is one of the major options in carbon sequestration of forestry. However, since the model is comparative static, the carbon supply schedule shifts with different assumptions of time horizons. The results of a shorter time horizon will look very different from those of a longer time horizon.

Sands and Kim (2009) provide another example of land use analysis in a CGE model with forestry. This model embodies different age classes of forests. Yet, instead of choosing optimal rotation ages, the model harvests each period at a fixed rotation age. The steady state rotation ages are determined using yield functions. These yield functions also determine the land rents of forest. The model allows land conversion between alternative uses based on relative land rents. The model might capture the impacts of climate change policies on land uses and steady state rotation ages in the long run correctly. However, we might not be able to learn about how the system adjusts itself in the near term. As suggested in Sohngen et al. (2008), short-term adjustments in the forestry sector can be very different from long-run adjustments.

To sum up, approaches in these studies vary from each other more or less, yet, each of them focuses on different aspect of forestry dynamics and none of them can comprehensively capture the forward-looking behavior in the forestry sector. By relying on a partial equilibrium model, the general equilibrium model mimics the dynamics of the forestry sector, however, it is always difficult for the general equilibrium model to fully adapt this dynamics, especially when the time horizon changes. If the general model only focuses on steady state adjustments, the short term changes are ignored. So steady state analysis might be inadequate for policies analysis which focuses on near term effects. These issues could be resolved to a large extent if the general equilibrium model has an inherently dynamic and forward-looking forestry sector with endogenous harvest ages and land use decisions.

2. A dynamic forest sector in a general equilibrium model

In this study, we illustrate how to introduce a dynamic forestry sector into a CGE model where all the sectors are forward looking. The forestry sector is land-based and embodies different age classes. In order to focus on the dynamics of forestry sector, we ignore international trade and government. So the model is closed for the time being. On the production side, there are three general sectors and one forestry sector. The general sectors produce heterogeneous final goods. Forestry products serve as intermediate inputs to the general sectors, so that gross production is determined by labor, capital and forestry input. There are homogenous consumers who consume final goods from the three general sectors. Both consumers and producers have an infinite horizon with perfect foresight (rational forward-looking expectations). The forestry production sector is endowed with forestland and forest inventory on the land, which is exogenous. The forest sector maximizes profits by adjusting optimal rotation ages. A detailed description of each sector's and consumer's behavior and the equilibrium conditions are presented in the Appendix.

For the analysis, four future scenarios are constructed. The baseline provides our base assumptions about economic growth and the forest sector. For modeling purposes, we have used simple assumptions about the general sector and population growth. Two additional scenarios are constructed to examine alternative future projections of the economy. One of these scenarios follows faster rates of population growth, and another scenario assumes faster rates of change in total factor productivity. Two other scenarios are constructed to examine alternative assumptions in the forest sector. One considers changing the initial class distribution to older trees. The other considers faster rates of tree growth.

Scenario 1 (Fast Population growth):

This scenario assumes that population grows more quickly over time. To accomplish this, we increase the population growth rate of the baseline to 1 percent per year. As a result, the labor supply in the model is also increased by 1 percent per year.

Scenario 2 (Fast technology innovation):

This scenario assumes that technology in the general sectors improves more quickly over time than the baseline. To accomplish this, we assume that total factor productivity grows by 1 percent per year and other parts of the production function unchanged.

Scenario 3 (Older age class distribution):

The baseline assumes that initial forest stocks are evenly distributed across age classes 1 to 30. This is also the age class distribution in the model steady state. In this scenario we assume that there are more mature trees initially. To accomplish this, we assume the stocks are evenly distributed between age classes 7 to 35.

Scenario 4 (High yield of trees):

This scenario assumes that the trees grow faster over time due to biotechnology innovation in the forest sector. To accomplish this, we increase the natural growth rate by 1 percent per year. As a result, a newly planted tree grows faster than previousy planted trees.

3. Results and discussion

Before moving to results, it is necessary to discuss the new algorithm we proposed in solving the model. Ideally, one should get the optimal solution by solving a system of intertemporal optimality conditions for behavior of consumers and producers of final goods and timber products. However, when we introduce the forest sector into the model, this method becomes infeasible due to the intrinsic nonlinearity of yield functions of trees and the complex dynamics of forest management. As an alternative, we solve the model by separating the forest sector from other parts of the economy and iterating between the two. The two parts are connected by time variant timber demand functions derived from the general equilibrium results. The general equilibrium part is solved as a nonlinear optimization problem by minimizing the distance between the solutions to the optimality conditions. This updates timber demand functions and the forestry model solves its optimal path of supply and prices given the demand functions. The process is terminated once the paths of timber prices from the two parts converge. Figures 1-7 present the projected paths of variables in the model for four scenarios with comparisons to the baseline projections.

Scenario 1-Fast population growth

This scenario assumes population grows faster than the baseline. As a result, labor supply increases 1 percent per year. Timber demand increases due to the complementary effects of increases in labor inputs. Forestland expands due to higher demand. This will lead to higher land rent and higher costs for timber production. As a result, we observe the rotation age at steady state is 27, 1 year younger than that of the baseline, despite the timber price being higher than the baseline and increasing over time. Unlike the timber price, the price of capital shows a downward trend. This is surprising but reasonable as well. While capital can be accumulated and adjusted annually through investment, forests stocks cannot be adjusted in the short run. The growth of forest stock depends on the stocks and the natural yield rate of trees.

