Journal of the Korea Academia-Industrial
cooperation Society
Vol. 14, No. 3 pp. 1164-1170, 2013

http://dx.doi.org/10.5762/KAIS.2013.14.3.1164

# The Optimal Harvest Scheme for Pine Trees When Carbon Value Is Considered

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# 탄소가치를 고려한 소나무림의 최적관리 방안

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**Abstract** Since trees sequestrate carbon and reduce the level of its concentrations in the atmosphere, forests should be considered as carbon pools as well as timber producers. This study focuses on finding optimal harvest age when carbon sequestration from trees is accounted by forest managers. A dynamic programming employs a static volume matrix, and solves the harvest decision problems. If carbon value is accounted in a tree harvest decision model, the optimal harvest age increases. The harvest age of pine trees set by the government for national forests is longer than the optimal solution. It is possible to say that the managers of national forests put more values on the standing pine trees than the value of carbon sequestration. The regulation for private forests, on the other hand, ends up in a shorter harvest age than the optimal solution, and this discrepancy could lead to an inefficient private forest management.

**요 약** 나무는 대기 중의 탄소를 흡수하기 때문에 산림은 목재의 생산지로서만 아니라 탄소저장고로 고려되어야한다. 이 연구는 산림의 탄소흡수 역할을 고려한 최적 벌채연령을 찾는 데 중점을 두고 있다. 관리방법별·연령별 재적자료를 이용하였으며, 문제해결을 위해 다이나믹프로그래밍을 적용하였다. 그 결과 벌채연령은 탄소의 가치를 고려하지 않은 경우보다 늘어나는 것으로 분석되었다. 그러나 정부가 규정하는 국유림 소나무에 대한 벌채연령보다는 짧은 것으로 나타났다. 따라서 국유림 소나무에 대한 정부의 관리에는 탄소흡수에 대한 가치뿐만 아니라 다른 공익적 가치가 포함되어 있다고 판단할 수 있다. 반면 사유림에 대한 규정은 적정 벌채연령보다 짧은 것으로 나타났으며, 이로 인해 사유림경영에 비효율성을 초래할 수 있다.

**Key Words :** Carbon sequestration, Dynamic programming, Optimal harvest age, Silvicultural treatment

## 1. Introduction

An increasing consumption of fossil fuels in company with industrial development resulted in negative impacts on the climate, and led to the global warming, which is the most serious environmental problem. Increasing density of greenhouse gases in the atmosphere has led a 0.74 degree Celsius increment of the average temperature in the last one hundred years [1]. Reduction efforts started from 2005, when the Kyoto Protocol entered into force. Forest is recognized as the source of carbon sequestration in the Kyoto Protocol, and it can be utilized for carbon pool from afforestation, reforestation and efficient management. Afforestation and reforestation are expanding the pool by increasing forest area. Efficient management, however, is applying proper cultural treatments for volume growth of standing trees in addition to quality improvements of other public goods. Since sixty four percent of total land is made up of mountains, forest is a very important implement to reduce greenhouse gases in

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Received February 20, 2013 Revised March 6, 2013 Accepted March 7, 2013

Korea. The small size of land and rapid urbanization, however, make it difficult to expand forest area. Efficient management of forests could be the main method to increase carbon pools domestically.

The main goal of Korean forest management from 2008 is to help to make a sustainable green country complying with the global demand. The basic direction of the sustainable forest management includes making forest for timber production, for preservation of biological diversity, and for enhancement of social and economical benefits. To maintain a sustainable forest, various management schemes have been applied. One of the major schemes is 'tending forest', which is a comprehensive fieldwork including silvicultural treatments such as mowing, thinning, and nursing trees. This work could maximize public as well as economical benefits, but is not assured to be efficient if the carbon uptake is fully accounted. Since some studies insist that making forest for timber production is known to conflict with management schemes for carbon sequestration particularly [2.3], the sustainable forest management scheme such as tending forest would not fully reflect the carbon circulation.

