EFFECTS OF FOREST CARBON SEQUESTRATION ON OPTIMUM PLANTING DENSITY

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ABSTRACT

In this study, the effects of the benefit of forest carbon sequestration on the optimal planting density for Scots pine plantation are analyzed. Analyses are performed by integrating the carbon benefit into the Faustmann framework, and then solving the integrated formulation. The benefit of carbon sequestration is measured by the Swedish CO_2 tax. Numerical results suggest that 1) forest owners prefer a high planting density as the benefit of carbon sequestration is included into forest management, and the increase in optimal planting density depends on the level of the CO_2 price; 2) the effect of carbon benefits on the optimal planting density is relatively greater on low productive sites than on high productive sites, others being equal. This is also true with respect to benefit gains in present value; and 3) the forest carbon benefit has a relatively larger effect when the interest rate is high than when it is low, others being equal. This is true with respect to benefit gains in present value as well.

Keywords: Carbon dioxide tax, carbon sequestration, planting density.

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INTRODUCTION

Forest carbon sequestration has been considering as one potential source of benefit to forest management. This may lead to adaptation of forest management schemes and policies in order to utilize fully the capacity of the forest for joint timber production and carbon sequestration. The reason for this adaptation is that their aggregate benefit depends to some extent on how the forests are managed. Hoen & Solberg (1994) showed that, if the management schemes were changed on the productive Norway spruce area, there would be a significant improvement in the present value of the flow of net carbon storage at a cost of a moderate

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decrease in the net present value of the flow of timber cash. Concern about the optimal time to harvest a forest stand, which is managed for joint timber and carbon benefit, has been examined by a number of researchers, through integrating the carbon benefit into the Faustmann framework. Studies indicated that the carbon benefit might have an effect on the optimal time to harvest trees. The optimal rotation that maximizes the joint timber and carbon benefit is longer than the optimal rotation that maximizes the single timber benefit. However, it is shorter than the optimal rotation that maximizes the single carbon benefit (Plantinga & Birdsey, 1994; van Kooten *et al.*, 1995; Hoen & Solberg, 1997). This study deals with how the planting density changes, as carbon benefits are included into forest management.

The planting density is one of the most decisive factors that determine the stock level of an established stand. In general, the planting density affects not only the total stock of a forest stand but also its growth patterns over time. Compared to a low planting density, a high planting density results in greater volume yield but smaller mean diameter at a certain dominant height (Chang, 1983; Pettesson, 1992; Petti, 1995, etc.). For a stand with a high planting density, its current annual growth is greater and reaches maximum at an earlier age. Furthermore, stands with different planting densities will eventually merge to a same level of stand volume (Chang, 1983). It seems therefore reasonable to understand that more carbon can be stored at an earlier time in a stand with a high planting density since the amount of carbon stored in forest biomass is positively related to the timber growth. Because the carbon sequestration offers, unlike timber, earlier and continuing benefits while the forest grows, additional carbon benefits may drive the optimal planting density up to a higher level than that when only timber is valued. Although a high planting density may bring additional benefit from carbon sequestration, it does have costs that must be balanced out against this benefit. Those costs include a direct cost of more trees being planted and indirect costs like smaller trees in diameter and more carbon being released to the atmosphere after harvest. Thus, a trade-off exists between losses caused by planting more trees and gains from additional carbon benefit.

METHOD

Suppose that a forest investor could receive a carbon-subsidy annually while the standing trees grow because these standing trees sequester carbon dioxide from the atmosphere. On the other hand, the investor has to pay a carbon-tax when he harvests that forest because a portion of carbon in the harvested trees is released into the atmosphere in the forms of carbon dioxide. We assume that the carbon-subsidy is equal to the carbon-tax at any point in time, and name them CO_2 price, denoted by P_c. Assume further that the investment criterion is to maximize the net present value (NPV), denoted by π, of both timber and carbon benefit. For a given planting density, N, the associated maximum NPV can be obtained through solving the Faustmann formulation that is extended to include the carbon benefit. There are a number of available variants of Faustmann formulation in the literature. They are in, among others, Englin & Callawy (1993), Plantinga & Birdsey (1994), van Kooten *et al*. (1995), and Hoen & Solberg (1997). The extended Faustmann formulation in this study is written as