Scenario 2-Fast technology innovation

This scenario focuses on the technology improvements and assumes total factor productivity is growing by 1 percent per year. Because the rest of the production function (Cobb-Douglas) is unchanged and labor supply is constant over time, we do not observe changes in timber demand or forestland. The labor price, as with prices of timber and capital, is increasing because the marginal productivity is increasing with total factor productivity.

Scenario 3-Older age class distributions

This scenario focuses on the effects of different age distributions. As the model starts with old trees, the supply of timber is expected to be higher in the initial periods. As expected older trees are harvested initially and the age class distribution gradually moves to younger trees. Accordingly, timber prices start lower initially with greater timber supply and then increase to the steady state level.

Scenario 4-High yield of trees

This scenario assumes trees are growing faster by 1 percent per year. As expected, the timber supply is growing steadily over time, as is total consumption. The timber price falls over time because the opportunity cost of timber production is going down. Forestland decreases and then increases to a level higher than that in baseline. The initial decline happens because the higher productivity could substitute for exiting forestland to alternative uses. Yet, as timber prices increase, the revenue for per unit of forestland is also increasing as well as the opportunity cost of abandoning forestland. As a result, the forest sectors starts to bring land back to forests by planting trees.

A number of important relationships can be analyzed by introducing a forward-looking forest sector. The optimal rotation age occurs when the value of the forestland equals the present value of forest products plus the value of replanted forests minus the cost of replantation. The value of forestland is based on the expectation of future revenues and also the interest rate which is endogenous in the model. The optimal rotation age should be shorter than the maximum sustainable yield because of the opportunity cost of forest investment as reflected in the interest rate. Prices of forestry products reflect both the marginal costs in the forest sector and its marginal product as intermediate inputs to the general sector. Therefore, the choice of rotation age is determined simultaneously by all the sectors in the economy together; the behavior within the forestry sector would also affect the other sectors via supply of timber products.

These techniques will be useful more widely for the integrated assessment modeling community in climate policy analysis, which so far has not considered dynamic land use applications. With a climate policy, forest management will be determined endogenously with carbon prices and demand for forestry products as inputs. As a result, in order to capture more carbon, the age class and land area of the forest inventory will adjust accordingly. Age class adjustment is one of the major management options in the forest sector, especially in the short run when forestland cannot be expanded. An increase in rotation age might increase the output of timber products in the long run, but it might decrease the supply in the short run because land owners need to hold certain trees from harvest in periods of adjustment. More importantly, all these adjustments will also affect the carbon price through carbon markets. The optimal climate change portfolio of the society should change accordingly. All of these effects could be captured in this CGE model where sectors are connected and forward looking.

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Figure 1-1 Path of Timber Demand

