

Climate Risks and Age-related Damage Probabilities – Effects on the Economically Optimal Rotation Length for Forest Stand Management in Japan

Hirofumi Kuboyama and Hiroyasu Oka

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We estimated the damage probability according to age class and major climatic disasters based on ‘Statistical Yearbook of National Forest Insurance’ from 1960 to 1996. The probability of snow damage is high for young stands, then gradually decreases with age. On the other hand, the risk of wind damage gradually increases with age. Decisions about rotation age should be based on the distribution of damage probability with stand age. Risk of damage has two contradictory effects on the optimal rotation period; one is that the rotation-shortening effect caused by risk of damage around harvest age; another is the rotation-extending effect due to decrease of rent by the risk of damage through the raising period. Change of optimal rotation depends on the relative magnitude of these effects. We examine this by calculating land expectation value (LEV) using a simulation model with the empirical damage probability, price and cost. Change of the optimal rotation period obtained from the national average damage probability is not significant. However, the optimal rotation is shorter in high wind risk areas and is longer in high snow risk areas. It is because the damage probability for a mature stand is high in the case of wind and low in the case of snow. In addition, the extent of decrease in LEV is smaller for wind than for snow. The results of simulation based on empirical data confirm that the optimal rotation period can become either shorter or longer through incorporating risk in decision making, depending on the damage probability distribution with stand age.

Keywords climatic risks, damage probability according to age class, optimal rotation period, land expectation value, simulation

Authors' address Forestry and Forest Products Research Institute Tohoku Center, Nabeyashiki 72, Shimo-Kuriyagawa, Morioka, Iwate, 020-0123 Japan

Fax +81-19-643-6747 **E-mail** kuboyama@ffpri-thk.affrc.go.jp

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1 Introduction

We treat the risk of random events in this study. Probability of damage is assumed to depend only on the age, tree species, and location of the stand, and to be constant over time for the stands of the same condition. Especially, we focus on the difference of damage probability with age classes to show that the effect of the damage probability on the optimal harvesting age is quite different according to the age classes which is affected by the risk.

Japanese forestry is faced with various risks, the most important of which can be classified into four major categories, (1) abiotic; (2) biotic; (3) anthropogenic, and (4) economic. Fig. 1 shows the annual damaged areas due to first three risk categories. The damage caused by insects and diseases, which were mainly related to primary plantations newly shifted from natural forests, has rapidly decreased along with the decrease in area of new plantations. Some other diseases which are not fatal but erode the timber value of mature stands, are statistically unknown but existing potentially.

Damage caused by forest fires has decreased markedly to 1/4 of the level before the 1970

when there were large areas of young plantations prone to accidental fires. On the other hand, abiotic damage caused by climatic disasters has not shown such a significant decline. As a consequence, climatic risks have now become the most serious physical risks in Japanese forestry. Detailed long-term statistical data for climatic damages are available. Thus, we focus on the climatic risks in this study.

The area of plantation forests in Japan was estimated to be more than ten million hectares in 1995 (Forest Agency 1995). Since their average stand age had reached 30 years of age and approached a merchantable size, an increase of annual harvest was expected. However, the area of harvest was not actually increased, because of the decline of stumpage price and high labor cost for reforestation. Consequently, about 6 million hectares of plantations are expected to be over 40 years old in 2010. The change in economic environment seems to have lengthened the economic rotations in Japan. Some foresters, however, are concerned that climatic risks may increase through adopting longer rotations. It is important for forest owners to weigh those risks in order to make rational harvest decisions.

