Central Asian Journal of Environmental Science and Technology Innovation **3** (2020) 134-142

RESEARCH PAPER

Fundamental principles of optimal utilization of forests with consideration of global warming

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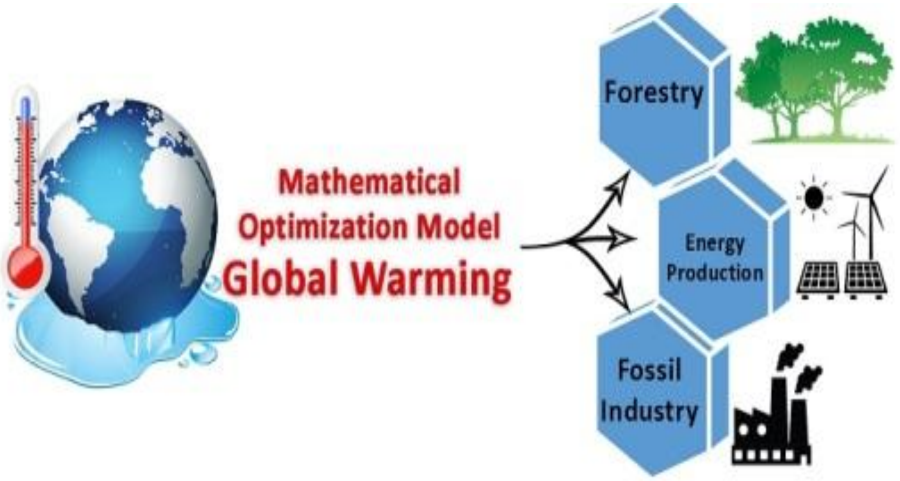
Highlights

- The global climate is found on the international agenda.
- Expansion of the managed forest area is highly important to reduce global warming.
- Forest management should be optimized with consideration of climate, energy, the fossil industry and CCS.

Graphical Abstract



Article Info

Receive Date: 27 September 2019
Revise Date: 20 January 2020
Accept Date: 15 February 2020
Available online: 25 February 2020

Keywords:
Global warming
CO_2 absorption
Forest management
Optimization

Abstract

The global climate can be affected via management of the forests in all parts of the world. A general global mathematical optimization model is defined. The average forest harvesting level is determined as proportional to the area under active forest management. If the area of active forest management increases, the area covered by forests in dynamic equilibria with net CO_2 absorption close to zero, decreases. Hence, the absorbed amount of CO_2 is an increasing function of the forest harvesting level. The total economic result in the form of the present value over an infinite horizon, is optimized, with consideration of global warming, subject to a constraint that makes sure that the total energy production is held constant. The results contradict the common opinion that the best way to use the forest with consideration of global warming, is to maximize the stock level in the forest, and if possible, to completely stop harvesting.

10.22034/CAJESTI.2020.03.02

E-ISSN: 2717-0519
P-ISSN: 2717-4034

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1. Introduction

We may ask ourselves how we should take the global warming and CO_2 issue into account when we determine the optimal way to manage the forests. In other research, various aspects of forests as carbon sinks were studied (Solberg, 1997; Kallio et al., 2018; Rautiainen et al., 2018). A growing forest captures and stores CO_2 from the atmosphere. Therefore, if we think that it is valuable to reduce the CO_2 contents of the atmosphere, it is valuable to let the stock of the forest grow large and store large amounts of CO_2. Economic plantation forestry with consideration of risk has been described and analyzed (Lohmander, 2000; 2007). Trees do not grow forever. Sooner or later, the growth level is reduced, because the age of the trees becomes too high and the competition between neighbor trees too strong for continued growth. Furthermore, at some age, trees die, and once again release the stored CO_2 to the atmosphere. Occasionally, many old trees die at the same time, for instance when we have storms or fires. Then, a lot of CO_2 is simultaneously released. The expected average stock level stabilizes at some level. As a consequence, in the long run, the forests can not store more CO_2 than some maximum level that we may denote XMAX. Let us define the present point in time as year 0.