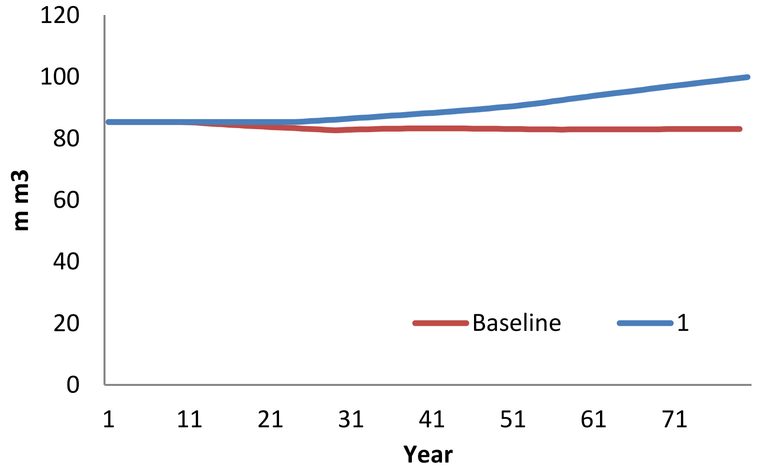


Figure 1-2 Path of age at harvest

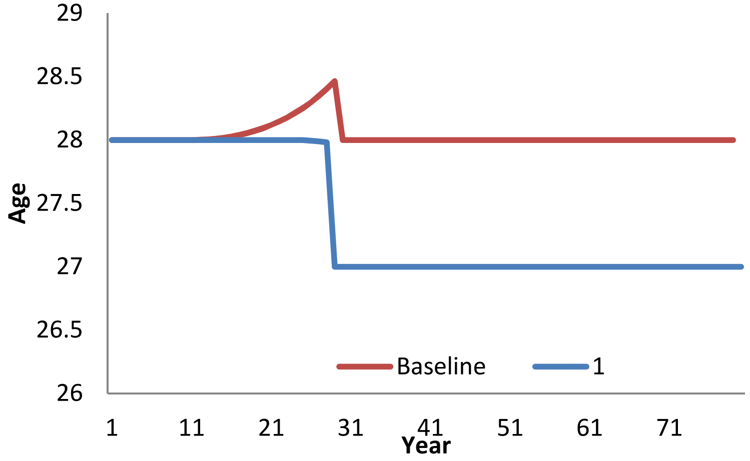


Figure1-3 Price of Timber

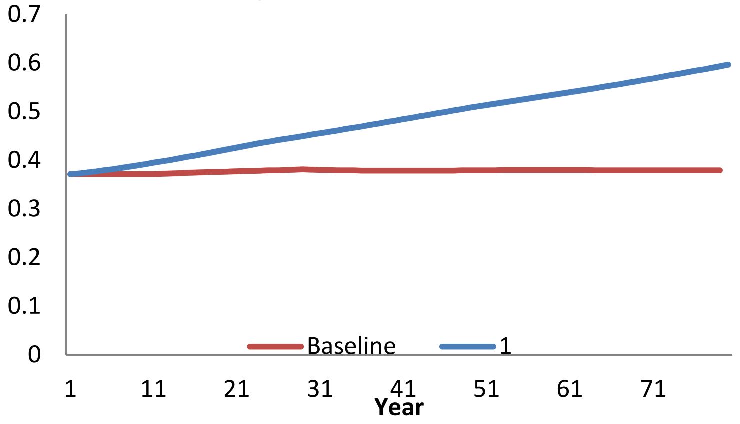


Figure1-4 Price of Capital

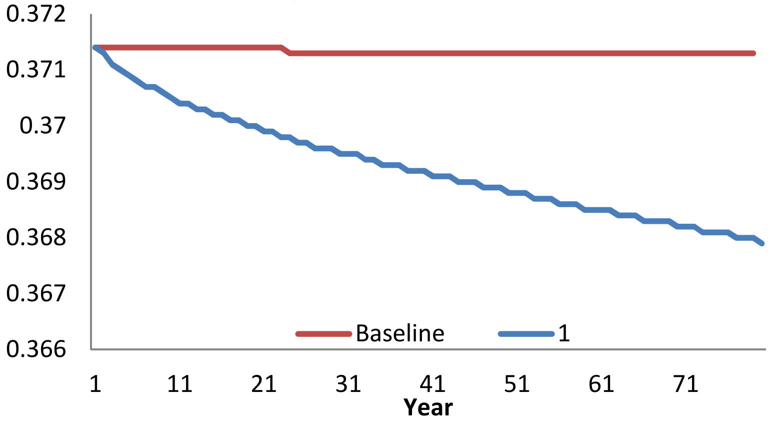


Figure-5 Price of Labor

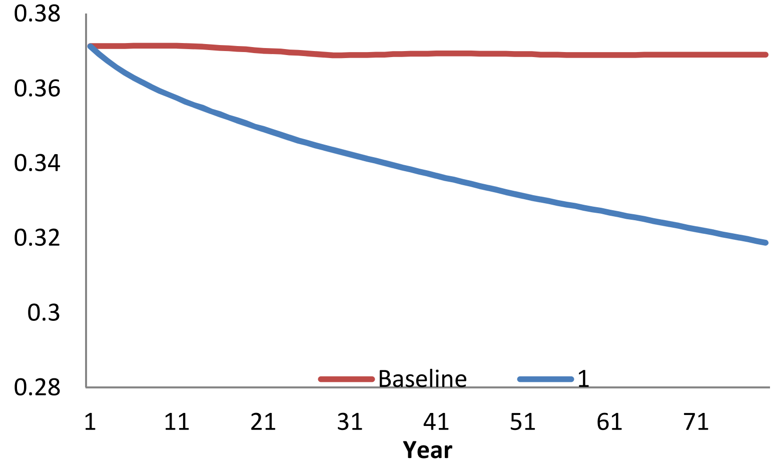


Figure-6 Consumption