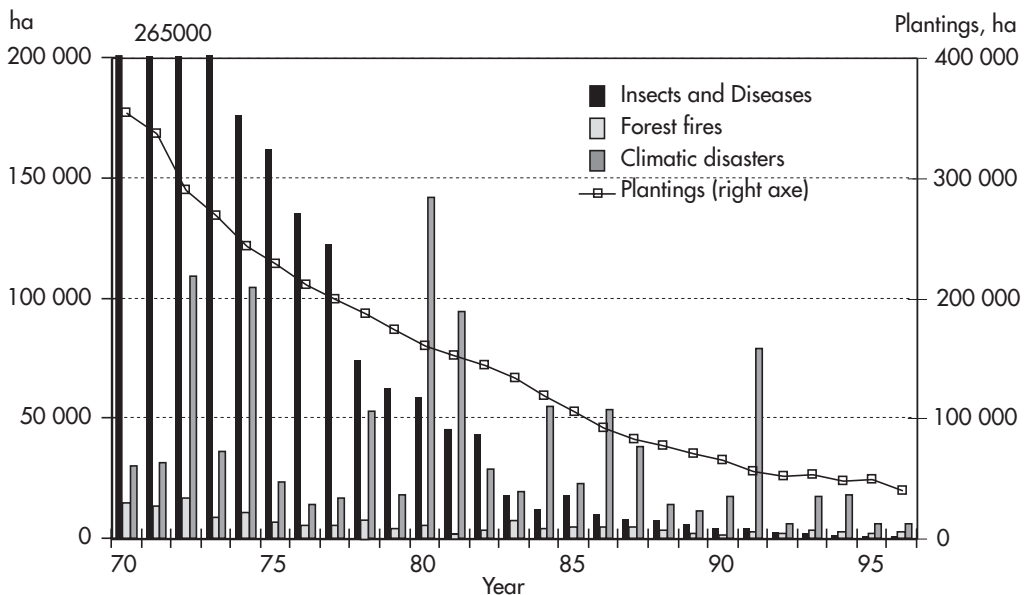


Fig. 1. Area affected by disasters in Japan’s forests, 1970–96. Source : Forest Agency 1970–96, Statistical Year Book of Forestry.

1.1 Rotation Length under Risk

Reed and Errico (1985), and Buongiorno and Gilliss (1987) pointed out that a shorter rotation was appropriate under the risk of fire. Both groups assumed a constant damage probability with stand age. Haight et al. (1995) investigated the effects of age-dependent hurricane risk, salvage proportion, and degree of initial stand damage on expected present value (EPV) and harvest age. They also found that presence of the risk made optimal rotation age shorter and EPV smaller. However, the effect of the risk became small by assuming lower risk in young stands and by introducing salvage proportion. Quine (1995) showed a conceptual model of threshold windspeed for windthrow which declined with stand age. This suggests that the risk of wind damage increases with stand age, which is consistent with the assumption made by Haight et al. (1995).

On the other hand, using the empirical data of snow damage, we showed an example in which a longer rotation period was preferred (Kuboyama et al. 1997). In this paper, we discuss the effects of age-dependent risks on the economically optimal rotation length, along with the theoretical analysis of maximizing expected net present value shown by Johansson and Löfgren (1985).

We estimate the distribution of damage probabilities according to age class and major climatic disasters, then assess the effects of these risks on the economically optimal rotation period of plantation forestry. For the assessment, we calculated the land expectation value through a stochastic simulation model using damage probability. Finally, we examined the above theoretical discussion with the results of the simulations.

1.2. Theoretical Analysis of the Effects of Age-dependent Risks on the Optimal Rotation Period

Consider a merchantable stand of age T . We defined the optimal rotation period (OP) as the harvest period which maximizes the net present value of expected revenue over an indefinite time horizon with a constant timber price system. It means that the forest owner is assumed to be risk neutral, and that the uncertainty of price change is

ignored in this study. Then we examined whether OP becomes shorter or longer in the presence of risk of damage compared with OP under no risk.

For simplicity, the stumpage price p (yen/m³) is assumed to be constant. Merchantable timber volume per hectare is expressed as a function of stand age T , denoted by $V(T)$. Risk is defined as damage probability d of having the entire stand collapse at age T . Denoting growth rate at T as i , the derivative of expected volume with respect to time can be written as follows:

$$\begin{aligned} \frac{dV(T)}{dT} &= \frac{V(T + \Delta T) - V(T)}{\Delta T} \\ &= V(T) \cdot (1 + i)(1 - d) - V(T) \\ &\equiv V(T) \cdot (i - d) \end{aligned} \quad (1)$$

It expresses the amount of volume growth at age T . We also assume that the growth rate $i(T)$ decreases with the age T .

The land expectation value of the forest stand managed with rotation period T_R with and without risk is denoted as $E_d(T_R)$ and $E(T_R)$, respectively. $E(T_R)$ can be written by using the interest rate r as follows:

$$\begin{aligned} E(T_R) &= \\ &= (pV(T_R) \cdot (1 + r)^{-T_R} - C) \cdot (1 - (1 + r)^{-T_R})^{-1} \end{aligned} \quad (2)$$

T^* is OP without risk. Using Formula (1), the marginal change of E with respect to the change of rotation period at around T^* can be written as follows (Johansson and Löfgren 1985):

$$\begin{aligned} \left. \frac{dE(T_R)}{dT_R} \right|_{T_R=T^*} &= \\ p \left. \frac{dV(T_R)}{dT_R} \right|_{T_R=T^*} - r p V(T^*) - r E_d(T^*) & \quad (3) \\ &\equiv p V(T^*) (i - r - d) - r E_d \end{aligned}$$

According to the Faustmann-Pressler-Ohlin's first order condition for a maximum forest present value, 'a forest should be harvested when the rate of change of its value with respect to time is equal to the interest on the value of the stand plus interest on the value of the forest land' (Johansson and Löfgren 1985). Or formally, harvest when:

$$pV(T^*)(i(T^*) - r) - rE = 0$$

In the Equation (3), $pV(T^*)(i(T^*) - d(T^*))$ is the expected rate of change of the stand value with respect to time, $pV(T^*)r$ is the interest on the value of the stand, and rE_d is the interest on the value of the forest land. By examining the sign of Formula (3), we can judge whether OP with risk is shorter or longer compared with that without risk. If the sign is positive at T^* , OP with risk should be longer than T^* , and if the sign is negative at T^* , OP with risk should be shorter than T^* .

