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Carbon pricing through subsidy payment for thinning activities in Japan

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Abstract
Carbon pricing was conducted through the subsidy payment for thinning activities in Japan within the optimization framework for the forest stand management. The optimal forest stand management model called DP-KYSS (dynamic programming model for Kyushu stand simulator) was utilized for the analysis of a sugi (Cryptomeria japonia) forest stand in the Kyushu region, Japan. The analyses showed that the thinning subsidy activated thinning activities with the reduction of carbon sequestered in a forest stand. Considering subsidies as a compensation for carbon loss by thinning, the evaluation of carbon showed that the present net value of cost per unit carbon loss became the highest for the rotation age of 35 years and the minimum for the rotation age of 50 to 65 years dependent upon the subsidy measure. At the rotation age of 100 years, the present net value of cost per unit carbon loss was found to be 44.56 to 110.13 Euro/Ct. The analyses showed that lengthening the period for subsidy would reduce the value of carbon. Subsidy pays more with more thinning reducing carbon sequestered in a forest stand.

Key words: Carbon evaluation, carbon pricing, thinning subsidy, dynamic programming, calculus of variation

Introduction

During the 1960's, the large scale of artificial forests were established by the lead of Japanese Forestry Agency with plantation subsidy to encourage forest owners for plantation activities. Since then, the subsidy payment has continued for plantation as well as thinning activities. This is to let private forest owners sustain their forestry practices including tending, weeding and thinning to satisfy the future domestic timber demand as well as multiple purpose benefits from forest resources under management at the same time. The recent decrease in timber price, is however discouraging them, and impinges on the sustainable forest management for a large amount of artificial forests. Current phenomena regarding the forest management is such that thinning tends to cease while final harvest tends to be postponed longer than we expected.

Several policy measures have been proposed with subsidies for thinning activities within the framework of the sustainable forest management in Japan. The current thinning subsidy is provided for forest stands with the age older than 10 years and younger than or equal to 35 years. Since the fiscal year of 2000, as a remedy for non-thinned or unmanaged forest stands older than 35 years, an additional subsidy as an emergency political action was proposed to forest stands up to age younger than or equal to 45 years from the fiscal year of 2000 to 2004. Currently, extending the subsidy period is under consideration.

While much of attention has been paid to the sustainable forest management, the global warning issue also became one of the serious environmental concerns internationally as well as domestically. After forests under management were considered as carbon sink by Article 3.4 of the Kyoto Protocol (UNFCC 2005), Japanese Forestry Agency has started to look for an opportunity to enhance thinning activities as well as other management activities required. At the same time, the emission trading under the Kyoto Protocol became active with carbon credits issued to forests. This trading is one of alternatives for a nation to meet the target of emission reduction.

In this paper, carbon pricing is conducted through subsidy payment for thinning in Japan within the forest stand optimization framework. Since thinning activities affect the amount of carbon sequestered by a forest stand, the subsidy payment for thinning can be regarded as a compensation for changing the amount of the credits. We evaluate how much is paid for the unit carbon change from a forest stand at the rotation period. The optimal forest stand management model called DP-KYSS (dynamic programming model for Kyushu stand simulator) is utilized for the analysis with a sugi (Cryptomeria japonia) forest stand growth simulator in the Kyushu region, Japan. The growth simulator is the stand density management diagram. The MSPATH (multiple stage projection alternative technique) algorithm is implemented in the optimization phase.

The dynamic programming approach has been developed and extensively applied due to its dynamic nature of forest stand growth (Arimizu 1958a, b; Amidon & Akin 1968; Schreuder 1971; Kilkki & Väisänen 1970; Adams & Ek 1974; Brodie et al. 1978; Brodie & Kao 1979; Chen et al. 1980; Martin & Ek 1981; Riitters et al. 1982; Brodie & Haight 1985; Haight et al. 1985; Valsta & Brodie 1985; Arthand & Klemperer 1988; Torres & Brodie 1990). While the curse of dimensionality had been the main problem for these early applications of dynamic programming, Paredes & Brodie (1987) introduced a new dynamic programming algorithm called PATH (Projection Alternative Technique) within the framework of both network theory and the theory of the Lagrange multipliers to resolve the problem. The shortcoming of PATH was pointed out by Yoshimoto et al. (1988) in considering a long-term effect of thinning activities on the objective function. The MSPATH (Multiple Stage PATH) algorithm was developed to overcome the problem by considering all possible future path combination.

The paper is organized as follows. In the second section, the MSPATH algorithm is mathematically elaborated, followed by the description of a growth simulator for sugi forest stands in the Kyushu region, Japan in the third section. In the fourth section, carbon pricing is conducted with DP-KYSS using the data collected from our study plot. Some concluding remarks are provided in the last section.