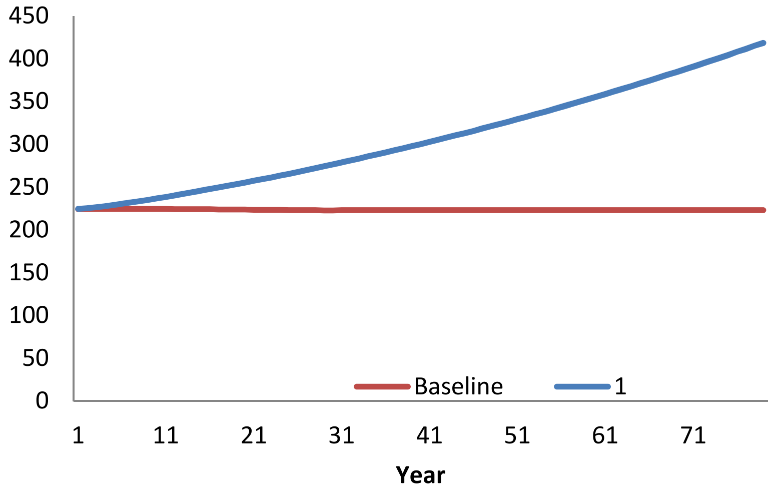
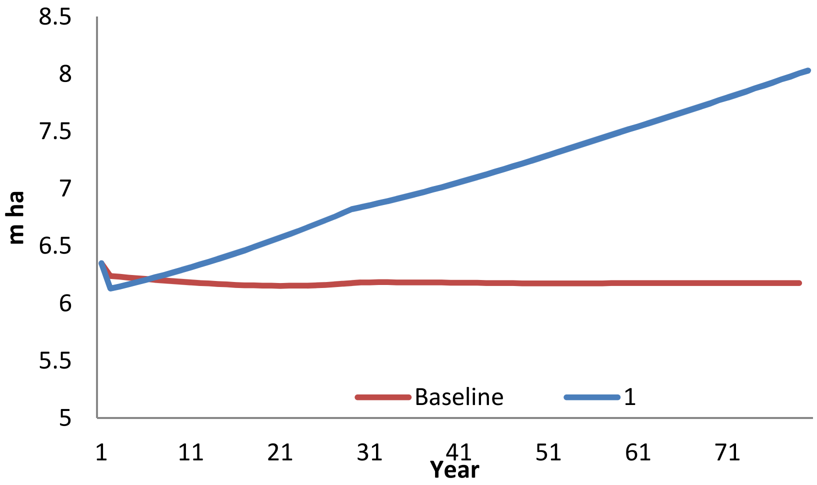
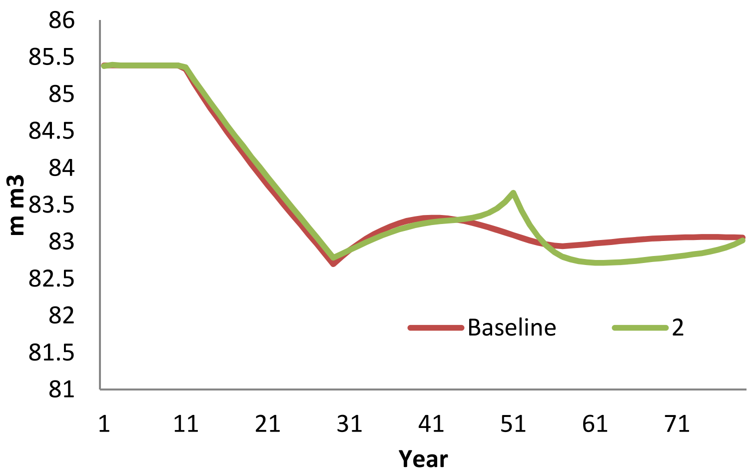


Figure-7 Path of Timberland





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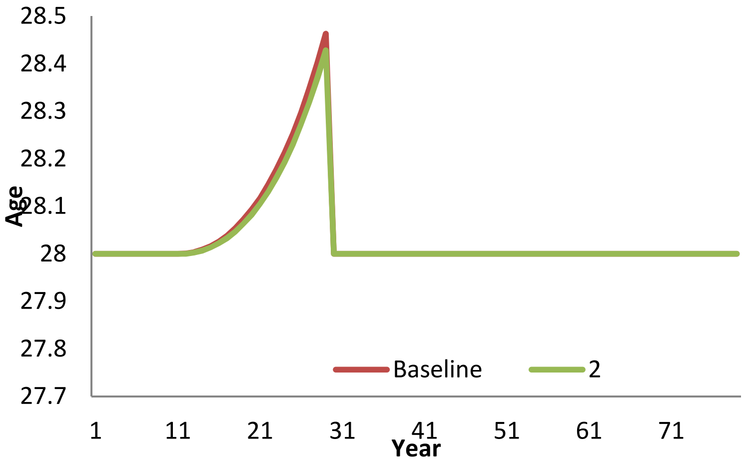

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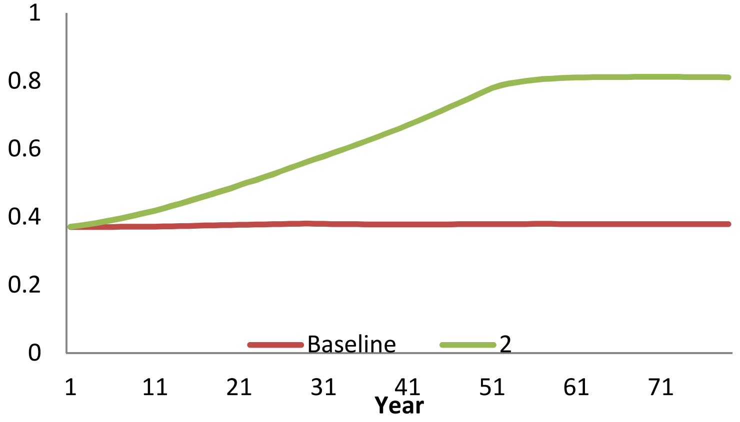

