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A carbon cycle optimization method for fossil and biomass energy utilization

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Abstract−A carbon cycle model based environmental optimization method is proposed that minimizes the maximum and steady state atmospheric CO_2 concentration. The proposed method is applied to a fossil to biomass energy transition problem. The optimization results indicate that a gradual change is more effective than immediate or delayed step changes, and that afforestation is essential in addition to reforestation. From these results, it is suggested that, in order to avoid a huge carbon debt, fossil fuels should be used as a complement until biomass resources are increased to an optimum level by afforestation. Furthermore, it is predicted that using biomass instead of fossils cannot fully recover the initial state, even if supported by intensive afforestation. The misleading concept of carbon neutrality of biomass is also clarified using the proposed model, which shows that biomass is not a preferable alternative to fossil fuels. Nonetheless, the proposed method is applicable to optimal energy utilization of fossil and biomass resources.

Keywords: Carbon Cycle, Optimization, Fossil, Biomass, Energy Utilization

INTRODUCTION

Carbon neutrality, which refers to achieving net zero carbon dioxide emissions [1], is now an urgent mission for the world. The chemical industry is reducing emissions by carbon capture and/or utilization, and by replacement of energy sources and/or raw materials [2]. These efforts should be intensified in order to achieve carbon neutrality. The ultimate goal of carbon neutrality is to maintain moderate levels of greenhouse gases in the atmosphere. Therefore, to correctly evaluate the effect of carbon neutrality, the earth should be viewed as a system of carbon cycle [3]. Yi et al. [4] reviewed carbon cycles in the coal based chemical industry, and suggested the conversion of CO_2 with the incorporation of renewable energy. Kätelhön et al. [5] analyzed product life cycles to evaluate climate change mitigation by carbon capture and utilization. Gabrielli et al. [6] reviewed methods to achieve a carbon neutral chemical industry, including the use of biomass. González-Garay et al. [7] proposed a process systems engineering (PSE) and life cycle assessment (LCA) based approach to a solar-based carbon neutral chemical industry. However, these works do not tell us how soon we can achieve our goal, i.e., a moderate steady state level of CO_2 in the atmosphere.

According to the Paris Agreement of 2015, the emission of greenhouse gases should be rapidly reduced in order to achieve a balance with the capture from 2050, with the goal of limiting the global temperature rise until 2100 to 1.5 °C above the preindustrial level [8]. Intergovernmental Panel on Climate Change (IPCC), which is a United Nations (UN) affiliated organization, takes the lead of this project by issuing assessment reports with data and guidelines [9]. The National Aeronautics and Space Administration (NASA) is also actively dealing with climate issues [10], and for educational purposes, is sponsoring the Global Learning and Observations to Benefit the Environment (GLOBE) program [11]. As one of the projects in this program, a carbon cycle model is provided [12], and its online demonstration is available on the internet [13]. As carbon cycle analysis is essential in pursuing the Paris Agreement, this model was improved and termed GLOBE+ in our previous work [14].

As an approach to contributing to climate change mitigation, many coal fired power plants are adopting wood pellets as an alternative fuel, especially in Europe [15]. Although woody biomass is generally considered a clean and renewable energy source, the effectiveness of reducing the emission of greenhouse gases is questionable [16]. Most importantly, deforestation is inevitable, which raises a serious concern [15]. As a potential solution, a coal-biomass cofiring technique is also studied [17]. However, sustainability is achieved only when the global carbon cycle can reach a steady state. Therefore, all fossil fuels should be eventually replaced by energy sources that do not increase the total carbon in the active cycle. Wood pellets satisfy this necessary condition. However, the Paris Agreement is a sufficient condition that is much more difficult to satisfy.