Assume that we start with bare land. We plant seedlings and we obtain a growing forest. After T years, the forest has captured S units of CO_2. $S < XMAX$ (In case we would let the forest grow forever, we would approach, and possibly reach, the stock level XMAX). At time T, we harvest the forest stand. We use 50% of the wood for energy and 50% for traditional forest industry products. When we produce energy by burning the biomass, we use the technology denoted CCS, carbon capture, and storage. We store the CO_2 permanently in a reliable way, far below the surface of the Earth, according to some of the available methods. The part of the biomass that is not used to produce energy, may be used to produce timber houses, paper, and other products. Some of these other products, such as timber houses, will store the CO_2 for a considerable time, maybe centuries (Simo-Tagne and Bennamoun, 2018). Other products, such as paper, maybe recycled many times and eventually burnt to produce energy. In the long run, most products produced from the forest raw material may burn and produce energy. To make this introductory example simple, we make the assumption that all of the coal contained in the CO_2 captured by the trees, sooner or later becomes available for energy production. Of course, as in all other models, more details may be introduced if necessary. Then, the CCS technology can once again be used to store the CO_2 permanently, below the surface of the Earth.

We may conclude that the total amount of CO_2 that may be captured from the atmosphere and permanently stored is much higher if we, in a repeated sequence, harvest the forest (for instance at stock level S), use some (let us say 50%) of the biomass for instant energy production, capture and store the CO_2 and replant the area again. This way, we may, in the long run, capture and store any amount of CO_2 from the atmosphere. This way, we do not reduce the emissions of CO_2 but we still make sure that the CO_2 level of the atmosphere is reduced. If you just leave the forest forever, without harvesting, you will not be able to capture and store more than XMAX. In the long run, if you use the suggested sequence of harvests and CCS, the permanently stored amount of CO_2 approaches, on average, S/T per year. The stock of permanently stored CO_2 approaches S*Y where Y is an integer. Y is the number of harvests and CCS cycles that have already taken place. The conclusion is the following: If we are interested to reduce global warming, one way to do this is to reduce the CO_2 contents of the atmosphere. In that case, we should not leave the forests without management. We may sequentially harvest and replant the area, using some part of the biomass for energy in combination with the CCS technology. This way, we can reduce the future level of CO_2 in the atmosphere.

Continuous extraction under risk is an area of relevance to many different natural resources (Xi et al., 2017). General optimal results in that area have been derived (Lohmander, 2007; Jacobsen et al., 2018). Now we know that and why plantation forestry and CCS can be used in combination to reduce the CO_2 level in the atmosphere. The reader may then argue that plantation forestry is not always consistent with a good environment from other perspectives. Furthermore, some people may dislike CCS, where CO_2 is stored below ground. Maybe the method is not safe? Maybe the stored CO_2 may suddenly be released again? The main forestry principle, *"Do not leave the forest without control"*, may still be applied, without even considering CCS and plantation forestry. It is quite possible to use CCF, continuous cover forestry, instead of plantation forestry. With this method, the forest always contains trees of different sizes.

Periodically, the larger trees are harvested and removed from the forest. These trees can be used for different purposes, such as logs and panels for buildings. The trees can also replace fossil fuels in the energy industry, directly or as a second use, when the trees have first been used for other purposes in the construction sector during some decades. This way, since the forest continuously produces fuels, it is feasible to decrease the level of fossil fuel extraction. Hence, forests can be considered as a source of renewable energy (Cambero et al., 2016; Lee and Den, 2016; Paolucci et al., 2016; Gutiérrez et al., 2017; Husgafvel et al., 2018; Pang et al., 2019). We may denote replacing fossil fuels by forestry fuels by "substitution". Hence, we do not store CO_2 below ground but we decrease the extraction of fossil fuels, which has the same kind of effect on the net emission of CO_2 released to the atmosphere. Of course, it is also possible to combine substitution with CCS. This way we may reduce the net emissions even more. An econometric study of bioenergy development has been made and provided for us with a cross-sector perspective on the forest products industry, where bioenergy is an important component (Lee, 2017; Guerrero and Hansen, 2018)

Furthermore, from an environmental point of view, CCF is usually considered more favorable than plantation forestry. Since the ground is constantly covered by trees of different sizes and sometimes also different species, such a forest is usually more suitable for many kinds of animals and plants. Continuous cover forests also give fewer problems with soil erosion, floods, landslides, and winds. Furthermore, forests of the CCF type are often more useful for different recreational purposes. In the rest of this paper, we consider a large scale decision problem. We have the global responsibility of energy, fossil fuels, forestry, and the climate. The following analysis makes it possible for the reader to investigate every assumption and step in the analysis. The assumptions have been selected for generality and simplicity. Of course, more detailed models may be constructed. That would however lead to reduced transparency.