Dynamic Programming Modeling

The DP formulation by PATH and MSPATH can be described by a canonical problem of the calculus of variations (Intriligator 1971). Let x(t) be a state variable representing a forest stand at time t, and $\dot{x}(t)$ be its first derivative with respect to time t. Introducing a marginal function of the objective for the management over time, $\pi(\cdot)$, an optimal solution is sought by maximizing its integral from the initial state (plantation) x0 at time t0, to the ending state (final harvest) xn at time tn with respect to a control variable, $\dot{x}(t)$.

$$\max_{\{\dot{x}(t)\}} J = \int_{t_0}^{t_n} \pi(x(t), \dot{x}(t), t)\, dt$$
$$x(t_0) = x_0$$
$$x(t_n) = x_n \qquad (1)$$

For the thinning management problem, only thinning intensity, T(t) at time t affects x(t) and $\dot{x}(t)$, so that the control variable in the above equation (1) can be replaced by thinning, T(t) as follows,

$$\max_{\{T(t)\}} J = \int_{t_0}^{t_n} \pi(x(t), T(t), t)\, dt$$
$$x(t_0) = x_0$$
$$x(t_n) = x_n \qquad (2)$$

where T(t) is the intensity of thinning at time t. In order to convert the objective function into the discrete thinning problem for $(t = t_0, t_1, \cdots, t_n)$, we have,

$$\max_{\{T(t_i)\}} J = \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} \pi(x(t), T(t_{i-1}), t)\, dt$$
$$x(t_0) = x_0$$
$$x(t_n) = x_n \qquad (3)$$

Defining

$$\Pi(x(t), T(t), t) = \int \pi(x(t), T(t), t) dt \qquad (4)$$

the objective function of equation (3) becomes,

$$\begin{aligned}\max_{\{T(t_i)\}} J &= \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} \pi(x(t), T(t_{i-1}), t)\, dt \\ &= \sum_{i=1}^{n} \{\Pi(x(t_i), T(t_{i-1}), t_i) - \Pi(x(t_{i-1}), T(t_{i-1}), t_{i-1})\}\end{aligned} \qquad (5)$$

Let us introduce the contribution value of thinning, $T(t_i)$, to the objective by $V(T(t_i))$ defined by,

$$V(T(t_i)) = \Pi(x(t_i), T(t_{i-1}), t_i) - \Pi(x(t_i), T(t_i), t_i) \qquad (6)$$

The first term of the right-hand side is the contribution value of a forest stand, $\Pi(\cdot)$, at time ti after having thinning $T(t_{i-1})$ at time ti-1 and the second term is that just after having thinning $T(t_i)$ at time ti, so that the difference, $V(T(t))$, is the contribution of thinning to the objective or the return from thinning. Inserting equation (6) into equation (5), we have

$$\begin{aligned}\max_{\{T(t_i)\}} J &= \sum_{i=1}^{n} \{\Pi(x(t_i), T(t_{i-1}), t_i) - \Pi(x(t_{i-1}), T(t_{i-1}), t_{i-1})\} \\ &= \sum_{i=1}^{n} \{\Pi(x(t_i), T(t_{i-1}), t_i) - \Pi(x(t_{i-1}), T(t_{i-2}), t_{i-1}) + V(T(t_{i-1}))\} \\ &= \sum_{i=1}^{n} \{\Pi(x(t_i), T(t_{i-1}), t_i) + V(T(t_{i-1})) - \Pi(x(t_{i-1}), T(t_{i-2}), t_{i-1})\}\end{aligned} \qquad (7)$$

By assuming that thinning at time (ti-1) only affects the objective value until time ti over one stage, the optimality equation within the DP optimization framework becomes

$$\begin{aligned} f_i^* &= \max_{\{T_{i-1}\}} \{f_i(T_{i-1})\} \\ f_i(T_{i-1}) &= \Pi_i(T_{i-1}) + V(T_{i-1}) - \Pi_{i-1}^*(T_{i-2}) + f_{i-1}^* \end{aligned} \qquad (8)$$

where $T_i = T(t_i)$ is the intensity of thinning at time ti, $\Pi_i(T_{i-1}) = \Pi(x(t_i), T(t_{i-1}), t_i)$ is the contribution value of a forest stand at time ti after having thinning Ti-1 at time ti-1, $V(T_i) = V(T(t_i))$ is the contribution value of thinning Ti at time ti, $\Pi_i^* = \Pi_i(T_{i-1}^*)$ is an optimal contribution value of a forest stand at time t after having optimal thinning T_{i-1}^* at time ti-1.