Finding optimal harvest age or rotation period has been studied for many years after the proposal of a dynamic model by Faustmann [4]. A mathematical theory is built up by Samuelson [5]. Hartman shows the changes of optimal rotation period if the values of non-timber services are introduced in the model [6]. The solution for the profit maximization problem, which is usually shorter than that of maximum sustainable yield, is decided by comparing the present value of cutting trees with the expected profit for holding trees another period [7]. For practical solutions, various researches have been studied with dynamic programming when cultural treatments such as thinning and etc. were applied [8,9]. Recently carbon value does an important role in the decision problems [10-12]. Some other ideas, such as compromise programming which minimizes a distance function between an infeasible point and an ideal point in production possibility frontier [13], and a real options model [14] are also applied to solve the problems.

In 2009, the Korean government set up the Five Year National Plan for Green Growth and declared the objective of reducing greenhouse gas emissions by four percent below the 2005 levels by 2020. Forest is expected to play an important role in the plan. This study is designed to find an optimal forest management scheme when carbon sequestration is considered. The solution model followed by data and results will be introduced in the next section. The optimal scheme is simulated with respect to parameters such as the rate of return, the price of carbon certification, the price of timber, and the costs. The current regulations of harvest ages are compared with the optimal solutions.

## 2. The model

An infinite horizon and deterministic dynamic model for making decisions on harvesting an even-aged forest is similar to the asset replacement model [15]. Trees, which are $t$ years old, yield revenue, b(vol($t$)), from timber sale when they are harvested. It is also assumed that new trees are planted right after the harvest. $C$ represents cost of harvest and reforestation, and is assumed to be constant. The annual carbon credits, a($t$), will be paid at the end of the year. The total amount of carbon credits returned is represented by d($t$). The state variable is the stock of forest volume(vol) at the end of each year, and it is bigger than zero and smaller than or equal to biological volume limit. The area, therefore, is always filled with trees, and they do not grow forever.

$$0 < vol(t) < \overline{vol}$$

Each year a manager needs to make a decision whether he/she will harvest trees or leave them for another year. There are two choices for the action variable that are not quantifiable.

$$x \in \begin{cases} replace \\ keep \end{cases}$$

The state transition function can be expressed as follows.

$$g(vol(t), x) = \begin{cases} vol(1), & \text{if } x = replace \\ vol(t+1), & \text{if } x = keep \end{cases}$$

If a manager decides to harvest trees, the volume of next period is vol(1). If his/her decision is to leave them for another period, the expected volume becomes vol($t$+1). The reward function, consequently, is

$$f(vol(t),x)=\begin{cases} b(vol(t))-C-d(t), & \text{if } x=replace \\ a(t), & \text{if } x=keep \end{cases}$$

It is assumed that all the carbon absorbed by the trees is released when the trees are harvested. Each year carbon sink credits are accumulated, but they are returned at once with harvest ([14]). Carbon sink credits at time $t$ can be calculated as

$$a(t)=P_{CO_2}\triangle vol(t)$$

where $P_{CO2}$ is the price of carbon sink credit, and Δ vol($t$) is the increased volume from year $t$. The sum of carbon sink credit, A($t$), is the total credit value at time $t$, if the trees are not harvested.

$$A(t)=\sum_{k=0}^{t-1}(1+\delta)^k P_{CO_2}\triangle vol(t-k)$$

The returned credits from carbon discharge, however, are calculated as

$$d(t)=\sum_{k=0}^{t-1}P_{CO_2}\triangle vol(t-k)$$

The benefits from carbon absorption are the difference between the sum of present credit value at time $t$ and the sum of current credit value, if the price of carbon does not change over the time horizon, consequently.

The value of trees at age $t$ satisfies the Bellman equation as follows.

$$V(t)=\max\left\{\begin{matrix} b(vol(t))-C-d(t)+\delta V(vol(1)), \\ a(t)+\delta V(vol(t+1)) \end{matrix}\right\}$$

Harvesting trees yields revenue from timber sale, but loses carbon sink credits. On the other hand, keeping trees for another period gives carbon sink credits corresponding to the annual volume increase. Without carbon sink credits as well as returned credits, the equation transfers to the classical tree harvest problem.