2. Materials and Methods

The problem and model to be analyzed in this section are defined here: We are producing hot water and electricity via CHP, combined heat, and power. CHP represents a very common energy industry, in particular in the Nordic countries. The hot water is used for district heating and electricity, power, if used for all kinds of purposes. The input is a mix of fossil fuels, such as coal and oil, denoted by f, and renewable raw materials from the forests, h. $h \propto A$ and A denotes an area of actively managed forest land. The units f and h are Mg Coal per year. $C_f(f)$ and $C_h(h)$ are cost functions per year. We are responsible for all costs associated with fossil fuel, $C_f(f)$. The marginal cost is strictly positive, $\frac{dC_f}{df} > 0$ and the cost function is strictly convex, $\frac{d^2C_f}{df^2} > 0$. We are also responsible for all costs of forest production, harvesting, and logistics, $C_h(h)$. The marginal cost is strictly positive, $\frac{dC_h}{dh} > 0$ and the cost function is strictly convex, $\frac{d^2C_h}{dh^2} > 0$.

The activities in CHP, the fossil industry, and forestry influence the long term development of the climate. The global average temperature, $T(N)$, is a function of the long-run net emission of CO_2, N. The function is strictly increasing. $\frac{dT}{dN} > 0$. The net emission is a function of the levels of fossil extraction and forestry.

$N = (1+\alpha_f)f + \alpha_h h$. α_f is the emission from extraction and logistics associated with fossil fuels. $\alpha_f > 0$. α_h is the emission caused by operations and logistics associated with forestry. $\alpha_h > 0$. With forestry in equilibrium, the harvest level, h, removes coal from the forests. This coal is released to the atmosphere in the CHP process. Then, the forests absorb the same amount of coal, via photosynthesis, when they grow back to the same stock level as before harvesting. The coal from fossil fuels behaves differently. It is no absorbed by the fossil layers again when it has been emitted to the atmosphere in the CHP process. We make the following assumption, which describes the typical real situation: $\alpha_h < 1+\alpha_f$. We want to minimize the present value of all costs. This is equivalent to maximizing the objective function Z, the present value of all costs multiplied by -1. (In this model, maximization is preferred to minimization, because it simplifies extensions of the model to handle more sectors, revenues and cost functions). k_π is the multiplier that transforms yearly costs to the present value of all costs during an infinite horizon. $k_\pi > 0$. k_T is the coefficient that transforms global mean temperature to the present value of the cost of global warming. $k_T > 0$. The objective function is:

$$Z = -k_\pi (C_f(f) + C_h(h)) - k_T T\left(N(.)\right) \tag{1}$$

We want to keep the CHP production constant. This means that the total input of coal, m, in the CHP process should be constant. $m > 0$. Hence, $f + h \geq m$. The objective function makes sure that the optimal total input will be exactly m. Now, our optimization problem can be stated as:

$$\begin{aligned}
&\max_{f,h} Z = -k_\pi (C_f(f) + C_h(h)) - k_T T(N(f,h;\alpha_f,\alpha_h)) \\
&s.t. \\
&f + h \geq m
\end{aligned} \tag{2}$$

The Lagrange function is:

$$L = -k_\pi (C_f(f) + C_h(h)) - k_T T(N(f,h;\alpha_f,\alpha_h)) + \lambda(f + h - m) \tag{3}$$