The PATH algorithm assumes that thinning only affects the objective value until the next possible thinning period, i.e., one stage look-ahead. By considering influence of thinning over multiple periods, i.e., multiple stage look-ahead, on the other hand the optimality equation of MSPATH becomes,

$$\begin{aligned} f_i^* &= \max_{\{T_{i,i-j}, j\}} \{f_{i,i-j}(T_{i,i-j})\} \\ f_{i-j}^i(T_{i,i-j}) &= \Pi_i(T_{i,i-j}) + V(T_{i,i-j}) - \Pi_{i-j}^* + f_{i-j}^* \end{aligned} \qquad (9)$$

This is to search for an optimal intensity of thinning as well as an optimal elapse of the stage, j, for two sequential thinning over multiple stages. Note that Ti,i-j is the intensity of thinning at time ti-j with the elapse of the stage j from the i-th stage, $\Pi_i(T_{i,i-j})$ is the contribution value of a forest stand at time ti after having thinning Ti,i-j at time ti-j, V(Ti,i-j) is the contribution value of thinning Ti,i-j implemented at time ti-j, j* is an optimal elapse of the stage from the i-th stage, $T^*_{i,i-j}$ is an optimal intensity of thinning at time ti-j targeting time ti, $\Pi^*_i = \Pi(T^*_{i,i-j})$ is the contribution value of a forest stand at time t_i after having thinning $T^*_{i,i-j}$ at time ti-j. Unlike PATH, MSPATH searches for not only an optimal intensity of thinning but also an optimal elapse of the stage for two sequential thinning activities. Nonetheless, both algorithms search for an optimal solution by maximizing the sum of the contribution value of a forest stand and thinning. Figure 1 shows the dynamic programming network for MSPATH for the four stage case. All combinations of thinning intervals are also compared for an optimal solution.

algorithm

Growth Simulator for Sugi Forest Stands

A growth simulator used here is the stand density management diagram for sugi (Cryptomeria japonica) forest stands in the Kyushu region, Japan. The main concepts of the model is in Ando (1966). The current number of trees per ha, N, and the dominant height, H are required to determine other elements of a forest stand as follows. Note that parameters were site specific to the Kyushu region and determined in Rinyacho (1980).

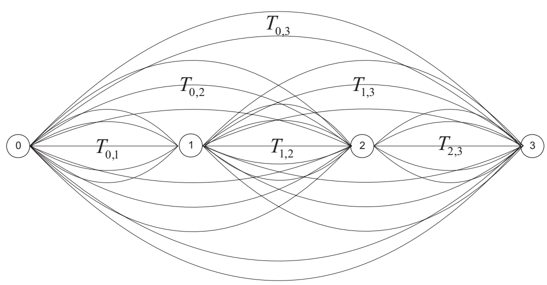


Figure 1. Dynamic programming network for the MSPATH

1) An average individual tree volume

$$v(N,H) = \frac{1}{0.068509N \cdot H^{-1.347464} + 2658.2 \cdot H^{-2.814651}} \qquad (10)$$

2) An average forest stand volume per ha

$$V(N,H) = v(N,H) \cdot N \qquad (11)$$

3) A forest stand height

$$HF(N,H) = 0.791213 + 0.244012H\sqrt{N}/100 + 0.353895H \qquad (12)$$

4) A basal area per ha

$$G(N,H) = \frac{V(N,H)}{HF(N,H)} \qquad (13)$$

5) An average diameter for a given basal area

$$\overline{D}g(N,H) = 200\sqrt{\frac{G(N,H)}{\pi \cdot N}} \qquad (14)$$

6) An average DBH (diameter at breast height) for the dominant trees

$$\overline{DBH}(N,H) = -0.048940 - 0.034814H\sqrt{N}/100 + 0.98937\bar{D}g(N,H) \quad (15)$$

7) The maximum tree density per ha in the log-transformed expression

$$\log_{10} N_{Rf}(H) = 5.3083 - 1.4672\log_{10} H \quad (16)$$

8) The volume at the maximum tree density

$$V_{Rf}(H) = \frac{N_{Rf}(H)}{0.068509N_{Rf}(H)\cdot H^{-1.347464} + 2658.2H^{-2.814651}} \quad (17)$$

9) Self-thinning relationship as a function of an average individual tree volume and the number of trees planted, N0

$$\frac{1}{N} = \frac{1}{N_0} + \frac{v(N,H)}{3.47089\times 10^6 N_0^{-0.9184}} \quad (18)$$

As can be seen from the above set of equations to describe a forest stand, the current number of trees per ha, N, and the dominant tree height, H, are enough to predict future growth of a forest stand. The dominant tree height in this paper was assumed to follow the Richards function (Richards 1958) with a time component.