Harvested plant biomass is often said to be carbon neutral even if combusted, because its carbon is originally from the atmosphere. However, note that, if it were just harvested and preserved, it would be technically carbon negative, i.e., the total carbon in the active cycle is reduced as if by carbon capture and storage. Therefore, carbon neutrality can be a misleading concept that encourages deforestation. From the environmental point of view, burning wood is equivalent to cutting trees and burning coal [14]. On the other hand, fossil fuels are carbon positive, i.e., the total carbon in the active cycle is increased, but increased CO_2 helps to grow forests [18]. It has been shown that biomass combustion causes more CO_2 in the atmosphere than fossil combustion, which is called carbon debt, for a period of time [14]. Therefore, fossil fuels are preferred in the short term and biomass in the long term, which poses an

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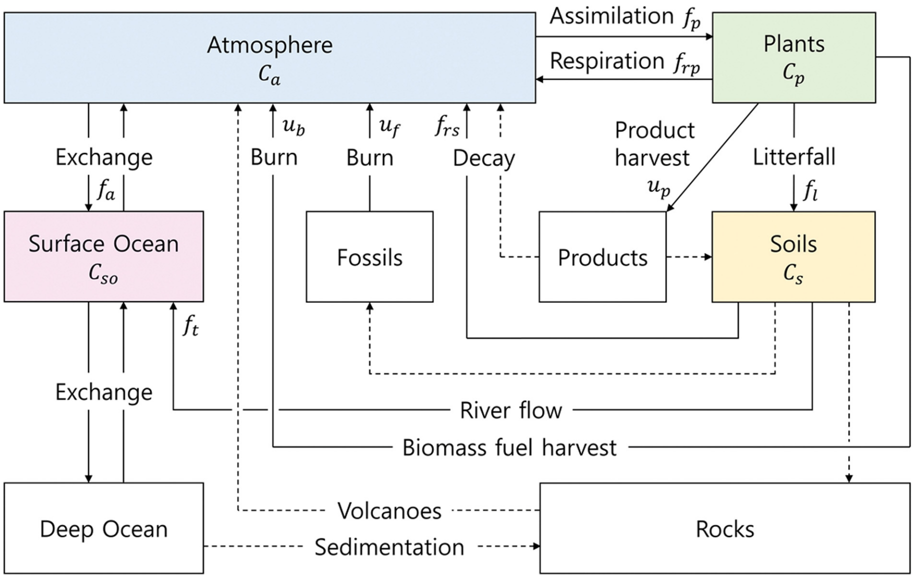

Fig. 1. Carbon cycle box model [14].

optimization problem.

PROPOSED METHOD

The suggested optimization problem is to minimize the maximum and steady state concentration of CO_2 in the atmosphere by managing fossil and biomass resources for specific energy demand. A carbon cycle model is proposed, which is extracted from the previous work [14]. The conceptual model is shown in Fig. 1. In the diagram, the boxes represent carbon reservoirs and the arrows represent the carbon flows. For simplification, only four carbon reservoirs (colored) and major carbon flows (solid arrows) are considered, which are mainly related to fuel combustion and plant harvesting. It is assumed that the influences of the deep ocean and the rocks are negligible, because they change on time scales of millennia [3]. It is also assumed that deforestation occurs only by harvesting. Then, the problem is formulated as follows.

$$\min_{h,s}(\max C_a,\ C_a(\infty))$$

subject to

$$\dot{C}_a = f_{rp}(C_p) + f_{rs}(C_s) - f_p(C_a, C_p, A_v) - f_a(C_a, C_{so}) + q \quad (1)$$

$$\dot{C}_p = f_p(C_a, C_p, A_v) - f_{rp}(C_p) - f_l(C_p) - h \quad (2)$$

$$\dot{C}_s = f_l(C_p) - f_{rs}(C_s) - f_t(C_s) \quad (3)$$

$$\dot{C}_{so} = f_a(C_a, C_{so}) + f_t(C_s) \quad (4)$$

$$\dot{A}_v = -f_d(h, s, C_p, A_v) \quad (5)$$

where
C_a=mass of carbon in the atmosphere, PgC
C_p=mass of carbon in plants, PgC
C_s=mass of carbon in soils, PgC
C_{so}=mass of carbon in the surface ocean, PgC
A_v=normalized vegetated land area
f_p=rate of photosynthesis, PgC/y
f_a=net rate of absorption to the surface ocean, PgC/y
f_{rp}=rate of plant respiration, PgC/y
f_{rs}=rate of soil respiration, PgC/y
f_l=rate of litterfall, PgC/y
f_t=rate of transfer from soils to the surface ocean by the river flow, PgC/y
f_d=net rate of deforestation, y^{-1}
q=rate of fuel combustion, PgC/y
h=rate of plant harvesting, PgC/y
s=target rate of biomass production by reforestation, PgC/y

