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Potential Influence of Carbon Fixation by Wood Carbonization on Atmospheric CO₂ Concentration and Temperature

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Abstract. Out of greenhouse gases causing global warming, CO₂ has the largest direct contribution after industrial revolution. To reduce CO₂ concentration, it is essential to collect CO₂ in the atmosphere and store it in separate places from the atmosphere. As a method of CO₂ capture and fixation, we studied a method using carbonization of wood. Based on the statistics of domestic wood production and import/export, we estimated possible amount of fixed CO₂ as 8 to 10% of annually emitted CO₂ in Japan. Influence of wood carbonization on CO₂ concentration in the atmosphere was also examined based on a prediction model for the atmospheric CO₂ concentration.

1. Introduction

CO₂ comprises approximately 93% of the current greenhouse gas emissions in Japan [1]. Therefore, significant reductions in atmospheric CO₂ concentrations are important to mitigate global warming.

Although previous research has focused on reducing the rate of CO₂ emissions, additional mechanisms for atmospheric CO₂ reduction should be considered due to the uncertainty associated with the consequences of the current CO₂ concentration levels. One mechanism to reduce atmospheric CO₂ is to collect it from the atmosphere and store it in non-atmospheric carbon reservoirs, leading to what is known as negative emissions [2]. Previous studies have investigated the transformation of CO₂ into useful materials by microbial activities, hydrogenation, or by direct storage of CO₂ in terrestrial and oceanic reservoirs [3]. However, the long-term behavior of the stored CO₂ and its influence on ecological systems has not been fully understood. Our study focuses specifically on using wood carbonization as a carbon capture method.

Trees grow by absorbing CO₂ from the air and converting it into organic materials. After a tree is fully grown, it can be utilized as a building material, fuel, or left unused. Within several decades, wood will naturally decompose or burn, returning the organic material to the atmosphere as CO₂ gas. Consequently, the cycle of tree growth and harvest does not generally influence the long-term concentration of atmospheric CO₂. However, if a harvested tree is carbonized, organic carbon is transformed into inorganic carbon and can be stored as charcoal. In this manner, atmospheric CO₂ can be fixed as stable inorganic carbon indefinitely, or until the charcoal is burned [4].

Charcoal is a result of the thermal decomposition process of inorganic matter. The carbon contained in organic matter is liberated as CO₂ by burning or decaying, but the carbon contained in charcoal produces inorganic polymer compounds, which are chemically stable and can be maintained long-term, unless they are burnt. Since this carbon originates from the CO₂ in the atmosphere and is absorbed by



trees through photosynthesis, the carbonization of organic matter can be regarded as a CO₂ capture method. The carbonization of wood interrupts the cycle where the CO₂ absorbed by trees returns to the atmosphere, and reduces the amount of CO₂ in the atmosphere, as shown in Fig. 1. Trees are reproducible, and CO₂ can be continuously captured. Furthermore, most of the energy required for carbonization can be supplied from the process of carbonizing the organic matter themselves. The essential point in this system is to store the carbonized charcoal, and not use it as a fuel.

Our aim in this research is to estimate the potential for CO₂ fixation by carbonization of the available wood base products (WBP) in Japan and demonstrate how this process could potentially contribute to the reduction of atmospheric CO₂ and prevent global warming. Here, WBP refer to the wood produced in the forest, and the wood and paper products produced using this wood as a raw material.

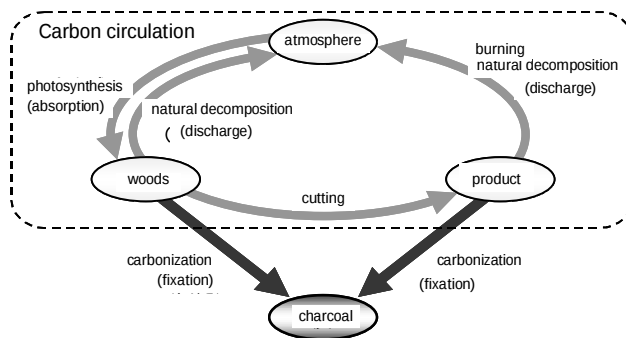


Fig. 1 Carbon circulation and wood carbonization.

2. Amount of Raw Materials Available for Carbonization

To evaluate CO₂ reduction by carbonization of WBP, the available amount of raw material for carbonization must first be estimated. In this study, the available WBP in Japan was considered, assuming that carbonization is performed only in Japan.

Both the WBP produced in Japan and the imported resources are discussed, and the available amount of wood was estimated. Figure 2 shows a simplified flow chart of the WBP, where 'WBP produced in Japan' is the growth rate of trees, exemplified by their weight increase, caused by the fixation of atmospheric CO₂. The total forested area of Japan will not decrease by this process. The term 'left' is the WBP that are neither thinned nor cut, but decay naturally.