Parameters of the Richards function were estimated with the field data collected from our study plot in Hoshino Village, Fukuoka Prefecture, located in the Kyushu region of Japan. Our study plot was a 23 years old sugi (Cryptomeria japonica) stand without previous thinning. The number of trees in the plot was 136 per 0.0466 ha. Thirty trees were thinned for the stem analysis. The average DBH of all sampled trees was 15.66cm with a standard deviation of 2.25cm, the average height was 14.82m with a standard deviation of 1.22m, and the average individual tree volume was 0.15m3 with a standard deviation of 0.055m3. Using the results of the stem analysis on the height growth, we estimated parameters of the Richards function with the following

$$H = 24.95(1-e^{-0.064\cdot t})^{1.97} \quad (19)$$

The amount of carbon sequestered in a forest stand was estimated by the following equation (see Matsumoto, 2001),

$$Wc = \rho_0 \times V \times E \times Coef \quad (20)$$

where Wc (Ct) is the amount of carbon sequestered, ρ0 is wood density (g/cm2), V is stem volume (m3), E is an expansion factor (here specified by 1.7), and Coef is a coefficient of carbon content (g/Ct: here specified by 0.5). Based on wood density estimation for the study plot, we obtained an average of 0.3372, so that carbon sequestered in trees was calculated by

$$Wc(Ct) = 0.3772 \times V \times 1.7 \times 0.5 \quad (21)$$

Table 1. Basic Settings for Optimization by DP-KYSS

1. A forest stand condition	
Stand Age	0 (year)
Plantation Density	3000 (trees/ha)
Discount Rate	1 %
Felling Costs	70 Euro/m3
Thinning Costs	84 Euro/m3
Utility Ratio for log	65 %
2. Carbon Related	
Wood Density	0.3372 (g/cm3)
Expansion Factor	1.7
Carbon Content Coef	0.5 (gC/g)
3. Management Constraints	
Minimum Thinning Age	15 year
Minimum TPH for Felling	300 trees/ha
4. Optimization Inputs	
Objective	maximization of PNV
Thinning Interval	50 trees/ha
Stage Interval	5 years
Planning Period	100 years

Carbon Pricing Through Thinning Subsidy

Carbon pricing was conducted by investigating effects of subsidy payment on change in the objective value along with change in the amount of carbon sequestered in a forest stand at the final harvest period. The basic settings in Table 1 were used for optimization. The initial forest stand age was set to 0 year old with plantation of 3,000 trees/ha. One percent interest rate was used as the discount factor. Thinning costs were set to be 84 Euro/m3, while 70 Euro/m3 was for final harvest based on the general forest management practice in Fukuoka prefecture, Japan. Utility ratio for a log converted from a stem was assumed to be 64%. Two management constraints were set; the minimum thinning age of 15 years and the minimum trees per ha for final harvest by 300 trees. The objective for the management was to maximize the present net value of the total profits from thinning and final harvest over one rotation. As for optimization parameters, the time interval was set to 5 years and the thinning interval was set to 50 trees. Also 100 years was used as the maximum management time horizon. A tree price was assumed to be a function of DBH (diameter at breast height) given in Table 2.

Table 2. A tree price function of DBH

Range of DBH (cm)	0 - 9	10 - 13	14 - 16	17 - 22	22 or more
Price (Euro/m3)	66.20	78.87	89.44	95.07	103.52

The thinning subsidy was added to benefits from thinning activities with the present net value of thinning, Ti,i-j, at time ti-j by,

$$V(T_{i,i-j}) = [P(\overline{DBH}_{i-j}) \cdot v(N_{i-j}, H_{i-j}) \cdot N^T_{i,i-j} - C_{thin} \cdot v(N_{i-j}, H_{i-j}) \cdot N^T_{i,i-j} + Subsidy_{i-j}(N^T_{i,i-j})]/(1+r)^{t_{i-j}} \quad (22)$$

where $P(\overline{DBH}_{i-j})$ is a price per tree volume as a function of an average DBHi-j at time ti-j, Cthin is thinning cost per tree volume, and $Subsidy_{i-j}(N^T_{i,i-j})$ is the applied subsidy for thinning as a function the number of trees removed, $N^T_{i,i-j}$ at time ti-j targeting the state at the i-th stage. The discount factor is r. The present net value of harvesting a forest stand was calculated in the same way as the value of thinning without the subsidy part.

$$\Pi_i(T_{i,i-j}) = [P(\overline{DBH}_i)\cdot v(N_i,H_i) - C_{fell}\cdot v(N_i,H_i)]/(1+r)^{t_i} \qquad (23)$$

where Cfell is final harvesting cost per tree volume.