The mass unit PgC represents 10^{15} grams of carbon, and thus equivalent to GtC. The rate expressions are obtained from the GLOBE+ model [14] as follows:

$$f_p(C_a, C_p, A_v) = k_p \eta_C(C_a)\eta_T(C_a) A_v^{1-\alpha}\left[\frac{C_p}{C_p(0)}\right]^{\alpha} \quad (6)$$

$$f_{rp}(C_p) = k_{rp}\frac{C_p}{C_p(0)} \quad (7)$$

$$f_{rs}(C_s) = k_{rs}\frac{C_s}{C_s(0)} \quad (8)$$

$$f_l(C_p) = k_l\frac{C_p}{C_p(0)} \quad (9)$$

$$f_t(C_s) = k_t\frac{C_s}{C_s(0)} \quad (10)$$

$$f_a(C_a, C_{so}) = k_{ao}[p_a(C_a) - p_a^*(C_a, C_{so})] \quad (11)$$

$$f_d(h, s, C_p, A_v) = \left[h(t) - \int_0^t s(t-\tau)\dot{g}(\tau)\,d\tau\right]\frac{A_v}{C_p} \quad (12)$$

where the rate constants are k_p=110 PgC/y, k_{rp}=55 PgC/y, k_{rs}=55 PgC/y, k_l=55 PgC/y, k_t=0.8 PgC/y, and k_{ao}=0.278 PgC/(ppm·y) [12]. The initial conditions are $C_a(0)$=750 PgC, $C_p(0)$=560 PgC, $C_s(0)$= 1,500 PgC, $C_{so}(0)$=890 PgC, and $A_v(0)$=1 [12], which correspond to the preindustrial levels [14].

In the photosynthesis rate function (6), η_C and η_T are CO_2 and temperature effect factors, respectively, which can be calculated as follows [12]:

$$\eta_C(C_a)=1.5\frac{p_a(C_a)-40}{p_a(C_a)+80} \tag{13}$$

$$\eta_T(C_a)=\frac{[60-T_g(C_a)][T_g(C_a)+15]}{1350} \tag{14}$$

where p_a is the concentration of CO_2 in the atmosphere (ppm), and T_g is the global temperature (°C), which can be predicted as follows [12]:

$$p_a(C_a)=\frac{280\text{ ppm}}{750\text{ PgC}}C_a \tag{15}$$

$$T_g(C_a)=15+0.01[p_a(C_a)-280] \tag{16}$$

In the absorption rate function (11), p_a^* is the equilibrium concentration of CO_2 in the atmosphere (ppm), which is calculated as follows [12]:

$$p_a^*(C_a, C_{so})=280\text{ (ppm/mM) } K_{CO_2}\frac{[HCO_3^-]^2}{[CO_3^{2-}]} \tag{17}$$

$$K_{CO_2}=0.0255+0.0019\ T_g(C_a) \tag{18}$$

$$[HCO_3^-]=\frac{[CO_2]_i-\sqrt{[CO_2]_i^2-A_T(2[CO_2]_i-A_T)(1-4K_{CO_3^{2-}})}}{1-4K_{CO_3^{2-}}} \tag{19}$$

$$K_{CO_3^{2-}}=0.000545+0.000006\ T_g(C_a) \tag{20}$$

$$[CO_2]_i=\frac{C_{so}}{(12\text{ gC/mol})(36.2\text{ PkL})} \tag{21}$$

$$[CO_3^{2-}]=\frac{A_T-[HCO_3^-]}{2} \tag{22}$$

where the volume unit PkL represents 10^{18} liters, from which the concentration unit mol/(kL) is derived, which is equivalent to mM, and A_T=2.222 mM, the total alkalinity of seawater [19].