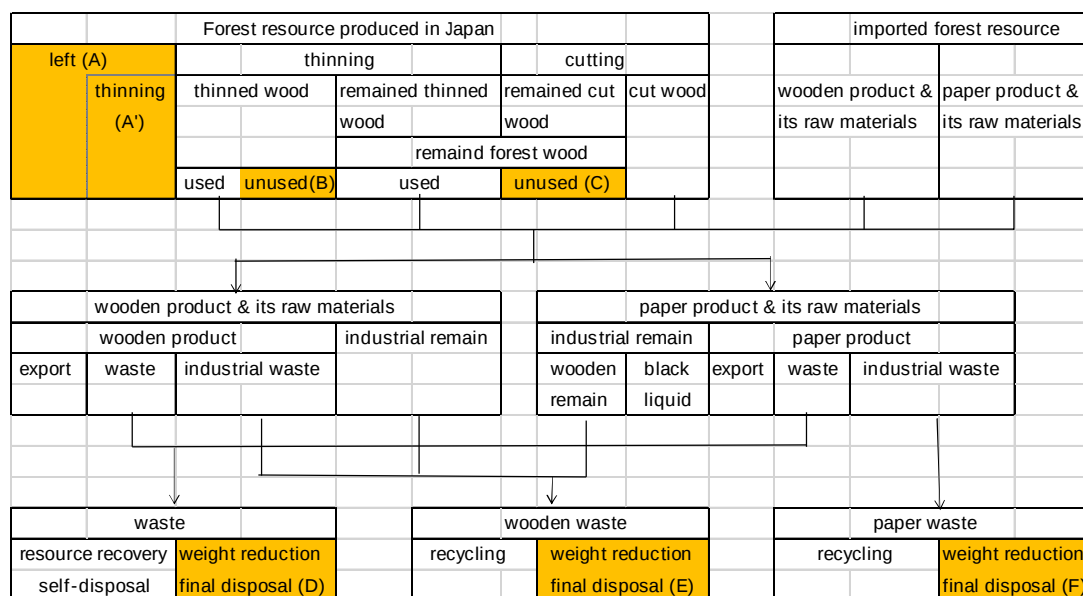


Fig. 2 Flow chart of wood base products.

'Thinned wood' is the wood processed into logs, and the remaining small diameter wood and slender twigs are called 'remaining thinned wood.' 'Cut wood' and 'remaining cut wood' in the cutting process are also defined in the same manner. The remaining thinned wood and remaining cut wood are altogether called 'remaining forest wood', and most of them are left in the forest. It is important to use the thinned wood and remaining wood in forests effectively.

The final use of the cut and thinned WBP can be classified into wooden and paper products. All wooden and paper products other than those that are exported are consumed or disposed of in Japan. The waste material can be classified into 'waste' [5] and 'industrial waste.' In the category of industrial waste, 'chips' and 'waste-paper' were considered in this study.

As available resources, (A) left forest, (B) unutilized thinned wood, (C) unutilized resources remaining in woodland, (D) wooden and paper waste products, (E) chips from industrial waste, and (F) waste-paper from industrial waste were examined based on available statistics. This model estimated the maximum amount of the WBP currently available in Japan and gave an estimate of approximately 122 million t/y (air-dry weight).

3. Relationship between Carbon Fixation Rate and Carbonization Temperature.

The production efficiency of charcoal^{A1)} as a function of carbonization temperature was determined, and the carbon fixation rate^{A2)} and carbon remaining ratio^{A3)} in the carbonization process of wood and paper were calculated based on the results of the references [6] and [7]. Charcoal and paper are primarily composed of carbon, hydrogen, oxygen, and ash. Figure 3 shows the charcoal weight [%] with respect to the air-dried wood weight as a function of carbonization temperature. The fraction of C drastically decreases between 200 and 400 °C because of pyrolysis and remains almost constant at higher temperatures. A carbon fixation rate of 20.9% was used in this study, and was taken from the average between 400 and 1100 °C. The remaining ratio of carbon was also nearly constant between 400 and 1100 °C with an average value of 49.1%.

Figure 4 shows the charcoal weight [%] of the waste paper. The carbon fixation rate and carbon remaining ratio of the waste paper were determined to be 19.6 and 45%, respectively, and were taken from the averages of the values between 700 and 1000 °C.