Three types of thinning subsidy used here are given in Table 3. The first one is called the current subsidy implemented from age 11 to 35 every five years, while the second is from age 11 to 45 every five years as the emergency subsidy. The last is from age 11 to 90 every five years as the extended subsidy. Subsidy is provided per unit area basis (ha) only with 10 to 20 % of standing trees for thinning. Thinning less than 10 % or more than 20 % is not considered for subsidy.

Table 3. The amount of subsidy (Euro/ha)

Age class	Current Subsidy	Emergency Subsidy	Extended Subsidy
10<Age≤15	1,331	1,331	1,331
15<Age≤20	1,331	1,331	1,331
20<Age≤25	1,331	1,331	1,331
25<Age≤30	1,894	1,894	1,894
30<Age≤35	1,894	1,894	1,894
35<Age≤40	1,894	1,894	1,894
40<Age≤45		3,345	3,345
45<Age≤50		3,345	3,345
50<Age≤55			3,345
55<Age≤60			3,345
60<Age≤65			3,345
65<Age≤70			3,345
70<Age≤75			3,345
75<Age≤80			3,345
80<Age≤85			3,345
85<Age≤90			3,345

Information Source: Fukuoka Prefectural Office, Japan

Optimal thinning regime and efficient level of subsidy

Figure 2 shows the optimal thinning regime under no subsidy and three different subsidy payments in terms of change in the number of trees over time. With no subsidy (Figure 2-a), thinning was implemented at age 15 and 20 up to the rotation age of 60 years, and additional thinning at age 55 up to the rotation age of 100 years. The thinning intensity was the same at age 15 across different rotation ages until 60 years, while less thinning intensity was observed at age 20 and more thinning intensity at age 55 for the longer rotation age than 60 years. The number of trees for final harvest with thinning activities varied from 1,322 under the rotation age of 25 years to 2,272 under the rotation age of 20 years along with 1772 trees/ha felled at final harvest in most cases. The optimal rotation age was found to be 50 years with 1,772 trees/ha for final harvest.

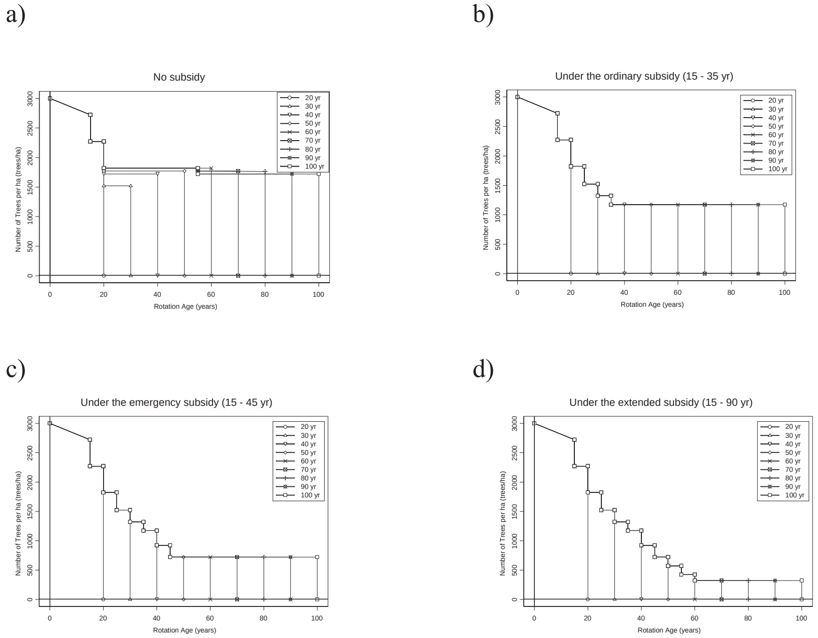
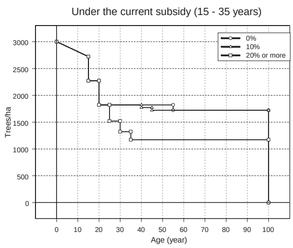


Figure 2. Optimal thinning regimes under different subsidies
a) no subsidy, b) ordinary subsidy, c) emergency subsidy, d) extended subsidy

With the current subsidy payment, thinning was implemented every 5 years whenever subsidy was provided (Figure 2-b). The same thinning regime was obtained up to age 35 with the emergency subsidy. With the emergency subsidy payment, thinning continued until age 45 years (Figure 2-c). Likewise with the extended subsidy payment, there was additional thinning until age 60, then thinning ceased afterwards due to the requirement of the number of trees for final harvest (Figure 2-d). As can be expected, the thinning subsidy payment emphasized thinning activities during the period eligible for subsidy.