In the deforestation rate function (12), s represents the target biomass production rate intended when planting seedlings. Therefore, s≥h is required. If s<h, h>0 leads to A_v=0, i.e., complete deforestation. Function g is a normalized tree mass growth function such that g(0)=0 and g(∞)=1. In this work, the Chapman-Richards growth function [20] is used.

$$g(t)=(1-e^{-kt})^p \tag{23}$$

where k (y^{-1}) and p (>1) are empirical parameters. This growth model is known to be accurate and frequently used [20]. Besides, it can also be derived from our photosynthetic growth model. In this case, its parameters are related to those in (6) as follows [14]:

$$p=\frac{1}{1-\alpha} \tag{24}$$

$$k=\frac{k_p}{pC_p(0)} \tag{25}$$

Theoretically, $\alpha\simeq 2/3$ is suggested [14], and thus $p\simeq 3$ and $k\simeq 11/168\ y^{-1}$ are expected.

Let us assume that the rate of fuel combustion is fixed by energy demand, and only fossils and harvested plant biomass are available as fuels. Assume also that harvested plant biomass is used either as a fuel or as a product. When the rates of fuel combustion and plant harvesting, i.e., q and h, are specified, the rates of fossil combustion and biomass usages can be determined from the following equations:

$$u_f+u_b=q \tag{26}$$

$$u_b+u_p=h \tag{27}$$

where
u_f=rate of fossil combustion, PgC/y
u_b=rate of biomass combustion, PgC/y
u_p=rate of biomass product storage, PgC/y

Note that, if q>0 and h>0, there are infinitely many solutions for u_f, u_b, and u_p. For u_f, a feasible range is given as follows:

$$\max(q-h, 0)\le u_f\le q \tag{28}$$

If h<q, i.e., biomass is insufficient as a fuel to meet the energy demand, the feasible range of fossil combustion rate is $q-h\le u_f\le q$. In this case, the solutions are linearly located between $u_f=q-h$, $u_b=h$, $u_p=0$ and $u_f=q$, $u_b=0$, $u_p=h$. If h>q, i.e., biomass is sufficient as a fuel to meet the energy demand, the feasible range of fossil combustion rate is $0\le u_f\le q$. In this case, the solutions are linearly located between $u_f=0$, $u_b=q$, $u_p=h-q$ and $u_f=q$, $u_b=0$, $u_p=h$. Note that all these solutions correspond to the same carbon cycle model Eqs. (1)-(5) as long as q and h are fixed. Now consider the case when h=q. In this case, $u_f=0$, $u_b=q$, $u_p=0$ and $u_f=q$, $u_b=0$, $u_p=q$ would result in the same carbon cycle. Therefore, from an environmental point of view, biomass fuel combustion is effectively the same as fossil fuel combustion plus biomass product harvest and storage in the same amount of carbon as combusted.

CASE STUDY

Let us assume that for specific energy demand, fossil fuels are currently used, and planned to be replaced by biomass fuels. It is necessary to optimize the replacement schedule and the reforestation plan. In this work, it is suggested that harvesting is linearly increased over a given period, and afforestation is applied in addition to reforestation as follows:

$$h=\frac{q}{\theta_2-\theta_1}[(t-\theta_1)u(t-\theta_1)-(t-\theta_2)u(t-\theta_2)] \tag{29}$$

$$s=h+\gamma q\left(1-\frac{A_v}{A_v^*}\right) \tag{30}$$

where
u=unit step function
θ_1=biomass use start time, y
θ_2=fossil fuel use end time, y
γ=afforestation factor
A_v^*=target normalized vegetated land area

Let q=10 PgC/y and A_v^*=1.25, which corresponds to the current fossil fuel usage [14] and the potential forest area [21], respectively.