$$\pi = \frac{P_{tm}V(T)e^{-rT} + \sum_{t=0}^{T} P_c \alpha \Delta V e^{-rt} - \left(P_c \alpha \beta(T) V(T) e^{-rT}\right) - C(N)}{1 - e^{-rT}} \quad (1)$$

where P_{tm} denotes the net timber price per m^3. T is the rotation length; $V(\cdot)$ is the timber volume at time t; α is a constant, defining the amount of CO_2 that 1 m^3 stem growth could sequester or release; $\beta(\cdot)$ measures the proportion of the harvested timber that is decomposed into the atmosphere in the forms of CO_2 at time t; r is the discount rate.

The numerator in Equation (1) consists of four components. The first,

$$P_{tm}V(T)e^{-rT},$$

represents the net timber value that is discounted back to the beginning of the rotation. The second,

$$\sum_{t=0}^{T} P_c \alpha \Delta V e^{-rt},$$

measures the carbon benefit that is the summation of a discounted flow of carbon payment over one rotation. The third,

$$P_c \alpha \beta(T) V(T) e^{-rT},$$

accounts for the cost because a portion of carbon in the harvested timber is released into the atmosphere in the forms of CO_2. The final term, $C(\cdot)$, indicates the regeneration cost which is a function of the planting density.

The model described above is then applied to Scots pine plantation on three productive sites: site index T16 (Scots pine trees reach a dominant height of 16m when the age is 100 years.), T20 and T24 in northern Sweden. We assume that, when the established stand reaches a dominant height of 6m, a pre-commercial thinning is made; thereafter, no treatments are performed until final harvest.

Two growth functions are combined to estimate the timber growth and the amount of the carbon fixed over the period from planting to final harvest. First, the function of Pettersson (see, Petterson, 1992; Gong, 1995; Zhou, 1998) is used to project the state of the established stand at a dominant height of 10m. One of the inputs to this function is the planting density. Dividing the estimated volume by the age then gives the mean annual timber growth, which is used to approximate the annual increment of carbon storage before the stand reaches a dominant height of 10m. Thereafter, the growth simulator of Persson (see, Persson, 1992; Gong, 1995; Zhou, 1998) is employed to project the dynamics of the stand. The inputs to this simulator come from the outputs of the first function. It is worth mentioning that the simulator of Persson (1992) has two application restrictions important in this context. First, the simulator requires that the valid stand density should be between 400 and 4,500 trees/ha. Considering the mortality of the trees before they reach a dominant height of 10m, we define the feasible planting densities between 500 and 4,500 trees/ha. The second restriction is on the age of the stand. The simulator requires it should be below 120 years. We arbitrarily extend it up to 200 years.

The amount of carbon that $1m^3$ of stem timber can sequester is estimated through converting the stem volume first into stem biomass and further to carbon content using four specific conversion factors. Several authors have used different factors related to Scots pine. Karjalainen *et al.* (1994) assumed that the dry weight density is 390 kg/m^3 and carbon comprises 52 % of the dry biomass. Kauppi & Posch (1997) assumed that the dry weight density is 480 kg/m^3 and 50 % of the dry biomass is carbon. In this study, it is conservatively assumed that the dry weight density is 390 kg/m^3 and carbon accounts for 50 % of the biomass by weight. Referring to Solberg (1997), the ration between the total tree biomass (i.e. including roots, branches, bark, and stump) and the biomass in the stem for Norway spruce is about 2.0. Applying it arbitrarily to Scots pine, the product of those three figures gives 390 kg/m^3; that is, the carbon content that is fixed by 1m^3 stem timber growth. Further, multiplying it with a constant 44/12 gives (α =) 1430 kg/m^3, the amount of carbon dioxide sequestered by or emitted from 1 m^3 stem timber. In 44/12, the numerator, 44, is the molecular weight of carbon dioxide, and the denominator, 12, is the weight of carbon atom.

An important factor in Equation (1) that has to be determined is β. As stated before, it indicates the proportion of the harvested timber that releases back into the atmosphere in the forms of CO_2. This study relates β to the yield of sawtimber and assumes that all yields other than sawtimber release back into the atmosphere when the stand is harvested at time T.