To calculate the amount of carbon absorbed from trees, it is required to divide standing trees into two aspects: the above-ground part and the root. Usually experiments of carbon sequestration focus on the stem. The amount of carbon absorbed depends on the dry weight of the stem, and it is known that a 50% of the dry weight is the amount of the carbon absorbed from stem. The calculated dry weight of the stem can be extended to the whole part of trees above the ground including crowns with well known index. Since the dry weight of stem can be expressed as stem volume multiplied by density, the equation for the amount of carbon absorbed from the above-ground part ($S_{CO2}$) is

$$S_{CO_2}=vol(t)\times stem\,density\times extension\,index\times 0.5$$

The pine tree, the subject of this study, has a stem density of 0.367 [16]. The extension index usually is about 2.0 for the young tree. It, however, decreases as the dry weight of stem increases, and stops at 1.5 after 10 years old [16]. There is no research on the carbon absorption from the root for the pine tree. In this study it is assumed that roots can sequestrate one fifth of carbon absorbed from the above-ground part [17].

## 3. Data

The volume data of an even-aged pine forest, made by Kim et al. [18], is adopted for this research. The data is not made from a single biological transition function but from a complicated dynamic stand growth model. The model gives different yields to each thinning age and each thinning rate. The data, thus, is included as a tabular form rather than produced by a transitional function in the model. For this study the beginning conditions are assumed that the ages of standing trees are ten, the heights are 4.5 meters, and the diameters at breast height are 4 centimeters. At the beginning stage 3,000 trees are planted. The site index of the target forest is 12.

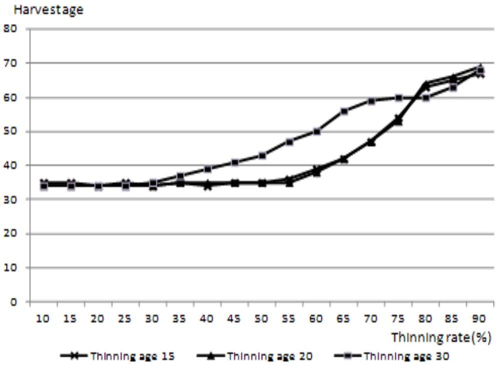
Since all silvicultural treatments could not be quantifiable, it is assumed that thinning is the only treatment that has direct influence on the volume growth and carbon sequestration. Before harvesting trees, the manager usually thins immature trees out to improve the growth rate of the remaining trees. Thinning is usually conducted twice. The first one, called ‘tending young trees’, is exercised at the age of 8～12, and the removal rate is in between 20% and 30% of all trees. The second one is taken place between 15～30 years old. Its rate varies from 10% up to 90%. Since the solution method to find the optimal harvest age is a non-stochastic discrete form, and the data from tabular forms are also discrete, it is assumed that the first thinning rate is 20% or 30% for the age of 10～12. The intensities of the second thinning are divided into 17 different rates from 10% to 90% with increments of 5% point for the age between 15 and 30.

Two different timber prices, which are drawn from the homeForest Products Distribution Information System, are applied to calculate the revenue from timber sale. The high timber price is KRW 58,000 per cubic meter, which is the producer price of the second grade timber of diameter 12～18cm. On the other hand, the low price, KRW 48,000 per cubic meter, is the producer price of timber traded without standardized size, and timber of this grade is usually used for producing chips or pellets. Timber products from 30 years old or younger trees have not enough diameters to make the second grade timber. The low price is applied for this age group. For the group with over 30 year old trees, on the other hand, the weighted average between high price and low price is applied according to the experimental result. which gives the second grade timber production ratio in a given forest. The result says that the 40 year old forest with a 74% thinning rate produces 67.9% of the second grade timber, a 46% thinning rate producing 29.8%, and no thinning producing 3.9% [19]. For the missing thinning rates, linear interpolation methods are applied to make the production ratios. The price of carbon dioxide is $\$3.9/tCO_2$, which is the average price of CDM market in 2011 [20]. The transition ratio of carbon into carbon dioxide is 44/12, and the calculated carbon price is \$1.06/tC. An average of 2011 daily final exchange rate of the US dollar is applied to convert the carbon dioxide price into Korean currency.