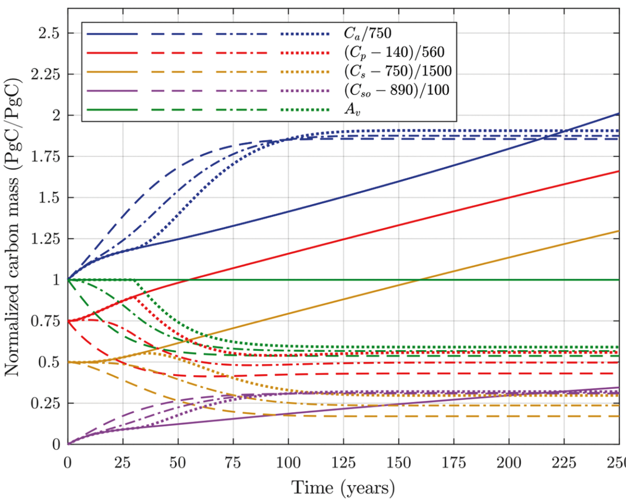

Fig. 2. Expected results of fossil to biomass transition with reforestation only (q=10 PgC/y, γ=0, solid: $\theta_1=\theta_2=\infty$, dashed: $\theta_1=\theta_2=0$, dash-dotted: θ_1=0, θ_2=30 y, dotted: $\theta_1=\theta_2$=30 y).

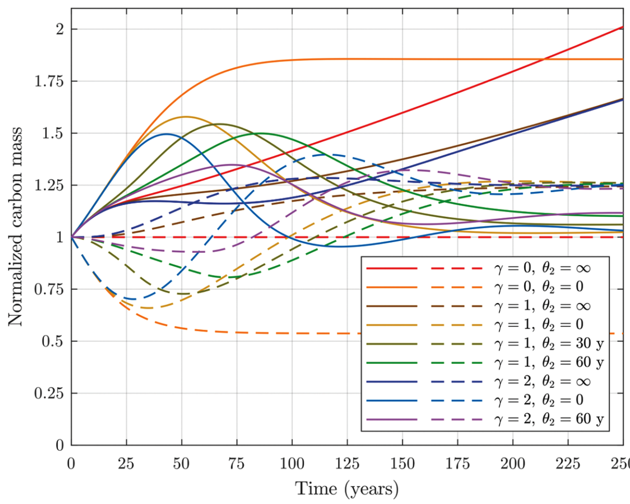

Fig. 4. Predictions of atmospheric CO_2 (solid) and vegetated land area (dashed) with (γ>0) or without (γ=0) additional forestation (q=10 PgC/y, A_v^*=1.25, θ_1=0).

The model Eq. (1)-(5) are numerically solved by a fifth-order Runge-Kutta method, using the MATLAB ode45 solver with relative error tolerance of 10^{-6} and absolute error tolerance of 10^{-8}. During the solution, the convolution integral in (12) is evaluated by the MATLAB integral function that uses a global adaptive quadrature method [22].

Let us consider fossil to biomass replacement strategies first. Three methods are suggested: immediate step change, linear change, and delayed step change. For step changes, (29) becomes h=qu(t−θ), where $\theta=\theta_1=\theta_2$, as can be verified by L'Hospital's rule. Fig. 2 shows the simulation results for a 30 year term example with reforestation only (γ=0). The plots represent the carbon mass in each reservoir normalized by the formulas defined in the legend. The predicted concentrations of CO_2 in the atmosphere, represented by the C_a curves, increase monotonously, and indicate that the immediate step change ($\theta_1=\theta_2$=0) results in the lowest steady state level (dashed), a delayed step change ($\theta_1=\theta_2$=30 y) results in the highest steady state level (dotted), and a linear change (θ_1=0, θ_2=30 y) results in between (dash-dotted), which means that an immediate step change is better than gradual or delayed changes. Fig. 3 shows the predictions when additional forestation is applied with γ=1. In this case, the immediate step change ($\theta_1=\theta_2$=0) results in the highest maximum and the lowest steady state level (dashed), a delayed step change ($\theta_1=\theta_2$=30 y) results in a lower maximum and the highest steady state level (dotted), and a linear change (θ_1=0, θ_2=30 y) results in the lowest maximum and a steady state level in between (dash-dotted). Therefore, optimization is necessary to negotiate between the immediate step change for the lowest steady state level and a linear change for the lowest maximum. As a result, a linear change method including the immediate step change is adopted (θ_1=0, $\theta_2\geq$0). Fig. 4 shows the results expected in such cases. The plots indicate that if θ_2 is increased, max C_a decreases and appears later, while $C_a(\infty)$ increases and converges later. If γ is increased, maxC_a decreases and appears earlier, but $C_a(\infty)$ is unchanged and attained later.