The expected growth of the stand value, $pV(T^*)(i(T^*) - d(T^*))$, decreases with the damage probability $d(T^*)$. The interest on the value of the stand, $pV(T^*)r$, is not affected by the risk. On the other hand, the interest on the value of the forest land, rE_d , decreases with $d(T)_{(T>0)}$. Therefore, we get interesting results for some special cases;

if $d(T^*) = 0$ and $d(T) > 0$ for at least one $T (0 < T < T^*)$,

$$\begin{aligned} \text{then } pV(T^*)(i(T^*) - d(T^*) - r) - rE_d \\ = pV(T^*)(i(T^*) - r) - rE_d \\ = r(E - E_d) > 0 \end{aligned}$$

And the optimal rotation period will be longer than T^* . Additional recovery costs after non-fatal damage in the young stand also decreases rE_d , such as the cost of propping up bent trees after snow damage, and supplementary planting after various types of damage.

On the contrary;

If $d(T) = 0$ for all $T (0 < T < T^*)$ and $d(T^*) > 0$,

$$\begin{aligned} \text{then } pV(T^*)(i(T^*) - d(T^*) - r) - rE_d \\ = r(E - E_d) - pV(T^*)d(T^*) \\ = pV(T^*)d(T^*)(1 + r)^{T^*} - pV(T^*)d(T^*) \\ = pV(T^*)d(T^*)(1/(1 + r)^{T^*} - 1) < 0 \text{ for } r > 0 \end{aligned}$$

And the optimal rotation period will be shorter than T^* .

For another special case;

If $d(T) = \text{constant}$

Then, the sign of the Equation (3) is ambiguous. However, it is negative, probably in all cases in the earlier studies, which assumed real annual discount rate not lower than 1 %. In such cases, the optimal rotation period is shorter than T^* .

The difference between rE and rE_d is related to the total risk until age T^* . Therefore, if $d(T^*)$ is small enough and if the damage probability is large in a young stand, the sign of Formula (3) is likely to be positive. On the contrary, if the damage probability is positive and almost equal at every age class, or increase with age, the sign of Formula (3) is likely to be negative.

More generally, we can denote the damage probability at age T for a standard case as $d_0(T)$, and the optimal rotation period with the given damage probability of $d_0(T)$ as T^{**} . Then, according to the Faustmann-Pressler-Ohlin's first order condition for a maximum forest present value;

$$pV(T^{**})(i(T^{**}) - d_0(T^{**}) - r) - rE_{d0} = 0$$

where E_{d0} expresses the land expectation value when the forest land is managed with optimal rotation with the given damage probability $d_0(T)$.

Consider a case of different damage probability $d_1(T)$, and assume that all other conditions are identical to the standard case.

If $d_1(T) = d_0(T)$ for all $T (0 < T < T^{**})$ and $d_1(T^{**}) > d_0(T^{**})$

$$\text{then } pV(T^{**})(i(T^{**}) - d_1(T^{**}) - r) - rE_{d1} < 0$$

and the optimal rotation period with the damage probability $d_1(T)$ is shorter than the optimal rotation period with $d_0(T)$. (If $d_1(T^{**}) < d_0(T^{**})$, we get the opposite result.)

On the contrary,

If $d_1(T) = d_0(T)$ for all $T (0 < T < T^{**})$, $d_1(T) > d_0(T)$ for at least one $T (0 < T < T^{**})$ and $d_1(T^{**}) = d_0(T^{**})$

$$\text{then } pV(T^{**})(i(T^{**}) - d_1(T^{**}) - r) - rE_{d1} > 0$$

and the optimal rotation period with the damage probability $d_1(T)$ is longer than the optimal rotation period with $d_0(T)$. (If the sign of inequality is opposite, we get the opposite result.)

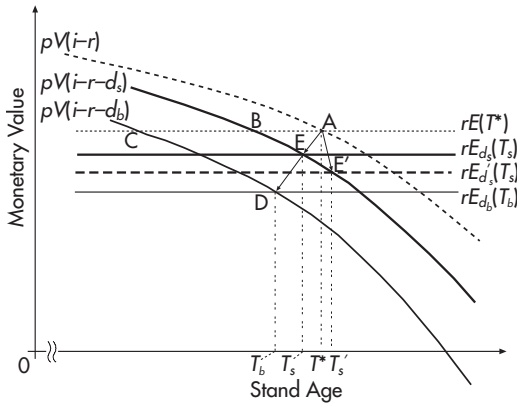


Fig. 2. Shifts of optimal rotation periods with different risks.