We let stars denote optimal values and make the following typical and reasonable assumptions: The shadow price of the input constraint in the CHP process (the dual variable) is strictly positive. $\lambda^* > 0$. This means that we should not produce more fossil fuels and forest fuels than what is needed in the CHP process. Hence, the input constraint in the CHP process is binding at optimum. We also assume that the optimal level of fossil input is strictly positive, $f^* > 0$. (Note that the level of f^* maybe extremely low.) We also assume that forestry activities are strictly positive, $h^* > 0$. Thanks to these assumptions, the Karush Kuhn Tucker conditions can be used to derive the following conclusions:

$$\left(\lambda^* > 0\right) \wedge \left(\lambda \frac{dL}{d\lambda} = 0\right) \Rightarrow \left(\frac{dL}{d\lambda} = 0\right) \tag{4}$$

$$\left(f^* > 0\right) \wedge \left(f \frac{dL}{df} = 0\right) \Rightarrow \left(\frac{dL}{df} = 0\right) \tag{5}$$

$$\left(h^* > 0\right) \wedge \left(h \frac{dL}{dh} = 0\right) \Rightarrow \left(\frac{dL}{dh} = 0\right) \tag{6}$$

Hence, the following three equations, first order optimum conditions, determine the optimal solution:

$$\frac{dL}{d\lambda} = f + h - m = 0 \tag{7}$$

$$\frac{dL}{df} = -k_\pi \frac{dC_f}{df} - k_T \frac{dT}{dN}\left(1+\alpha_f\right) + \lambda = 0 \tag{8}$$

$$\frac{dL}{dh} = -k_\pi \frac{dC_h}{dh} - k_T \frac{dT}{dN}\alpha_h + \lambda = 0 \tag{9}$$

The second-order conditions of a unique maximum are assumed to be satisfied. Now, we are interested to know how the optimal mix of inputs changes if the importance of global warming increases. How should the optimal levels of f and h change if the parameter k_T in the objective function increases? In order to answer this question, we have to investigate how the optimal decisions f^* and h^* the optimized shadow price, λ^*, simultaneously change, when the parameter change $dk_T > 0$ occurs. First, let us investigate some functions and derivatives that will soon be needed in the calculations.

$$U = T\left(N\left(f,h;a_f,\alpha_h\right)\right) \tag{10}$$

$$\frac{dU}{df} = \frac{dT\left(N\left(f,h;a_f,\alpha_h\right)\right)}{dN}\frac{dN\left(f,h;a_f,\alpha_h\right)}{df} \tag{11}$$

$$\begin{aligned}\frac{d^2U}{df^2} &= \left(\frac{d^2T\left(N\left(f,h;a_f,\alpha_h\right)\right)}{dN^2}\frac{dN\left(f,h;a_f,\alpha_h\right)}{df}\right)\frac{dN\left(f,h;a_f,\alpha_h\right)}{df}\\ &\quad+\frac{dT\left(N\left(f,h;a_f,\alpha_h\right)\right)}{dN}\underbrace{\frac{d^2N\left(f,h;a_f,\alpha_h\right)}{df^2}}_{=0}\end{aligned} \tag{12}$$

$$\frac{d^2U}{df^2} = \frac{d^2T}{dN^2}\left(\frac{dN}{df}\right)^2 + \frac{dT}{dN}(0) \tag{13}$$

$$\frac{d^2U}{df^2} = \frac{d^2T}{dN^2}\left(\frac{dN}{df}\right)^2 \tag{14}$$

In a similar way, we may also make the following derivations:

$$\frac{d^2U}{dfdh} = \frac{d^2T}{dN^2}\left(\frac{dN}{df}\right)\left(\frac{dN}{dh}\right) \tag{15}$$

and

$$\frac{d^2U}{dh^2} = \frac{d^2T}{dN^2}\left(\frac{dN}{dh}\right)^2 \tag{16}$$

Now, we differentiate the first order of optimum conditions with respect to λ^*, f^*, h^* and k_T.