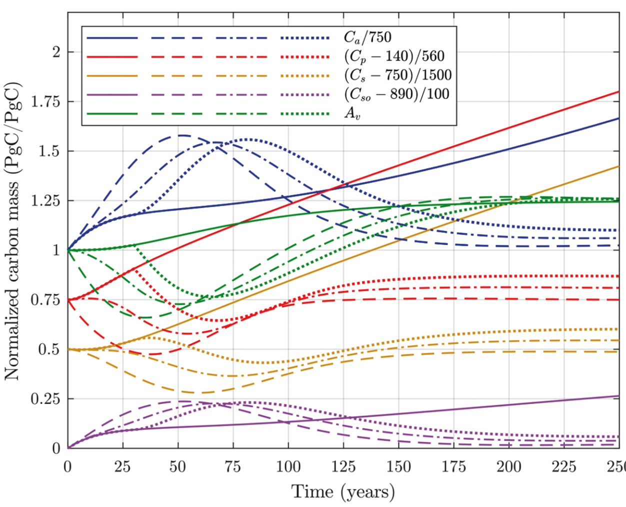

Fig. 3. Expected results of fossil to biomass transition with additional forestation (q=10 PgC/y, A_v^*=1.25, γ=1, solid: $\theta_1=\theta_2=\infty$, dashed: $\theta_1=\theta_2$=0, dash-dotted: θ_1=0, θ_2=30 y, dotted: $\theta_1=\theta_2$=30 y).

The results are summarized in Table 1. If γ=0, maxC_a=$C_a(\infty)$, so the optimum is found without difficulty at $\theta_1=\theta_2$=0 (case 2). In this case, 86% increase in $C_a(\infty)$ and 46% decrease in $A_v(\infty)$ are expected. If γ=1, the optimum is not obvious, because $\theta_1=\theta_2$=0 gives the lowest $C_a(\infty)$, but the highest maxC_a. Therefore, considering maxC_a and $C_a(\infty)$ together, it is suggested that θ_1=0, $\theta_2\simeq$60 y is optimal (case 9). In this case, 50% increase in maxC_a, 11% increase in $C_a(\infty)$, 26% increase in max A_v, and 25% increase in $A_v(\infty)$ are expected. If the afforestation is intensified to γ=2, which is considered to be difficult in practice, 35% increase in maxC_a, 11% increase in $C_a(\infty)$, 32% increase in max A_v, and 25% increase in $A_v(\infty)$ are expected (case 12). Note that increasing γ lowers maxC_a, and raises max A_v, while $C_a(\infty)$ and $A_v(\infty)$ are unchanged (case 6 vs. 11, and case 9 vs. 12). Therefore, to minimize maxC_a and $C_a(\infty)$ together,

Table 1. Results of simulation with selected afforestation and harvesting parameters