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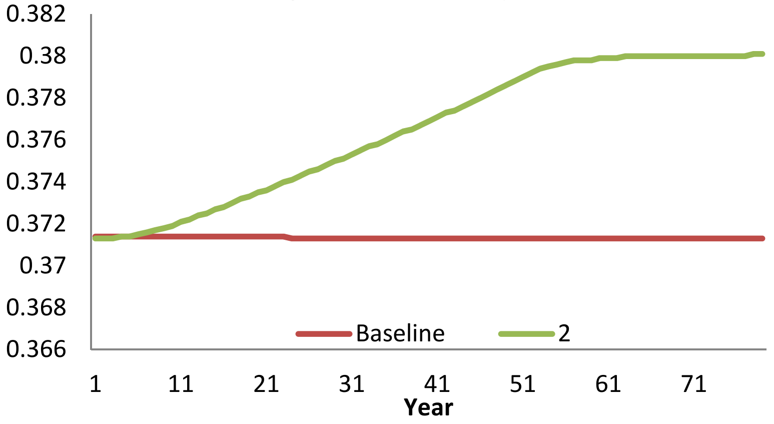
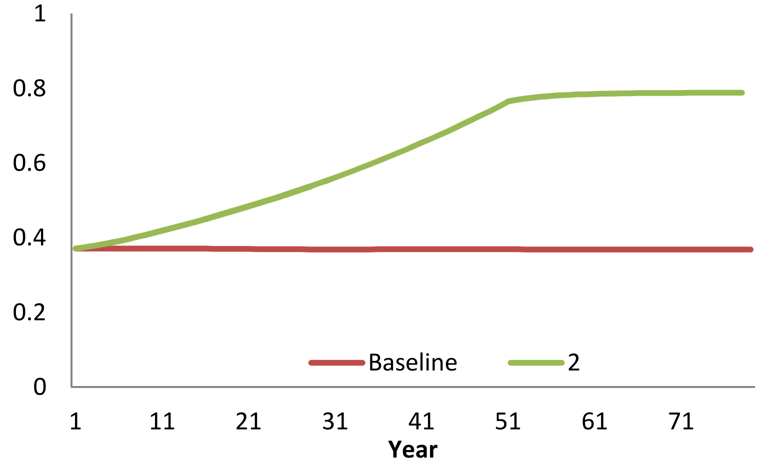


Figure 2-4 Price of Capital

Figure2-5 Price of Labor



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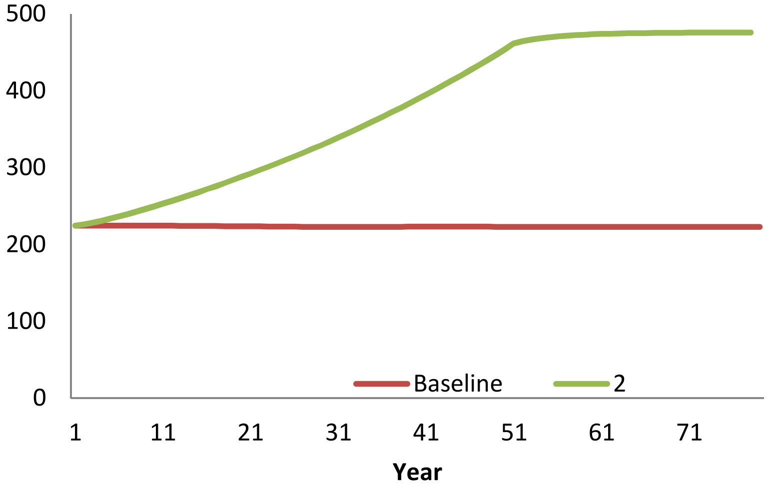

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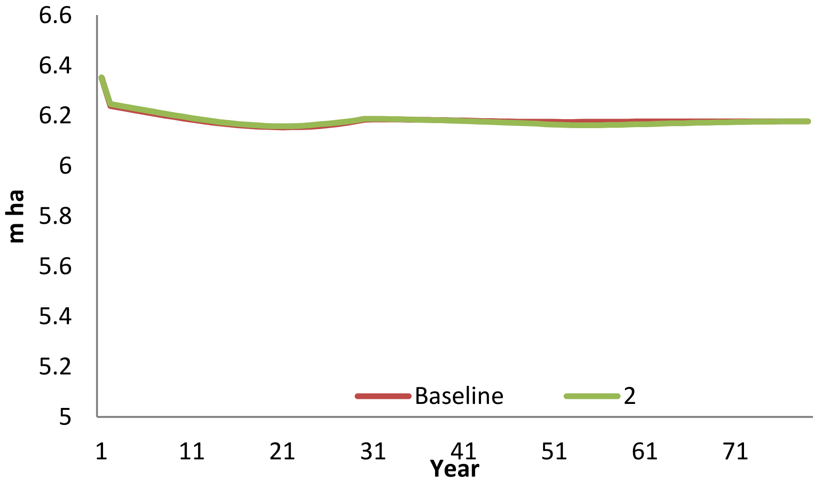
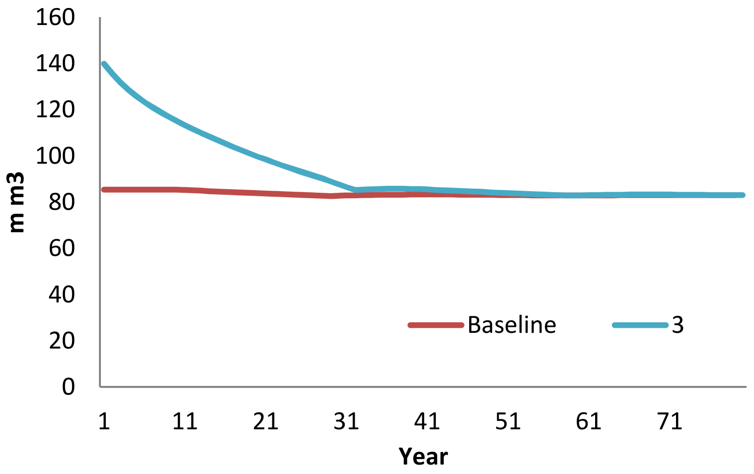