$$\begin{bmatrix} 0 & 1 & 1 \\ 1 & \left(-k_\pi\frac{d^2C_f}{df^2} - k_T\frac{d^2T}{dN^2}\left(1+\alpha_f\right)^2\right) & \left(-k_T\frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right)\right) \\ 1 & \left(-k_T\frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right)\right) & \left(-k_\pi\frac{d^2C_h}{dh^2} - k_T\frac{d^2T}{dN^2}\left(\alpha_h\right)^2\right) \end{bmatrix}\begin{bmatrix} d\lambda^* \\ df^* \\ dh^* \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{dT}{dN}\left(1+\alpha_f\right)dk_T \\ \frac{dT}{dN}\alpha_h dk_T \end{bmatrix} \tag{17}$$

We define the following determinant:

$$|D| = \begin{vmatrix} 0 & 1 & 1 \\ 1 & \left(-k_\pi \frac{d^2C_f}{df^2} - k_T \frac{d^2T}{dN^2}\left(1+\alpha_f\right)^2\right) & \left(-k_T \frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right)\right) \\ 1 & \left(-k_T \frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right)\right) & \left(-k_\pi \frac{d^2C_h}{dh^2} - k_T \frac{d^2T}{dN^2}\left(\alpha_h\right)^2\right) \end{vmatrix} \tag{18}$$

$$\begin{aligned} |D| = &-k_T \frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right) - k_T \frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right) \\ &+k_\pi \frac{d^2C_h}{dh^2} + k_T \frac{d^2T}{dN^2}\left(\alpha_h\right)^2 + k_\pi \frac{d^2C_f}{df^2} + k_T \frac{d^2T}{dN^2}\left(1+\alpha_f\right)^2 \end{aligned} \tag{19}$$

$$|D| = k_\pi\left(\frac{d^2C_h}{dh^2} + \frac{d^2C_f}{df^2}\right) + k_T \frac{d^2T}{dN^2}\left(\left(\alpha_h\right)^2 + \left(1+\alpha_f\right)^2 - 2\alpha_h\left(1+\alpha_f\right)\right) \tag{20}$$

$$\begin{aligned} |D| = k_\pi&\left(\frac{d^2C_h}{dh^2} + \frac{d^2C_f}{df^2}\right) + k_T \frac{d^2T}{dN^2}\left(\alpha_h - \left(1+\alpha_f\right)\right)^2 \\ >0 \quad &\quad >0 \qquad\quad \geq 0 \qquad\qquad >0 \end{aligned} \tag{21}$$

In case $\frac{d^2T}{dN^2} \geq 0$, we know that $|D| > 0$. $|D| > 0$. This is also a unique second-order maximum condition. Observation: If the absolute value $\frac{d^2T}{dN^2}$ is sufficiently low, we may allow $\frac{d^2T}{dN^2} < 0$, even if $|D| > 0$. In any case, we assume that $|D| > 0$ and that we have a unique maximum. Now, Cramer's rule can be used to determine the sign $\frac{df^*}{dk_T}$.

$$\frac{df^*}{dk_T} = \frac{\begin{vmatrix} 0 & 0 & 1 \\ 1 & \left(\frac{dT}{dN}\left(1+\alpha_f\right)\right) & \left(-k_T \frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right)\right) \\ 1 & \left(\frac{dT}{dN}\alpha_h\right) & \left(-k_\pi \frac{d^2C_h}{dh^2} - k_T \frac{d^2T}{dN^2}\left(\alpha_h\right)^2\right) \end{vmatrix}}{|D|} \tag{22}$$

$$\frac{df^*}{dk_T} = \frac{\frac{dT}{dN}\left(\alpha_h - \left(1+\alpha_f\right)\right)}{|D|} \tag{23}$$

$$\frac{df^*}{dk_T} < 0 \tag{24}$$

Conclusion: The optimal level of f^*, the fossil energy input in the CHP process, is a strictly decreasing function of the value of k_T, the parameter representing the cost of global warming in the objective function. Cramer's rule can also be used to determine the sign $\frac{dh^*}{dk_T}$.