Sweden has introduced a tax on carbon dioxide since 1991. Such a tax provides a monetary measure of the value of carbon sequestration. Currently, the level of the tax differs in the sources of CO_2 emission. The tax is 0.09 SEK/kg$\times CO_2$ on emissions from the manufacturing industry, or 0.37 SEK/kg$\times CO_2$ otherwise (see, Kriström, 1997). This study assumes that the CO_2 price, P_c, is equal to the current levels of CO_2 tax.

Numerical solutions are based on the following economic data. Regeneration cost includes a fixed cost, 1,150 SEK/ha, and a variable cost, 2.0 SEK/seedling. Pre-commercial thinning costs 1,530 SEK/ha. The cost of final harvest is 90 SEK/m^3. Timber products at final harvest include saw-timber and pulpwood. The distribution of sawtimber and pulpwood per m^3 yield at a certain age is estimated using the function of Gong (1995). The net price of sawtimber is 460 SEK/m^3 and pulpwood 290 SEK/m^3 (Johansson, 1997).

RESULTS AND DISCUSSION

Define as a timber production (TP) stand a forest stand that is managed for single timber production, and as a timber-carbon (TC) stand a forest stand that is managed for joint timber production and carbon sequestration. Equation (1) is used to estimate the optimal planting density and the corresponding optimal rotation and present value for each of these two stands. We obtain the optimal solution to a TP stand simply by setting the CO_2 price, P_c, in Equation (1) being zero. Table 1 presents the optimal solutions for site index T16, T20 and T24 at three levels of interest rate and two levels of the CO_2 price. In Table 1, the optimal planting density, optimal rotation and the corresponding present value are denoted by N_{tp}, T_{tp} and NPV_{tp}, respectively, to a TP stand and by N_{tc}, T_{tc} and NPV_{tc} to a TC stand.

TABLE 1. OPTIMAL SOLUTIONS TO THE STANDS WHEN FOREST CARBON SEQUESTRATION IS VALUED OR NOT.

P_c	0.0 SEK per kg CO_2			0.09 SEKper kg CO_2					0.37 SEKper kg CO_2				
	N_{tm}	T_{tm}	NPV_{tm}	N_{tc}		T_{tc}	NPV_{tc}		N_{tc}		T_{tc}	NPV_{tc}	
						Interest rate = 2%							
T16	1190	86	4668	2110	77%	128	16338	250%	4500	278%	200	77546	1561%
T20	1480	72	13347	2280	54%	108	31288	134%	4500	204%	200	126286	846%
T24	1810	63	25690	2440	35%	92	50795	98%	4500	149%	200	183216	613%
						Interest rate = 3%							
T16	610	76	–149	1690	177%	108	6404	/	4370	616%	200	44059	/
T20	1130	61	3510	1980	75%	92	14254	306%	4500	298%	200	74287	2016%
T24	1350	53	9457	2210	64%	81	25062	165%	4500	233%	200	111365	1078%
						Interest rate = 4%							
T16	500	69	–1406	1350	170%	96	2631	/	3910	682%	200	27919	/
T20	670	56	222	1770	164%	82	7268	3174%	4500	572%	200	48321	21666%
T24	1010	47	3345	2080	106%	73	13987	318%	4500	346%	200	74317	2122%

Table 1 shows that the inclusion of carbon sequestration benefits into forest management encourages forest owners to use a high planting density, compared to the optimal planting density that maximizes only timber value. In the case where the site index = T20 and the interest rate = 3%, for example, the N_{tm} is 1,130 trees/ha. However, when the carbon benefit is included and optimized together with the timber value, the optimal planting density (N_{tc}) goes up to 1,980 trees/ha at 0.09 SEK/kg×CO_2 and 4,500 trees/ha at 0.37 SEK/kg×CO_2. The increase in the optimal planting density is 75% (Table 1, column 6) and 298% (Table 1, column 11), respectively. Figure 1 shows that the percentage increase of the optimal planting density increases as the CO_2 price increases. In some cases, the optimal planting density is bounded at 4,500 trees/ha when the CO_2 price is at 0.37 SEK/kg×CO_2. The main reason for this is the restriction of the growth simulator on the stand density as stated before.