Figure 3-1 Path of Timber Demand



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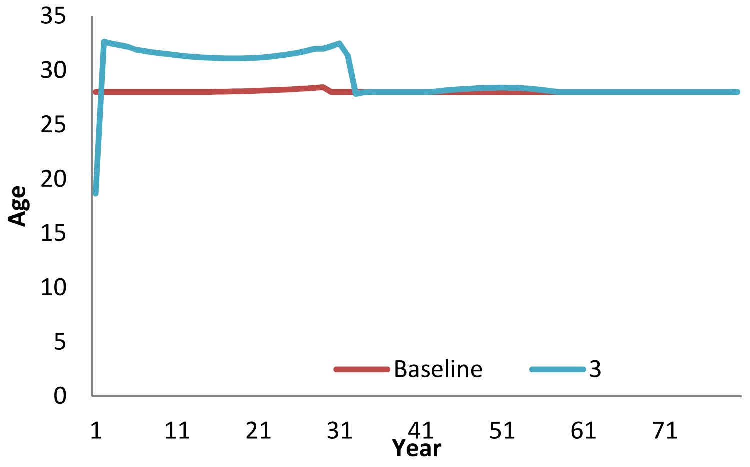

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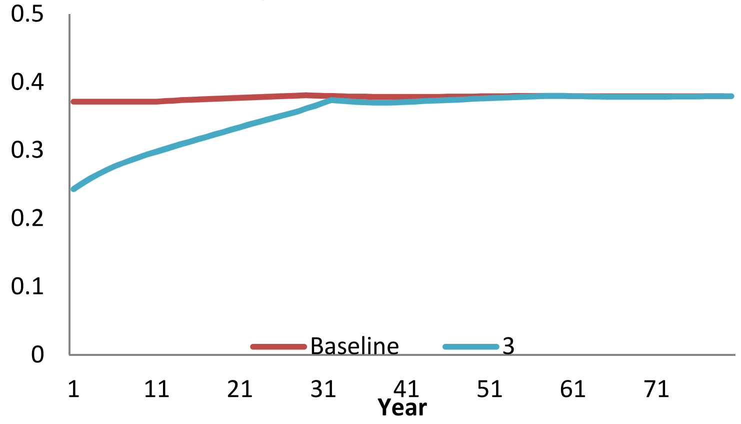

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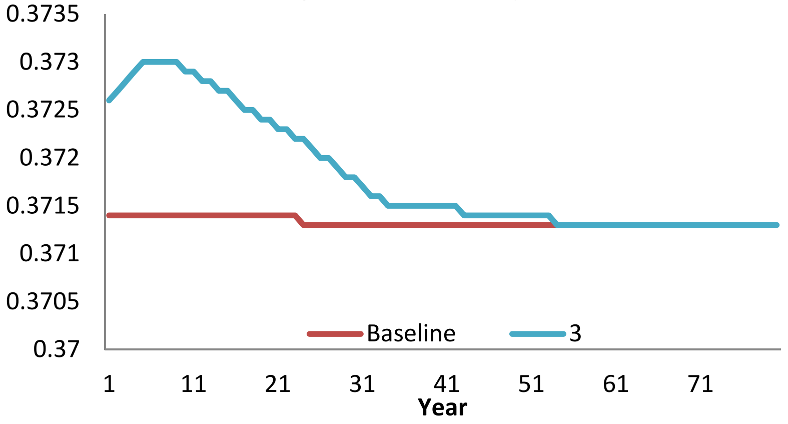

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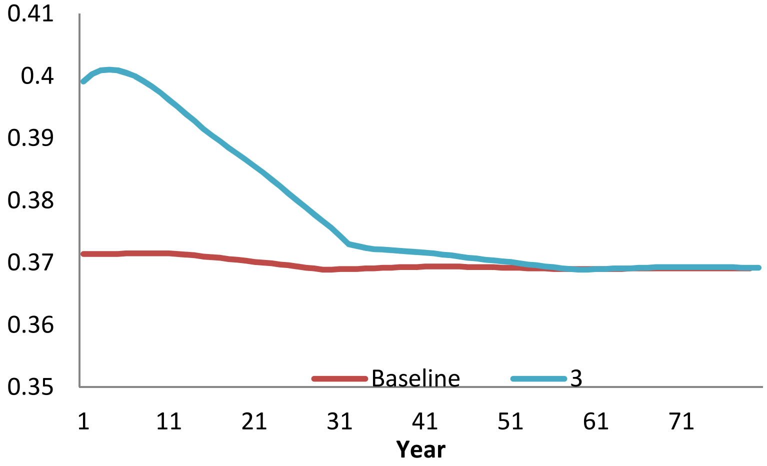

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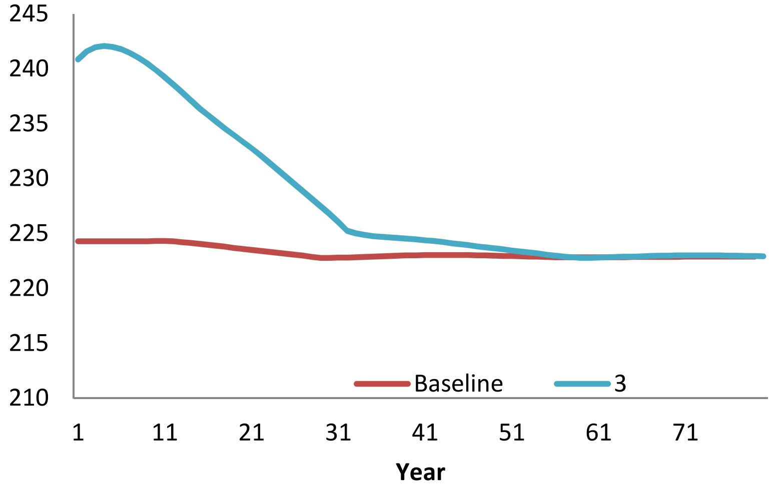