$$\frac{dh^*}{dk_T} = \frac{\begin{vmatrix} 0 & 1 & 0 \\ 1 & \left(-k_\pi \frac{d^2C_f}{df^2} - k_T \frac{d^2T}{dN^2}\left(1+\alpha_f\right)^2\right) & \left(\frac{dT}{dN}\left(1+\alpha_f\right)\right) \\ 1 & \left(-k_T \frac{d^2T}{dN^2}\alpha_h\left(1+\alpha_f\right)\right) & \left(\frac{dT}{dN}\alpha_h\right) \end{vmatrix}}{|D|} \tag{25}$$

$$\frac{dh^*}{dk_T} = \frac{\frac{dT}{dN}\left(\left(1+\alpha_f\right)-\alpha_h\right)}{|D|} \tag{26}$$

$$\frac{dh^*}{dk_T} > 0 \tag{27}$$

The optimal level of h^*, the renewable forestry input in the CHP process, is a strictly increasing function of the value of k_T, the parameter representing the cost of global warming in the objective function.

3. Results and Discussion

A quite general global model including the central components in, and relevant links between, energy production, the fossil industry, forestry, and global warming, was created. The total economic result in the form of the present value over an infinite horizon was optimized, with consideration of global warming, subject to a constraint that makes sure that the total energy production is held constant. Two general results were proved: The optimal level of f^*, the fossil energy input in the CHP process, is a strictly decreasing function of the value of k_T, the parameter representing the cost of global warming in the objective function. The optimal level of h^*, the renewable forestry input in the CHP process, is a strictly increasing function of the value of k_T, the parameter representing the cost of global warming in the objective function.

Hence, if it is considered more important to avoid global warming, then we should increase the use of forest energy inputs and decrease the use of fossil energy inputs in the combined heat and power industry. This result may seem obvious to some readers. However, it explicitly contradicts the opinion that is often expressed in the policy debate: It is a very common opinion that the best way to use the forest with consideration of global warming, is to maximize the stock level in the forest, and if possible, to completely stop harvesting. This paper has focused on optimal forest management with consideration of global warming and other aspects. It is quite clear that the number of possible alternative model specifications is enormous. In this paper, the main ambition has been to develop a highly transparent and general model that can be used to derive general conclusions. The interested reader is encouraged to extend the model in different ways, including locally relevant conditions in the different sectors and more decision variables. With such models, it is in however usually not possible to derive general conclusions of the type found in this paper.

As always, it is important to be aware that the model assumptions influence the results. One of the important assumptions in this model is that the average harvest volume is proportional to the area of actively managed forest. In large parts of the world, this can be considered typical. For instance, in Canada and in the Russian Federation, forests have often been intensively harvested close to sawmills, pulp mills, roads, and railroads. The forests in remote areas have often not been managed at all. Sometimes these unmanaged remote forests burn and sometimes they are felled by storms. The carbon levels of these forests are, on average, close to dynamic equilibria. Hence, the net uptake of CO_2 is on average close to zero. In such cases, it is quite clear that the average net uptake of CO_2 increases if also these forest areas are integrated into the actively managed forest class with periodic harvests of the largest trees. In case we would not have the assumption that the average harvest volume is proportional to the area of actively managed forest, then it is not always the case that the average CO_2 uptake is an increasing function of the average harvest volume. Then, we also have to consider and analyze the intensity of the management of each area unit. Such analyses have been made and new general results in that area will hopefully soon be reported in future publications. Finally, we should not forget that forests are essential to many kinds of life. Some species are very sensitive to disturbances and need undisturbed forests in order to survive. For this reason, it is important to maintain some natural reserves in our forests. These should never be harvested.

4. Conclusions

a. Presently, the global climate is found on the international agenda. The forests of the world provide many options to influence the future climate. Since it is considered highly important to avoid global warming, the use of forest energy inputs should increase and the use of fossil energy inputs in the combined heat and power industry should decrease.

b. The analysis of optimal forest management with consideration of climate, energy, the fossil industry, and CCS can be extended in several directions. The value of preservation of natural forest reserves and the value of recreation in forest areas may be integrated into the model system in future studies.

Acknowledgments

The author is grateful to the energy company Eon. The research grants from Eon made it possible to start a research project in the bioenergy field.

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How to cite this paper:

Lohmander, P., 2020. Fundamental principles of optimal utilization of forests with consideration of global warming. *Cent. Asian J. Environ. Sci. Technol. Innov.*, **3**, 134-142.