The geometry of the effects of the risk in the neighborhood of T^* is illustrated in Fig. 2. The ordinate shows the monetary value and the abscissa shows the stand age T . We defined the upper curve as the value growth curve (VGC), which shows the advantage of expected timber value growth compare to bank savings after harvest. It is calculated by subtracting interest on timber capital $pV(T)r$ and expected damage loss $pV(T)d$ from value growth of stand timber $pV(T)i$. It decreases with age due to the increase of interest on timber capital as well as the decline of growth rate. Considering a small risk d_s , VGC shifts down to the middle curve. Similarly with a large risk d_b , the curve shifts down to the lower curve. On the other hand, the upper horizontal line shows $rE(T^*)$. The OP without risk is T^* at point A, where the upper VGC intersects with the line of $rE(T^*)$.

Given a small risk d_s , the land rent rE decreases to rE_{d_s} due to the risk, and the optimal period T_s shifts to E where VGC for d_s intersects rE_{d_s} (T_s). Similarly with a larger risk d_b , the optimal period should be at D. In the above cases, both E and D indicate shorter OP than T^* .

Assume a risk pattern d'_s , which is high for the young stand but decreases to the same level as d_s in the neighborhood of T^* . Since rE_{d_s} decreases to $rE_{d'_s}$ due to high risk in its young stand, OP shifts from E to E' where VGC for d'_s intersects $rE_{d'_s}$ (T'_s). As a result, a longer rotation period may be suitable in such cases. In addition, in the case where the damage probability or recovery

cost is high in the young stage, the OP is shifted further to the right side. We can see two contradictory effects caused by the risk; one is the rotation-shortening effect due to the risk at T^* ; another is the rotation-extending effect due to a decrease of rent. Which of these effects are stronger? And how large is the effect? To answer these questions, we need numerical calculations based on empirical data.

We can conclude that the decision of rotation age for a stand should be based on the empirical distribution of damage probability with stand age. We analyze, in the following section, the difference in OP using the empirical damage probabilities observed in Japan.

1.3 Estimation of Damage Probability According to Age Class

In the former section, we found that the damage probability, especially at around the age of harvest, is one of the key factors to decide the OP under risk. Thus we estimated the damage probability according to age class for the major five climatic risks; wind, flood, snow, drought and frost.

To make the estimation, we used the statistics from 1960 to 1996 in the ‘Statistical Yearbook of National Forest Insurance’, which gives the aggregated annual damaged area for each climatic damage according to age class at a national level. The damaged area has been obtained by accumulating the area where fallen or broken trees supposed to occupy before the damage.

Since the distribution of stand age changed during the observation period, the susceptibility to damage also changed. This problem is adjusted by dividing damaged area by forest area in each age class. We define damage probability $d(T)$ as follows,

$$d(T) = \frac{\sum_{t=1960}^{1996} \text{ Damaged area of age } T}{\sum_{t=1960}^{1996} \text{ Stand area of age } T} \times 100 (\%) \quad (4)$$

where both upper and lower aggregation of area exclude National Forests because of the data

availability. Damage occurred in the natural forest is less than 10 % of the total damaged area. Therefore, the obtained data approximately explains the damage probability in private plantations.

Fig. 3 shows the results of the estimation where the interval of age class reflects the original statistics. The probability of damage by frost, drought and snow are high in the first age class. They decrease rapidly as age increases, but the probability of snow damage remains high up to age 20. Even for snow, the probability is small when the trees are over 40 years old. On the contrary, the risk of wind gradually increases with age. This trend is consistent with the model shown by Quine (1995). The damage probability of flood is low in every age class.

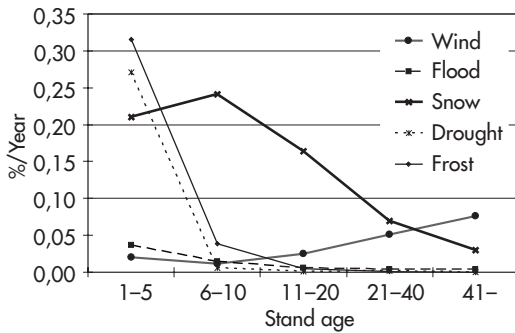


Fig. 3. Damage probabilities by disaster and stand age for private plantations.