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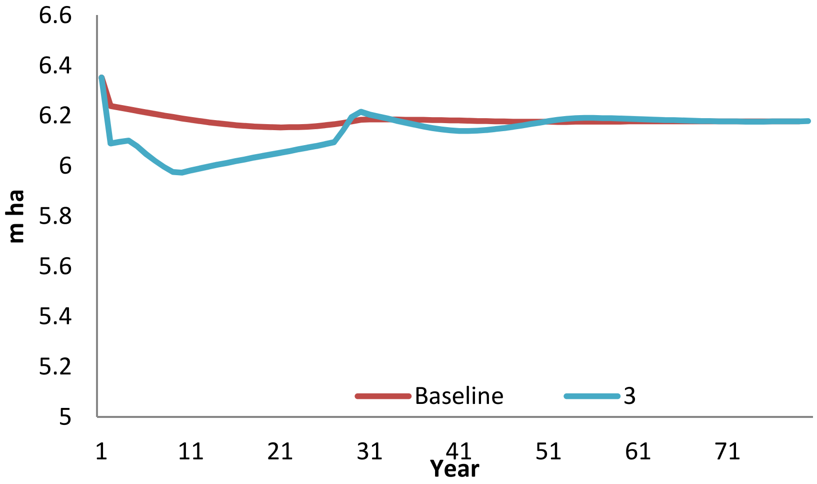