The costs of treatments are represented by labors per hectare [21], and the labor cost is KRW 41,218 per labor [22]. The first thinning, which is tending young tree, requires 19.5 labors per hectare equivalent to KRW 803,751/ha. The second thinning needs 16.7 labors. The labor for harvest and reforestation is 64.6, and the cost is KRW 2,662,683/ha.

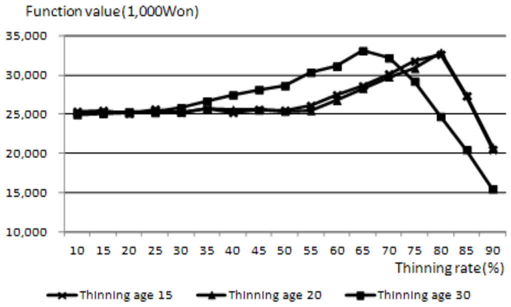
## 4. Results

For the solutions of the problem, MATLAB(ver. 2009a) is used, and an iteration method is applied. Six sheets of data composed of 26,112 observations from 1,536 by 17 matrix are prepared to draw optimal solutions from 272 (16 by 17 matrix) suboptimal harvest ages for six different first thinning cases. Figure 1 shows suboptimal harvest ages for the second thinning ages 15, 20 and 30 when the first thinning age is 10 and the thinning rate is 20%. Suboptimal ages increase as the second thinning rates go up. This tendency is consistent with other cases. For the second thinning rates between 10% and 30%, the best suboptimal harvest ages are 34 or 35 years old. The higher the second thinning rate is, the longer harvest age goes.



[Fig. 1] Suboptimal harvest ages for each second thinning rate with 20% first thinning rate at 10.

With 20% of first thinning rate at age 10, the highest function values of each second thinning rate appear at age 15 or 16 for the lower levels between 10～25%. The highest values for the higher levels, however, are found at age 30 until the thinning rates lie in between 30～65%. Then the second thinning age of the highest function values decreases to 29 for 70%, and 20 for 90%. For 20% of the first thinning rate at age 10, the best suboptimal harvest age is 60, and the best suboptimal second harvest rate is 70%. The best suboptimal harvest ages, the second thinning rates and ages are the same for the 20% of the first thinning rate at different ages 10, 11 and 12. The function values, however, are slightly different among three cases. The best suboptimal solutions for 30% of first thinning rate at age 10 and 11 are the same. The harvest age is 61, and the second thinning should be done at 15 with 75% rate. The solutions for the first thinning age at 12, however, are the same with 20% of first thinning rate cases (Table 1). When the function values are compared, the management schemes with 20% of the first thinning rate have higher values than 30%, and the first thinning age at 10 has the highest value.



[Fig. 2] Function values for each thinning rate with 20% first thinning rate at age 10.

The higher second thinning rate increases volume as well as quality of timber. A seventy percent of thinning rate will make about 60% of the second grade timber from all products. Strong thinning may apply to the forest for the volume growth, which is an important factor to the timber production as well as carbon absorption.

If carbon is not accounted in the decision model, the optimal harvest age is 56, when the first thinning rate is 30% at age 10. The optimal harvest age is four years shorter than the previous case. The results are different from the previous study by Lee et al. (2011). Different data and assumptions applied between two studies may lead to different results. The optimal harvest age, however, becomes older when carbon value is considered in both models.