The above optimal solutions were derived with the full amount of the subsidy provided. In order to investigate an effect of subsidy payment, it is necessary to search for an efficient level of the subsidy for change in an optimal thinning regime. In other words, redundant subsidy payment should be avoided to evaluate carbon through the subsidy payment. This was done by changing the level of the payment from 0% to 100% of the current amount with 10% increase. Figure 3 shows optimal thinning regimes with different subsidy payment and different percentage of the payment. From Figure 3, twenty percent of the current amount in Table 3 under all subsidy payments became efficient in terms of change in the optimal thinning regime. That is, more than twenty percent would not make any difference and became redundant for the optimal thinning regime. Thus, the following analysis applied only 20% of the payment in Table 3 to investigate effects of subsidy payment on change in the objective value.

a)



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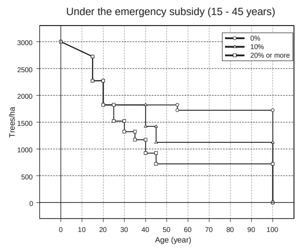

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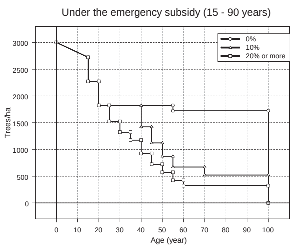

Figure 3. Effect of subsidy on an optimal thinning regime
a) current subsidy, b) emergency subsidy c) extended subsidy

Carbon pricing

Figure 4 depicts the objective value change over different rotation ages. As Figure 4 shows, the optimal rotation age became 50 years with no subsidy, the current subsidy and the emergency subsidy, while it was 60 years with the extended subsidy. Figure 5 is the amount of carbon sequestered in a forest stand at final harvest. The amount of carbon sequestered in a forest stand became the largest with no subsidy over all rotation age except 25 year rotation age. This was due to more thinning than those with subsidies. The second largest was that with the current subsidy, followed by that with the emergency and extended subsidy. The amount of carbon sequestered gradually increased over time with no subsidy and the current subsidy, while with the emergency subsidy it reached to the first peak at age 45, decreased till age 50, then increase afterwards. The same increasing and decreasing trend was observed with the extended subsidy till age 65. These decreases in the amount with the emergency and extended subsidy were due to thinning activities at rather older thinning periods stimulated by the subsidy payment. While the amount recovered more than the first peak with the emergency subsidy after age 55, it had never occurred with the extended subsidy. That is, the first peak was the maximum amount of carbon sequestered in a forest stand with the extended subsidy. At age 100, the amount became 155.59 Ct/ha, 144.22 Ct/ha, 126.22 Ct/ha, and 89.92 Ct/ha with no subsidy, the current, emergency and extended subsidy, respectively.

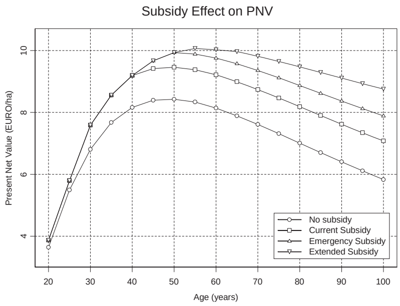

Figure 4. Present net value over different rotation ages

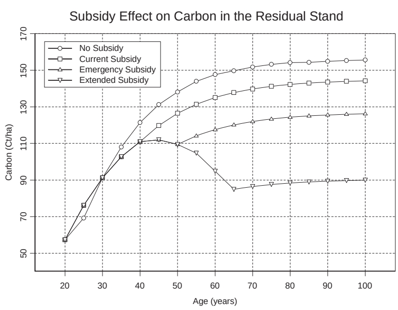

Figure 5. Total carbon sequestered in a forest stand at final harvest period

As was observed above, thinning subsidies could result in reduction of carbon sequestered in a forest stand at the final harvest period. At the same time, monetary benefits were provided as subsidies, so that we next evaluate carbon through subsidy benefits as follows. The cost of unit carbon loss, or shadow price of carbon, Cco2, over different rotation ages was first estimated on the basis of the derived optimal solution without any subsidy by,

$$C_{CO2} = -\frac{\partial J}{\partial Carbon} = -\frac{PNV(No\,Subsidy) - PNV(Subsidy)}{CBN(No\,Subsidy) - CBN(Subsidy)} \quad (24)$$

where $PNV(\cdot)$ is the present net value of the optimal thinning regime and $CBN(\cdot)$ is the amount of the corresponding carbon sequestered at final harvest period. We also estimated the annual payment, APT, over the given rotation age, T, by equating Cco2 to the sum of present net value of the annual payment over the given rotation age as follows,