Figure 1 shows that the percentage increase in the optimal planting density increases with the increase of the interest rate, others being equal. This implies that the effect of carbon benefits on the optimal planting density is relatively larger when the interest rate is high than when it is low. Let us consider an extreme situation when the inter-

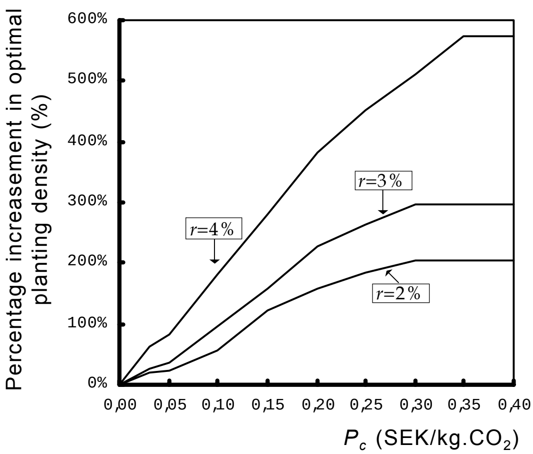

FIGURE 1. PERCENTAGE INCREASE IN OPTIMAL PLANTING DENSITY INCREASES WITH THE INCREASE OF THE CO_2 PRICE AND IS RELATIVELY HIGH WHEN THE INTEREST RATE IS HIGH. SITE INDEX: T20.

est rate is zero, at which the discount coefficient to the benefit of carbon sequestration and the cost of carbon releases is equal to 1.0 at any point in time. In this case, the total benefit of carbon sequestration over time should be almost completely balanced out by the total cost of the carbon release, and the net benefit of forest carbon sequestration would be close to zero. Consequently, the carbon sequestration only slightly affects the optimal planting density. In the case where the interest rate is high, the benefits of carbon sequestration will dominate the total profits, especially when the carbon price is high, and the optimal planting density is determined mainly by the benefit from carbon sequestration. Therefore, the effects of carbon sequestration benefits on the optimal planting density are relatively high when the interest rate is high.

Figure 2 shows that the percentage increase in the optimal planting density increases with the decrease of the site index, others being equal. It implies that, the inclusion of carbon benefit into forest management has a relatively greater impact on the optimal planting density on high productive sites than on low productive sites. Compared to high productive sites, the benefits of carbon sequestration on low productive sites contribute a dominant part to the total profits, and the optimal planting density on low productive site is mainly determined by the carbon sequestration benefit. Therefore, the effect of carbon benefit is relatively larger on the low productive site than on the high productive site.

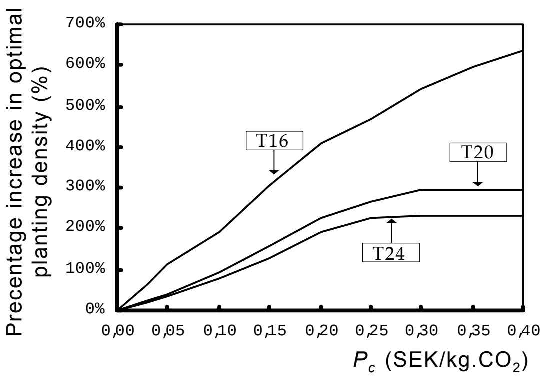

FIGURE 2. PERCENTAGE INCREASE IN OPTIMAL PLANTING DENSITY IS RELATIVELY HIGH ON LOW PRODUCTIVE SITES. INTEREST RATE: 3%.

Carbon sequestration benefits may make an unprofitable investment switch to profitable (Table 1). In the case where the site index = T16 and the interest rate = 3%, for example, the optimal N_{tm} is 610 trees/ha and the optimal NPV_{tm} is negative (–149 SEK/ha). This investment is not profitable. When the value of carbon sequestration is included and optimized, however, the optimal planting density (N_{tc}) moves up to 1,690 trees/ha and the optimal NPV_{tc} is 6,404 SEK/ha at 0.09 SEK/kg×CO_2. In this case, the investment is profitable.