This estimation neglects the regional and topographical difference of damage sensitivity. As Nykänen et al. (1997) pointed out, geographic location and topography influence the occurrence of damage. Also in Japan, the probabilities are actually different among regions. By using other data sets of the statistics, which are the aggregated annual damaged area according not to age class but to each prefecture, we calculated damage probability for each prefecture by assuming that the age-class distribution is similar between prefectures. We found that wind damage is distributed from the northern part of Kyushu to the middle of Honshu, and that snow damage spreads over Honshu and its probability is highest in the northern part of the Kansai area (see Fig. 4). The average probability within five most risky prefectures is 4.2 times larger than the average of the whole country for wind damage and is 5.2 times larger for snow damage.

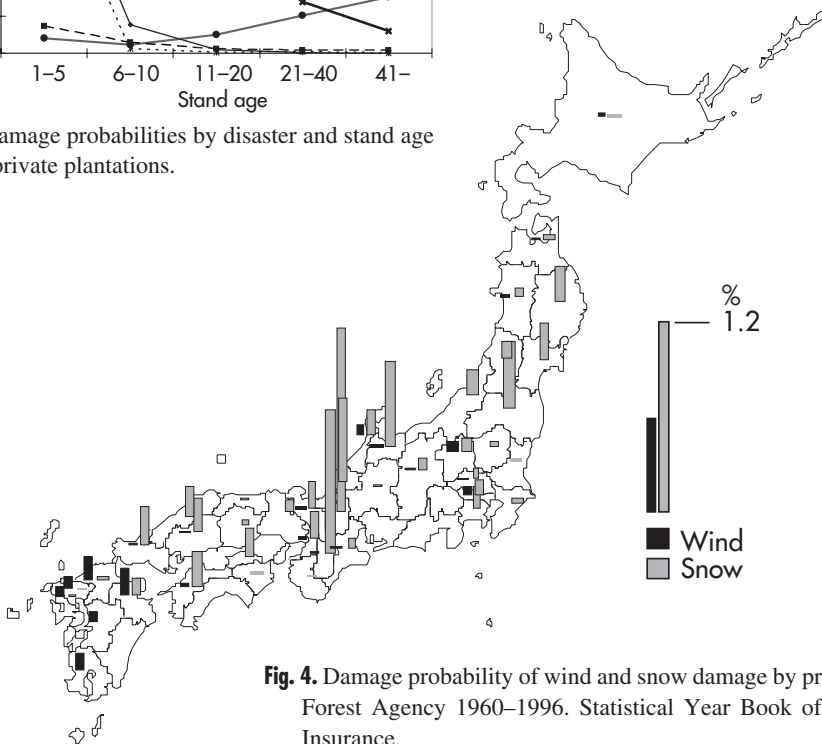


Fig. 4. Damage probability of wind and snow damage by prefecture. Source: Forest Agency 1960–1996. Statistical Year Book of National Forest Insurance.

In the following section, we simulate a forest management model which considers a sugi (*Cryptomeria japonica*) plantation. We assume that the damage probability for sugi is identical to that for the whole plantation. Because nearly half of the plantation is shared by sugi and the total damage probabilities by climatic hazards for sugi were not significantly different from those for the plantation as a whole.

2 Methods – Construction of Simulation model

2.1. Structure of the Simulation Model

Consider management of a sugi stand, which is the most common timber plantation species in Japan, starting from reforestation on a unit area of bare land. Suppose that the forest stand becomes T years old at the calculation year t in a simulation. Stumpage price, stand volume, merchantable harvest volume, merchantable thinned volume, tending cost and discount rate are denoted by $p(T)$, $V(T)$, $Vh(T)$, $Vt(T)$, $s(T)$ and r , respectively.

We assume that climatic disasters are stochastic events and all trees in the forest stand would entirely damaged with probability $d(T)$. We assumed a different probability with the age class estimated from the Formula (4). Damaged trees are assumed to be removed at a cost of C_s per unit volume and to be sold in the proportion of m . That proportion is different with the type of disaster. For example, it is 20 % for the wind damage. We developed a Monte Carlo type simulation model. Whether damage occurs or not is examined every calculation year in terms of a random variable $Rnd(t)$.

Damage does not occur unless $d(T) < Rnd(t)$; if it does, then proceed to $T = T + 1$. The income $R(t, T)$ and the cost $C(t, T)$ are,

$$R(t, T) = p(T) \cdot V_h(T), C(t, T) = s(T)$$

in case that the T reaches the rotation age, proceed to $T = 0$. $R(t, T)$ and $C(t, T)$ are,

$$R(t, T) = p(T) \cdot V_h(T), C(t, T) = 0$$

On the other hand, damage occurs when $d(T) > Rnd(t)$; when it does, then proceed to $T = 0$ at time t . $R(t, T)$ and $C(t, T)$ are,

$$R(t, T) = m \cdot p(T) \cdot V(T), C(t, T) = C_s \cdot V(T)$$

The land expectation value with the rotation period of T_R , denoted by $E_d(T_R)$, is written as follows:

$$E_d(T_R) = \sum_{t=1}^{\infty} (R(t, T) - C(t, T)) / (1+r)^t \quad (T \leq T_R)$$