$$C_{CO2} = AP_T \frac{1-(\frac{1}{1+r})^T}{1-(\frac{1}{1+r})} \quad (25)$$

Table 4. Payment for carbon

Rotation Age (years)	Cco2 (Euro/Ct)			APT (Euro/Ct/yr)		
	Current Subsidy	Emergency Subsidy	Extended Subsidy	Current Subsidy	Emergency Subsidy	Extended Su
35	167.23	167.23	167.23	5.63	5.63	5.63
40	98.16	98.16	98.16	2.96	2.96	2.96
45	88.95	65.98	65.98	2.44	1.81	1.81
50	89.07	52.65	52.65	2.25	1.33	1.33
55	83.43	52.36	44.27	1.96	1.23	1.04
60	85.36	53.58	35.42	1.88	1.18	0.78
65	92.36	56.76	32.23	1.92	1.18	0.67
70	94.25	58.27	33.95	1.86	1.15	0.67
75	95.60	60.02	35.59	1.80	1.13	0.67
80	98.12	62.64	37.70	1.77	1.13	0.68
85	105.50	65.14	39.78	1.83	1.13	0.69
90	107.55	66.92	41.23	1.80	1.12	0.69
95	108.69	68.55	43.23	1.76	1.11	0.70
100	110.13	70.03	44.56	1.73	1.10	0.70

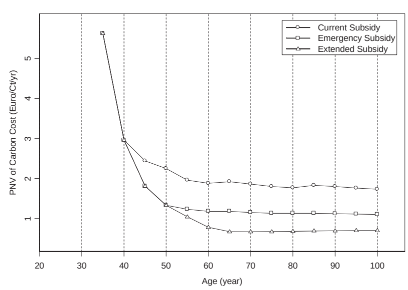

Figure 6. Annual payment for carbon loss

Calculation results are in Table 4. The current subsidy induced the most payment for the unit carbon loss. At the rotation age of 100 years, it was 110.13 Euro/Ct, while that with the emergency and the extended subsidy was 70.03 and 44.56 Euro/Ct. Figure 6 depicts annual payment for unit carbon loss. The annual payment at different rotation ages with different subsidies for the rotation age longer than 30 years. There existed such a tendency that the longer the rotation age, the less the annual payment was. The lowest was 0.67 Euro/Ct/yr for the rotation age of 65 to 75 years with the extended subsidy. The highest increased to 5.63 Euro/Ct/yr for all subsidy policies at the rotation age of 35 years. For such a rotation age over 60 years, the annual payment ranged from 1.73 to 1.92 Euro/Ct/yr with the current subsidy, from 1.10 to 1.18 Euro/Ct/yr with the emergency subsidy, and from 0.67 to 0.78 Euro/Ct/yr with the extended subsidy.

Concluding Remarks

Thinning subsidy has been utilized to activate forestry practices for artificial forest stands toward the sustainable forest management. While the subsidy keeps forest owners to continue the regular thinning to maintain forests, it also induces reduction of carbon sequestered in a forest stand at the final harvest period. In this paper, carbon pricing was conducted through subsidy payment within the optimization framework for the forest stand management. The optimal forest stand management model called DP-KYSS was utilized for the analysis of a sugi forest stand in the Kyushu region, Japan. A field data from our study plot was used to develop the growth simulator in DP-KYSS.

The analyses showed that the thinning subsidy activated thinning activities with the reduction of carbon sequestered in a forest stand. Over the different rotation age, the amount of carbon sequestered in a forest stand gradually increased as the rotation age became longer in the case of no subsidy and the current subsidy payment. On the other hand, with the emergency and extended subsidy payment, a peak of carbon sequestered was observed. The amount decreased due to thinning activities at rather older thinning periods stimulated by the emergency and extended subsidy.

Considering subsidies as a compensation for carbon loss, the evaluation of carbon showed that the present net value of cost per unit carbon loss became the highest for the rotation age of 35 years for all subsidies and the minimum for the rotation age of 55 years with the current subsidy, 50 years with the emergency subsidy, and 65 years with the extended subsidy. The current subsidy induced the most payment for the unit carbon. At the rotation age of 100 years, the present net value of cost per unit carbon loss was 110.13 Euro/Ct with the current subsidy, while that with the emergency and the extended subsidy was 70.03 and 44.56 Euro/Ct, respectively. This implies that lengthening the period for subsidy to some point would reduce the value of carbon. Subsidy pays more with more thinning which reduces carbon sequestered in a forest stand. For the amount of carbon sequestered in a forest stand, the annual payment became as low as 0.67 Euro/Ct/yr for the rotation age of 65 to 75 years, while the highest increased to 5.63 Euro/Ct/yr at the rotation age of 35 years.