The optimal rotation of a TC stand is longer than the one of a TP stand (Table 1). Moreover, the optimal rotation increases as the CO_2 price increases. This is consistent with the results of other researchers (Plantinga & Birdsey, 1994; van Kooten, Binkley & Delcourt, 1995; Hone & Solberg, 1997). It should be noted that the maximum optimal rotation obtained in the study is 200 years as shown in the tables. It has been mentioned in the proceeding section that the growth simulator employed restricts the longest stand age to be at 120 years and we arbitrarily extend it up to 200 years. If this restriction is further relaxed, the optimal rotation may exceed 200 years, and possibly, it might be never optimal to harvest a stand at all when the CO_2 price is very high. However, a further relaxation to the restricted stand age might bring about the numerical results much unreliable. Growth simulators that cover a long period are needed for forest management when carbon sequestration benefits are included.

The NPV_{tp}s of the TP stands that we present in Table 1 are calculated without counting the benefits of carbon sequestration. Consider that the carbon benefits are still available even in the TP stands, the NPV of the TP stand including the carbon benefit is recalculated. Table 2 shows the new NPV, denoted by NPV_{tp+c}, and the benefit gain of NPV_{tc} compared to NPV_{tp+c}. It is shown that the benefit is significantly less when the investment is optimized only for timber production than when it is optimized for joint timber production and carbon sequestration. In other words, the benefits of forest management could be significantly improved through adjusting the planting density if the forest carbon sequestration provides benefits. Figure 3 shows that both NPV_{tc} and NPV_{tp+c} increases as the CO_2 price

TABLE 2. THE PRESENT VALUES WHEN FOREST CARBON BENEFITS ARE COUNTED.

CO_2 price	0.0 SEK per kg CO_2		0.09 SEK per kg CO_2		0.37 SEK per kg CO_2	
	N_{tm} (tree/ha)	T_{tm} (year)	NPV_{tm+c}	Gain	NPV_{tm+c}	Gain
			Interest rate = 2%			
T16	1190	86	13566	20%	41246	88%
T20	1480	72	27353	14%	70926	78%
T24	1810	63	45982	10%	109113	68%
			Interest rate = 3%			
T16	610	76	4061	58%	17160	157%
T20	1130	61	11598	23%	36761	102%
T24	1350	53	21292	18%	58113	92%
			Interest rate = 4%			
T16	500	69	1323	99%	9818	184%
T20	670	56	4888	49%	19404	149%
T24	1010	47	10946	28%	34597	115%

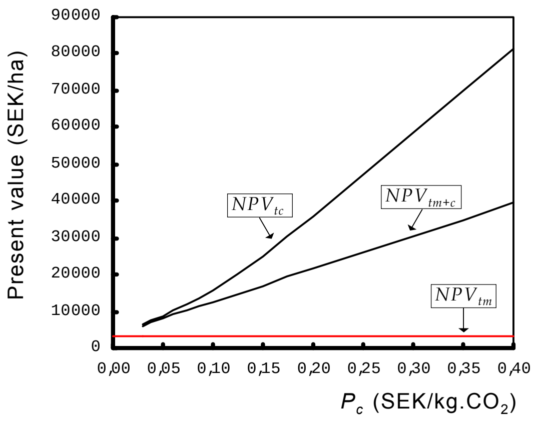

FIGURE 3. THE DISTANCE BETWEEN NPV_{tc} AND NPV_{tm+c} INCREASES WITH THE INCREASE OF THE CO_2 PRICE. INTEREST RATE = 3%, SITE INDEX = T20.

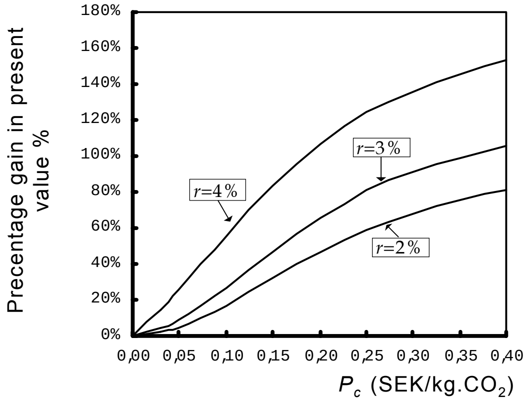

FIGURE 4. PERCENTAGE GAIN IN PRESENT VALUE IS RELATIVELY HIGH WHEN THE INTEREST RATE IS HIGH. SITE INDEX: T20.

increases, but the distance between NPV_{tc} and NPV_{tp+c} also increases with the increase of the CO_2 price.