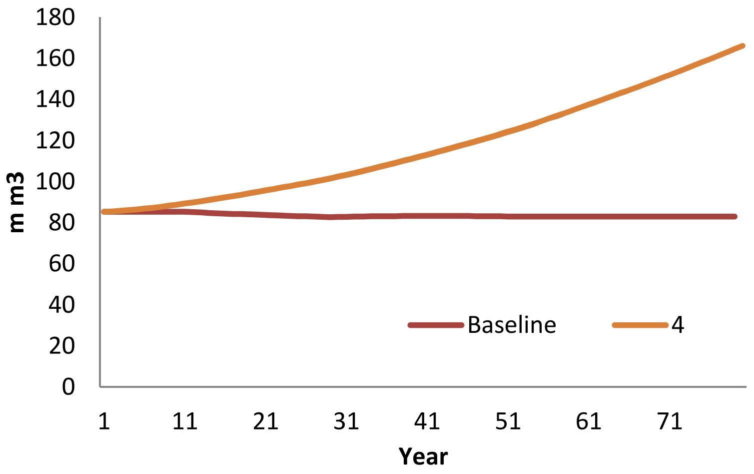


Figure 4-1 Path of Timber Demand

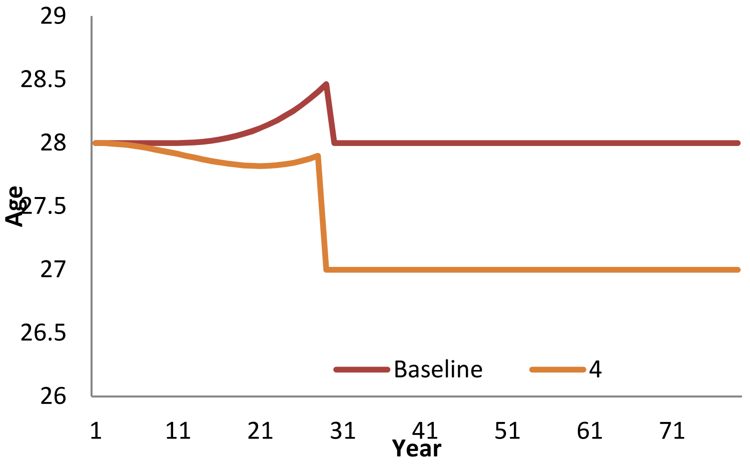


Figure 4-2 Path of age at harvest

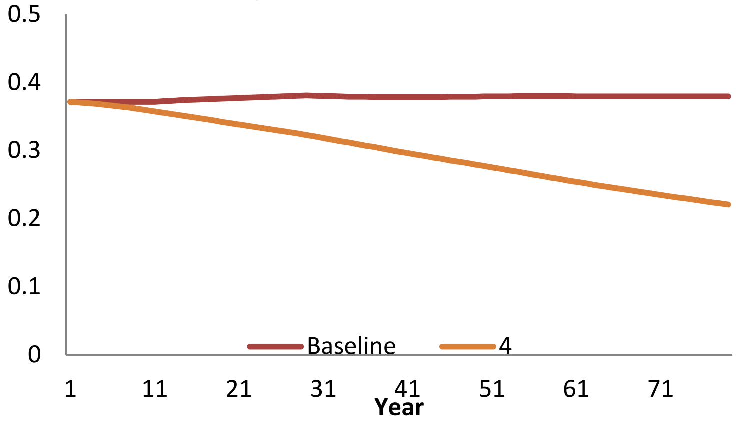
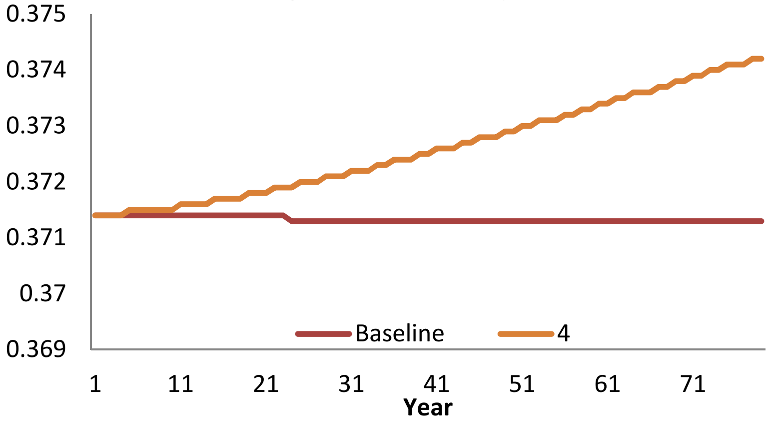


Figure 4-3 Price of Timber



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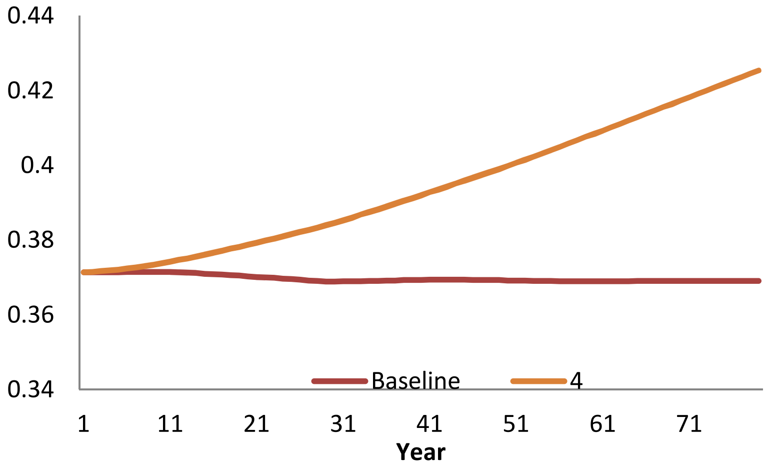
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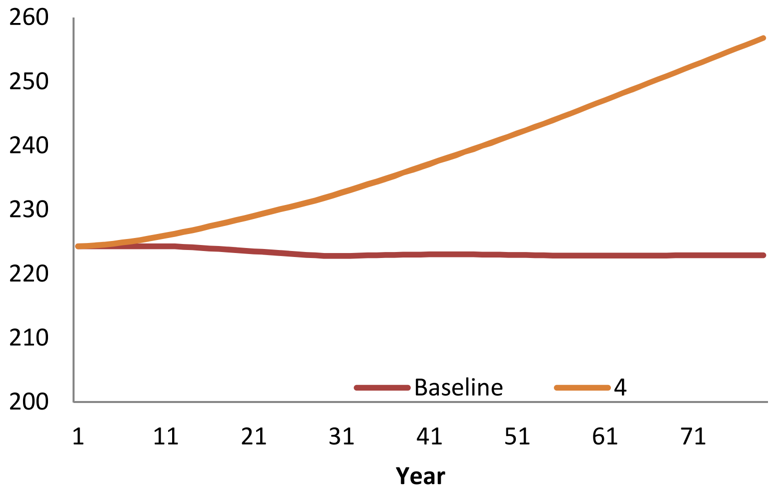
Figure 4-6 Consumption

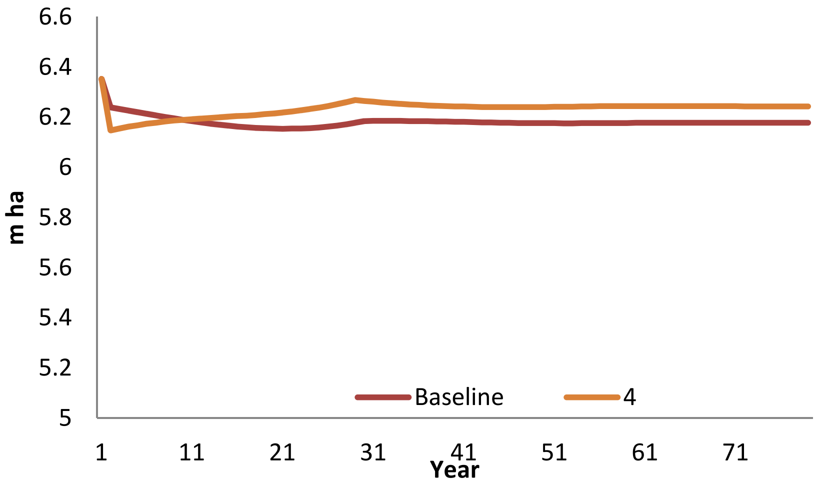
Figure 4-7 Path of Timberland