Currently, the emission markets have been paid a great deal of attention. The price of carbon dioxide was sometimes priced at 10 to 20 Euro/tCO2 which is more or less equivalent to 2.72 to 3.27 Euro/Ct. If this price were applied to the amount of carbon sequestered in a forest stand, forest owners would still stay with the current thinning subsidy. In other words, unless the price of CO2 at least exceeds the induced price with the subsidy, no incentive would be created for forest owners.

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Literature Cited

Adams, D.M. & Ek, A.R. 1974. Optimizing the management of uneven-aged forest stands. Canadian Journal of Forest Research 4: 274-287

Amidon, E.L. & Akin, G.S. 1968. Dynamic programming to determine optimum levels of growing stock. Forest Science 14: 287-291

Ando, T. 1966. The stand density management diagram and its use. Norin Press, Tokyo. (in Japanese)

Arimizu, T. 1958a. Regulation of the cut by dynamic programming. Journal of the Operations Research Society of Japan 1: 175-182

Arimizu, T. 1958b. Working group matrix in dynamic model of forest management. Journal of the Japanese Forest Society 40: 185-190

Arthaud, G.J. & Klemperer, W.D. 1988. Optimizing high and low thinnings in loblolly pine with dynamic programming. Canadian Journal of Forest Research 18: 1118-1122

Brodie, J.D., Adams, D.M. & Kao, C. 1978. Analysis of economic impacts on thinning and rotation for Douglas-fir, using dynamic programming. Forest Science 24: 513-522

Brodie, J.D. & Haight, R.G. 1985. Optimization of silvicultural investment for several types of stand projection systems. Canadian Journal of Forest Research 15: 188-191

Brodie, J.D. & Kao, C. 1979. Optimizing thinning in Douglas-fir with three descriptor dynamic programming to account for accelerated diameter growth. Forest Science 25: 665-672

Chen, C.M., Rose, D.W. & Leary, R.A. 1980. Derivation of optimal stand density over time - a discrete stage, continuous state dynamic programming solution. Forest Science 26: 217-227

Haight, R.G., Brodie, J.D. & Dahms, W.G. 1985. A dynamic programming algorithm for optimization of lodgepole pine management. Forest Science 31: 321-330

Intriligator, M.D. 1971. Mathematical optimization and economic theory. Prentice Hall, Inc.

Kilkki, P. & Väisänen, U. 1970. Determination of the optimum cutting policy for the forest stand by means of dynamic programming. Seloste: Metsikön optimihakkuuohjelman määrittäminen dynaamisen ohjelmoinnin avulla. Acta Forestalia Fennica 102: 1-23

Martin, G.L. & Ek, A.R. 1981. A dynamic programming analysis of silvicultural alternatives for red pine plantations in Wisconsin. Canadian Journal of Forest Research 11: 370-379

Matsumoto, M. 2001. The amount of carbon storage and sequestrated by Japanese forest. Shinrin Kagaku 33:30-36. (in Japanese)

Paredes V., G.L. & Brodie, J.D. 1987. Efficient specification and solution of the evenaged rotation and thinning problem. Forest Science 33: 14-29

Richards, F.J. 1958. A flexible growth function to empirical use. Journal of Experimental Botany 10: 290-300

Riitters, K., Brodie, J.D. & Hann, D.W. 1982. Dynamic programming for optimization of timber production and grazing in ponderosa pine. Forest Science 28: 517-526

Rinyacho. 1980. The guide book of the stand density management diagram for sugi artificial forests (Northern Kinki, Chugoku, Southern Kinki, Shikoku and Kyushu regions), Rinyacho. (in Japanese)

Schreuder, G.F. 1971. The simultaneous determination of optimal thinning schedule and rotation for an even-aged forest. Forest Science 17: 333-339

Torres-Rojo, J.M. & Brodie, J.D. 1990. Demonstration of benefits from an optimization approach to the economic analysis of natural pine stands in Central Mexico. Forest Ecology and Management 36: 267-278

UNFCC. 2005. Kyoto protocol to the United Nations framework convention on climate change, http://unfccc.int/resource/docs/convkp/kpeng.pdf, 23p.

Valsta, L.T. & Brodie, J.D. 1985. An economic analysis of hardwood treatment in loblolly pine plantations - a whole rotation dynamic programming approach. The 1985 symposium on system analysis in forest resources (Dress, P.E. & Field, R.C. eds), Georgia Center for Continuing Education, Athens, Georgia, USA. pp. 201-214

Yoshimoto, A., Paredes V., G.L. & Brodie, J.D. 1988. Efficient optimization of an individual tree growth model. The 1988 symposium on systems analysis in forest resources (Kent, B.M. & Davis, L.S. eds), USDA Forest Service. General Technical Report RM-161, pp. 154-162