[Table 1] Optimal solutions for different first thinning cases of pine tree

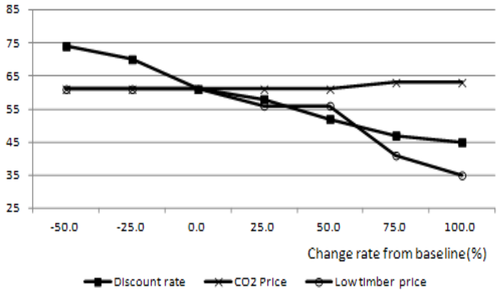
| 1st thinning rate(%) | 20 | | | 30 | | |
|---|---|---|---|---|---|---|
| 1st thinning age | 10 | 11 | 12 | 10 | 11 | 12 |
| optimal harvest age | 60 | 60 | 60 | 61 | 61 | 60 |
| optimal harvest rate(%) | 70 | 70 | 70 | 75 | 75 | 70 |
| optimal thinning age | 29 | 29 | 29 | 15 | 15 | 29 |
| Function value*(KRW1,000) | 10,230 | 10,227 | 10,229 | 9,850 | 9,840 | 9,977 |

* Function values are converted into the present values to compare between different harvest ages.

## 5. Simulations

For comparative analysis of the decision rules, different values of the discount rate, the lumber prices, and the costs are applied. Discount rate is a very important factor for a investment decision. If the discount rate goes up, the value of the investment object will be discounted faster than the lower rate case. Keeping asset is not a good strategy to the investors in this case accordingly. In the tree harvest decision model, the higher discount rate increases, the faster optimal harvest age arrives. The optimal harvest ages for different discount rates are found on a scale of 0.01%~0.04%, in 0.005 increments, and the ages decrease from 74 to 45 with increments of discount rates.

The price of carbon dioxide has a positive relationship with the optimal harvest age. This means that optimal harvest age goes up if annual additional value of the standing tree is increased. As seen in the figure 3, rising price of carbon dioxide up to 75% from the baseline, \$3.70, increases the optimal harvest age from 60 to 63. If the price moves up to \$10/t$CO_2$, which is 170.3% increase from the baseline, the optimal harvest age increases to 71.



[Fig. 3] Variations of harvest age to parameter changes from the baseline.

The relatively higher price of timber to carbon cuts slightly down the optimal harvest age. If the price is increased to KRW 88,000/㎥ from KRW 58,000/㎥, the optimal age does not change. An increment of 170% from the baseline, however, reduces the optimal age to 58. A decrease of the high price, on the other hand, is not consistent, and it is hard to explain. In the lower level from the baseline the low timber price moves against the optimal harvest age, but the influence is not strong. In the higher level the low price also moves against the optimal harvest age. If the importance of bio-energy increases the prices of pellets and chips, and the high and the low timber prices flip over, then the optimal harvest age decreases from 60 to 56 with 20% increase of the low timber price, to 41 with 63% increase, and to 35 with 83% increase. The second thinning rate is also decreased from 75% to 30%. These results come from the fact that the lower harvest age and thinning rate produces more volume of the low grade timber.

Harvest and reforestation cost has a positive relationship with the optimal harvest age, since the cost recovery span takes longer when the cost is more expensive. The thinning cost, however, does not change harvest age even with 200% increase. This would result from relatively less expensive thinning cost that does not need to alter harvest age to recover.

## 6. Concluding Remarks

There are many ways to find an optimal harvest age of a standing forest problem. In this study, a deterministic dynamic model which is similar to the asset replacement method is applied. Among several cultural treatments, thinning is the only work to be quantified in this study, and it is basically assumed to be applied twice in a lifetime. Although it is not able to reflect all the real circumstances, we may be able to draw some meaningful implications by comparing the results with the regulations applied to the pine tree harvest. The Korean government recommends standard pine tree harvest age of 70 years for national forests and 50 years for private forests. The optimal harvest age from the dynamic programming is 60 years. If the dynamic model is applied to find harvest age without accounting carbon, the optimal harvest age is 56. The optimal harvest age depends on the managers' value on the forest. The higher the optimal harvest age is, the more value is placed on by forest managers. There exist some discrepancies between the optimal solutions and the regulations. Intentionally or accidentally the government puts more values other than carbon sequestration in managing national forests. However, it does not place enough values in private forests even for timber production, and this could lead to an inefficient use of forest resources of private forests, which accounted for 68% of total forests in 2010. To remove the efficiency the government can extend the harvest age, and provide some monetary compensations such as direct payments to private forest managers for providing non-timber services.

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