Similar as the effects of carbon benefits on optimal planting density, Figure 4 shows that the percentage gain in present value increases as the interest rate increases, others being equal. This implies that the benefit gains are relatively larger when the interest rate is high than when it is low if carbon benefits are included into forest management. Figure 5 shows that the percentage gain in present value decreases as the site index increases, others being equal. It implies that the benefit gains are relatively larger on low productive sites than on high productive sites.

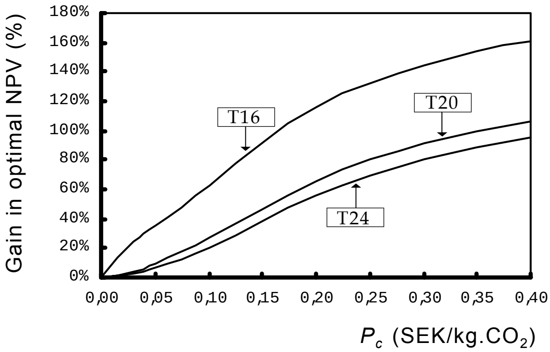

FIGURE 5. PERCENTAGE GAIN IN PRESENT VALUE IS RELATIVELY HIGH ON LOW PRODUCTIVE SITES, OTHERS BEING EQUAL. INTEREST RATE: 3%.

CONCLUSIONS

This study analyzes the effects of the benefit of forest carbon sequestration on the optimal planting density of Scots pine. Numerical results obtained are to a large extent specific to what has been in the context, but they do have general implications important to investments in forest plantations in which forest carbon sequestration are considered to have benefits.

The main conclusion is that, first, when carbon sequestration benefits are included into forest management, forest owners prefer to establish denser forest stands. Meanwhile, forest owners may extend their investments on some of low productive sites. Investments on these sites are unprofitable when carbon benefits are not counted. Since the additional benefit of carbon sequestration, the profitability has been increased.

Second, the effect of carbon benefits on the optimal planting density is relatively greater on low productive sites than on high productive sites, others being equal. This is also true with respect to the benefit gain in present value. Third, the effect of carbon benefits on the optimal planting density is relatively greater when the interest rate is high than when it is low, others being equal. This is also true with respect to the benefit gain in present value.

It is assumed in the study that a tax would be imposed on carbon released at the end of the rotation. The tax the forest owner should pay is calculated simply based on the amount of the non-sawtimber. The tax imposed in this way is to some extent arbitary. In the real forestry world, the carbon fixed in the timber would release in the normal case back into the atmosphere gradually. It is more reasonable to calculate the tax based on the specific patterns of the carbon release process. In this case the amount of the tax should be the summation of the discounted flow of the carbon tax over the whole process of the carbon release. This should not incease the amount of tax significantly because of the discount.If this is true, our general implications should not change.

This study applies an age-limited stand growth function to the estimation of both timber growth and the amount of carbon stored. This limitation results in a number of binding optimal rotations being obtained. It would thus be of applied interest to develop growth functions that covers a long period. If so, it is expected that the approximation of at least the optimal rotation may be improved. In addition, we use the mean annual growth of timber in stead of the current annual growth of timber to approximate the amount of the carbon flow from planting to the time at which the stand reaches a dominant height of 10m. To better the estimation of the amount of the carbon stored during the earlier stage of an established stand, it is necessary to build growth functions that are able to estimate the annual growth at earlier stages in the stand development.

The optimal planting density that maximizes the profit of joint timber production and carbon sequestration may be much higher than the one that maximizes only the profit of timber production. Meanwhile, the gain in present value through adjusting the planting density is very large when the carbon price is high. It must be noted that a gain in the carbon benefit is at a cost of a reduction in the timber benefit when the planting density is above the planting density that optimizes the profit of timber production. This brings about a question of how to subsidize private forest owners so that they would like to adjust the privately optimal planting density to the socially optimal level. It would be of interest to include this issue in future research. One possible alternative is to pay the forest owner in a way that the forest investment in carbon sequestration is as profitable as timber management. In other words, we should pay the forest owners the economic loss in the timber value if they adjust the planting density above the level that maximizes only the timber value. This would leave the investors indifferent between the two alternatives. However, the forest owner would prefer the management of carbon sequestration forest, if they can get the subsidy. The forest owner would prefer to get an annual flow of economic return other than get a return in 60–70 years future, which are in full of uncertainty.

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