2.2 Specification of the Stand Management Model

We developed a stand management model based on a typical case in the northern part of Ibaraki prefecture and the southern part of Fukushima prefecture, which are located in central Japan. As shown in Table 1, planting after site preparation and weeding may be done in the first year. Weeding is continued until 8 years old and pre-commercial thinning may be done at 10 and 20 years old. There-after commercial thinning may be carried out every ten years. Stand growth is assumed to follow the yield table for sugi stands on moderate sites (Forest Agency and Forestry Institute 1955). Timber price is assumed to be a logarithmic function of stand age approximated from the standard stumpage price table summarized by the Maebashi Regional Forestry Office in 1994. Calculation is done by using a discount rate of 2.6 %, which is the average real rate of return of government bonds over 10 years between 1972 and 1993, and by setting the time horizon at 500 years.

3 Results

3.1 Land Expectation Values Based on Average Damage Probability of the Whole Country

Fig. 5 shows the results of simulations based on 900 observations. E_d is hardly affected by flood, drought and frost, but is substantially reduced by the risk of wind and snow damage. The land

Table 1. Schedule of tending and harvesting.

	1	2..8	10	20	30	40	50	60	70	80
	Site preparation and planting	Weeding	Improvement cutting	Improvement cutting	Age Operation Thinning	Thinning or harvesting	Thinning or harvesting	Thinning or harvesting	Thinning or harvesting	Harvesting
Number of standing trees	3500		2850	2175	1360	947	724	587	495	429
D.B.H (cm)			7.2	14.3	20.1	24.9	29.2	33.1	36.6	39.7
Thinned volume (m ³ /ha)					72.4	69.4	65.4	60.8	56.2	
Harvested volume (m ³ /ha)			34	197.3	327.4	428.7	515.7	592	658.6	717.2

Source: “Yield table for sugi stands in Northern Kanto district and Abukuma region”, Forest Agency & Forest Institute (1955) and data obtained from forest owners and Forest Owner’s Cooperative of Satomi village.

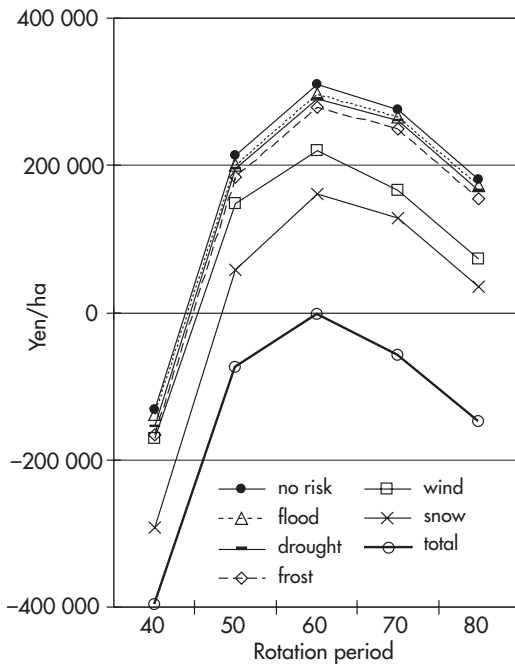


Fig. 5. Changes of E_d .

expectation value calculated by using total damage probability lies just below zero. This suggests that forestry investment is not profitable regarding the total risk. No significant change in optimal rotation period by climatic risks is observed here.

3.2 Land Expectation Values in High Risk Areas

As we mentioned before, damage sensitivity differs between regions. The damage probabilities for the high wind risk area and high snow risk area are obtained by multiplying the national average by a Factor of 4.2 and 5.4 (see Section 3). We assume that the damage probability distribution for the stands of different age in high risk areas are proportional to the one in the whole country. Additionally, we assume that recovery costs to prop up bent trees are needed every year in the young stage only in the snow risk area. Fig. 6 shows a result of our simulation. Since the curves of E_d lie below zero in both risky areas, the investment in a plantation is not suitable in these areas, especially in risky areas of snow.

3.3 Land Expectation Values in High Risk Areas with Subsidy

The Japanese government provides several cost-share programs. Suppose that the average reforestation cost, such as site preparation, planting and weed control, paid by forest owners was reduced to 30 % of the original cost in risky areas. Then E_d becomes positive even in risky areas (Fig. 7).