Case	γ	θ_1 (y)	θ_2 (y)	$\frac{\max C_a}{C_a(0)}$	$\frac{C_a(\infty)}{C_a(0)}$	$\max A_v$	$A_v(\infty)$	Carbon debt period (y)
1	0	∞	∞	∞	∞	1.000	1.000	0
2	0	0	0	1.857	1.856	1.000	0.537	214.1
3	0	0	30	1.876	1.875	1.000	0.567	218.6
4	0	30	30	1.907	1.906	1.000	0.591	196.0
5	1	∞	∞	∞	∞	1.250	1.250	0
6	1	0	0	1.579	1.030	1.269	1.250	98.0
7	1	0	30	1.543	1.067	1.263	1.250	112.8
8	1	30	30	1.558	1.106	1.258	1.250	98.0
9	1	0	60	1.499	1.106	1.258	1.250	128.4
10	2	∞	∞	∞	∞	1.285	1.250	0
11	2	0	0	1.495	1.030	1.397	1.250	78.3
12	2	0	60	1.348	1.106	1.322	1.250	108.1

γ is to be maximized, and θ_2 is to be optimized. Let us consider the carbon debt payback period of biomass, which is defined by the time interval during which C_a is greater than when fossil fuels are used, i.e., $\theta_1=\theta_2=\infty$. The simulation results indicate that the carbon debts can also be moderated by optimization (cases 9 and 12).

The proposed optimization problem has been posed as a multi-objective optimization problem, for which the optimum is not unique. In this case, conceptual approaches are required as described above. To determine the optimum precisely, the objective functions, $\max C_a$ and $C_a(\infty)$ in our case, should be combined into a single function. For example, if the overshoot $\max C_a-C_a(\infty)$ and the final value $C_a(\infty)$ are equally weighted and linearly combined, the objective function to minimize is $f_1=\max C_a-C_a(\infty)+C_a(\infty)=\max C_a$. If the weight for the final value is doubled, the objective function becomes $f_2=\max C_a-C_a(\infty)+2C_a(\infty)=\max C_a+C_a(\infty)$. If the time integrated impact $\int_0^\infty[C_a(t)-C_a(0)]dt$ is to be minimized, the objective function is $f_3=C_a(\infty)$. Let us choose $f_2/C_a(0)$ as the objective function, and designate γ and θ_2 as decision variables ($\theta_1=0$). Using the MATLAB function fminsearch, it has been verified that, as γ increases, the objective function decreases, as predicted above. For $\gamma=1$, the optimum is found at $\theta_2=75.19$ y, where $\max C_a/C_a(0)=1.478$ and $C_a(\infty)/C_a(0)=1.125$. In this case, a marginal overshoot is expected in A_v, because $\max A_v=1.256$ and $A_v(\infty)=1.250$. If $\gamma=2$ is feasible, the optimum is at $\theta_2=90.09$ y, where $\max C_a/C_a(0)=1.287$ and $C_a(\infty)/C_a(0)=1.145$. However, about 3% overshoot in A_v should be allowed, because $\max A_v=1.291$ and $A_v(\infty)=1.250$.

CONCLUSIONS

A carbon cycle model based method is proposed for environmental optimization of fossil and biomass fuel combustion. As a case study, a fossil to biomass energy transition problem was investigated. It was found that using biomass instead of fossils cannot reduce the atmospheric CO_2 concentration to the initial value, even if extremely intensive afforestation is accomplished. For example, if we harvest and burn trees at a rate of 10 PgC/y, at least 3% ultimate increase of CO_2 in the atmosphere is predicted, no matter how many seedlings we may plant (Table 1). Therefore, biomass is not truly carbon neutral. It only guarantees a steady state. It has been verified that biomass is more harmful than fossils in the short term, and less harmful in the long term. The carbon debt of biomass is inevitable. If we just plant the same number of seedlings as harvested trees ($\gamma=0$), the carbon debt period, for which biomass is worse than fossils, can be over 200 years (Table 1). The optimization results indicate that fossil fuels are needed until biomass resources are significantly increased by afforestation. For example, if we additionally plant as many seedlings as the empty area fraction times the number of trees to be combusted in the future ($\gamma=1$), the optimal fossil to biomass transition period is about 75 years ($\theta_1=0$, $\theta_2=75.19$ y). Therefore, plant biomass should be harvested from strictly managed forests only. Furthermore, like fossil fuels used today, the use of biomass fuels will also be restricted someday. The proposed optimization method is expected to be applicable to this problem also.

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