While the optimal rotation period (OP) without risk shifts from 60 to 50 through introducing cost-share payments, $E_d(40)$ is almost equal to

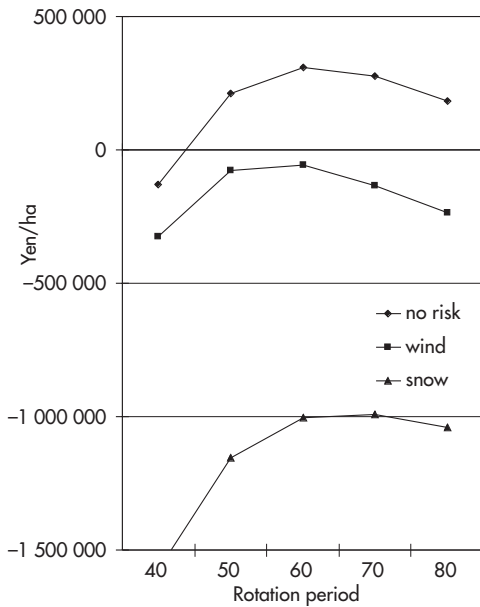


Fig. 6. Changes of E_d in high risk areas.

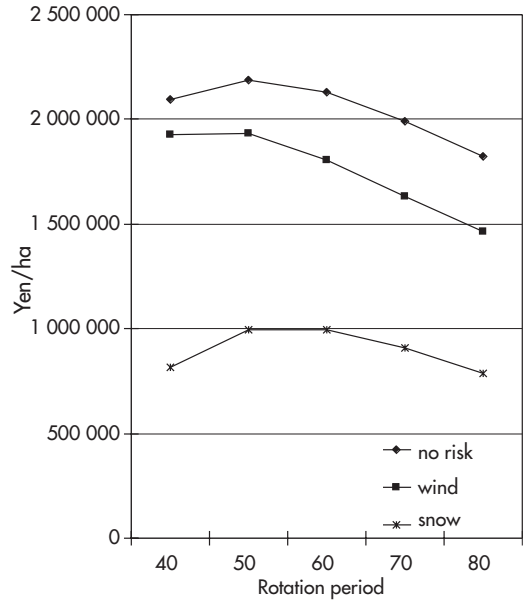


Fig. 7. Changes of E_d considering cost-share.

$E_d(50)$ in wind risk areas. The difference between $E_d(40)$ and $E_d(50)$ is not statistically significant in wind risk areas. This suggests that a shorter rotation is rather suitable in wind risk areas. On the contrary, $E_d(60)$ is almost equal to $E_d(50)$ in snow risk areas. This suggests that OP is longer in a snow risk area than in an area without risk.

3.4 Relation between Expected Growth, Rent and Interest

Using the third result of simulation (see Figs. 8 and 9), let us examine the theory by illustrating graphs as shown in Fig. 2. We approximate damage probability distribution functions from Fig. 3, and illustrate the value growth curve (VGC) for the wind risk case in Fig. 8. Since the damage probability is large at the age 50 years but the decrease in $rE_d(50)$ is small, OP shifts from 50 years to a shorter period of between 40 and 50 years.

In the areas of high snow risk, Fig. 9 shows an opposite result. E_d declines significantly by snow, while damage probability of over 41 years is

small enough, which makes the OP longer than that in the case without risk.

4 Discussion

We pointed out two contradictory effects caused by risks in the theoretical analysis. One is the rotation-shortening effect due to the damage probability for mature stands. Another is the rotation-extending effect due to decrease of rent by the risks. The change of OP depends on the relative magnitude of these effects.

As far as climatic disasters in Japan are concerned, average damage probabilities for mature stands are low, and those for immature stands are relatively high. Therefore, the presence of climatic risk does not significantly affect OP. If we take five climatic risks into account, however, land expectation value decreased largely. This effect was caused mainly by the risk of wind and snow damages.

On the other hand, we observed that OP becomes shorter under a high wind risk. The reasons for the shifts are that the damage probability around OP is high in case of wind damage,

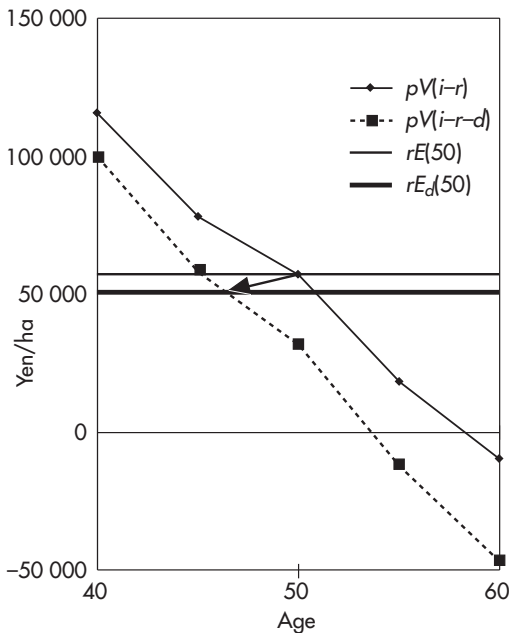


Fig. 8. Relationship between value growth curve and rent in the high wind risk area.

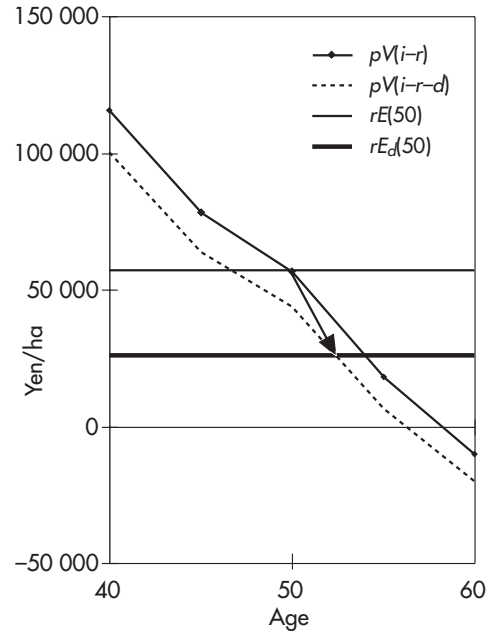


Fig. 9. Relationship between value growth curve and rent in the high snow risk area.

and the extent of the decrease in E_d is relatively small because of low damage probability in young stands. The principle, “harvest before it is damaged”, would be applied in this case.

On the contrary, OP becomes longer under a high snow risk. Damage probability of snow decreases with stand age. The damage probability around OP is low, while the decrease in E_d is large because its damage probability sustains high level through younger age. As a result, it is found that the OP may become either longer or shorter depending on risk, although the shift may not be large in Japanese cases.

If we use a higher discount rate, optimal rotation would become shorter than the case with the lower discount rate, because the interest on timber capital increases rapidly after the stand trees become commercial size. Therefore, the effect of risk on OP shifts may be weakened. However, under a high discount rate, damage loss becomes relatively large compared to future income, then, net present value will likely to be negative even in average snow or wind risk area.

Another important finding is that E_d is greatly decreased even by the average probability of

risk. This suggests that the cost-share programs are indispensable to encourage forestry investment by forest owners in risky areas. However, if those programs were provided inappropriately, they would promote inadequate forestry investment. For example, forest owners would prefer high yield species or high yield silvicultural methods in spite of their high risks.

There are some alternatives to softwood plantation, such as management of natural hardwood to produce pulpwood, bed logs for mushroom cultivation and lumber. For example, hardwood management with a short rotation to produce pulp wood and bed logs has more than 200 000 yen per hectare as land expectation value because it has low risk of climatic damage even though it can generate low timber value. Therefore, natural forest management can be an alternative in high risk areas.

5 Conclusion with Remarks on Some Possible Extensions of the Result

In this study, we assumed that all trees in a stand were fallen or broken by climatic hazards. In reality, damage form varies from total collapse to partial collapse. As far as the partial collapse as a group is concerned, our simulation can handle the case with a minor change which divide calculation into damaged part and undamaged part, because most of forest owner would replant trees in the damaged area. Of course, we can deal with no-replanting case in a partially collapsed area, which is similar to the calculation for alternative stocking level done by Haight et al. (1995). In this case, damaged area will be left as unproductive land until the rest of the stand is harvested and the land is replanted altogether. Then optimal harvesting age of the undamaged part of the stand will be younger than that for the case with no part of the stand is damaged, because the expected value growth is smaller, while the rent for the land is the same. However, about the critical stocking level on which a forest owner should be based to decide whether harvesting remaining sound trees and replanting all stand after a damage, further investigation will be needed.

The other damage form, damage like thinning, is difficult to treat because stocking level would be changed by the past damages. In this case, either, optimal harvest age can not be decided by the stand age alone but by relationship between the expected value growth, interest on the timber capital, and the land rent, of which the first two are the function of the age and the damage history of the stand. Since change of growth rate brought by thinning effect depends on density and crown size, more flexible model is necessary to address this problem.

We assumed that the forest owner is risk-neutral. If we suppose the case of risk-averse forest owner, it is expected that shorter rotation would be selected to avoid the risk of future damage and forest owners would become more reluctant to invest in reforestation (Price 1989).

In this study, the climate pattern is assumed to be unchanged in the future. According to some research results, however, it is predicted that the

frequency and scale of rainstorm will increase as a result of global warming. If this prediction becomes true, the damage probability by the wind risk would increase in the future. On the other hand, global warming may decrease snow risk in Japan.

The growth of timber volume used in this study is declining rapidly after 20 years of age. It reflects the yield table which was adjusted from limited sample plots of older stands. However, some foresters suggest that sugi stands maintain higher growth rate even in a high age class. If it is true, OP without risk would become longer. Then the shift of OP by climatic risks may be more significant than the results obtained here.

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