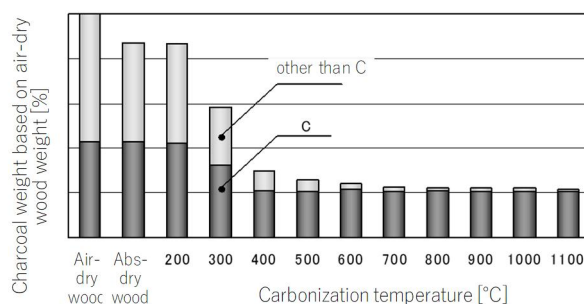


Fig. 3 Charcoal weight from the wood as a function of carbonization temperature.

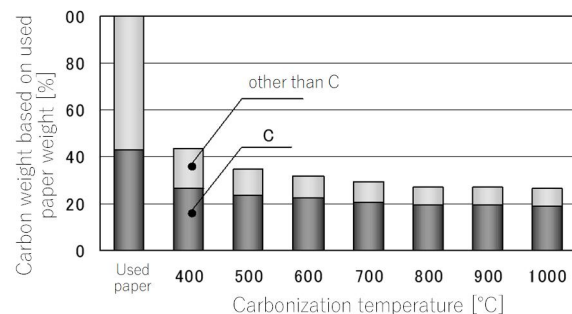


Fig. 4 Charcoal weight from the waste paper as a function of carbonization temperature.

4. Carbon Dioxide emissions from the carbonization system.

The amount of CO₂ emitted from the carbonization of WBP, which originates from the use of fossil fuel, was calculated relative to the unit weight of the air-dried raw charcoal material. The following five processes were examined; (1) cultivation and cutting of the left forest, (2) transportation of the raw charcoal materials to the carbonization factory, (3) production and operation of the carbonization facility, (4) construction and operation of the carbonization factory, (5) transportation of the charcoal to storage. The raw charcoal materials were classified into 4 categories from I to IV, as listed in Table 1, and the unit CO₂ emission rates were calculated for each material.

4.1 Forest cultivation and cutting of the left forest

Forest cultivation, which is necessary to produce the raw carbonization material I, includes afforestation, brushing, thinning, cutting, and take-out. To evaluate the amount of CO₂ emissions, the sum of overseas and domestic emissions during production, and the division 'Raw materials (domestic)' was used. This is given in the table of CO₂ emission rates per unit production, which was estimated based on the input-output table [8].

4.2 Transportation of the raw charcoal material

CO₂ emissions were calculated as a product of units of CO₂ emitted per unit loading capacity of the truck per unit distance to be 0.08 kg-C/t/km [8][9], and the transported distance was assumed to be 30 km. Here, the weight was corrected for moisture content.

4.3 CO₂ emissions from the production and operation of the carbonization facility

A continuous self-combusting carbonization system consisting of a crusher, dryer, and carbonization furnace was assumed [10]. The units CO₂ emission during the construction process was evaluated based on the weight of the raw materials used such as steel, stainless-steel, and cement; their respective unit CO₂ emission rates; depreciation of machines; and annual production rate. The unit CO₂ emissions for plant operation were calculated based on the consumed energy, unit energy use, and operation processing capacity. Since the raw charcoal materials III and IV do not require drying, only the unit CO₂ for crusher and carbonization furnace operation were summed.

4.4 CO₂ emissions from the construction and operation of the carbonization factory

The CO₂ emissions from the construction and operation of carbonization factory was evaluated by multiplication of unit Life Cycle CO₂ (LCCO₂) emission rate per floor area per year, 390 kg-CO₂/m²/y, with the total floor area of the carbonization factory assumed to be 800 m²/ward, taking the annual production rate into consideration. The unit LCCO₂ emission was obtained from the 'steel division' in the LCA guideline for buildings [11].

4.5 Transportation of the charcoal

In the same manner as described in Section 4.2, the unit CO₂ emission per unit loaded weight was evaluated assuming a 30 km distance by truck and corrected considering the load weight ratio against the air-dried weight of the raw charcoal material.

Table 1 Classification of the raw charcoal material

	forestation • cutting	Original material	carbide	Wood base Products
I	necessary	raw wood	charcoal	A
II	unnecessary	raw wood	charcoal	B, C
III	unnecessary	waste	charcoal	wood product of D, E
IV	unnecessary	waste	paper charcoal	paper product of D, F

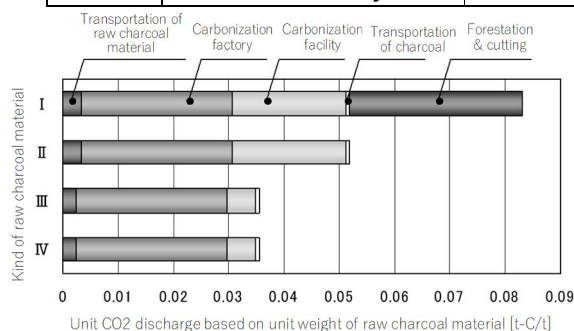


Fig. 5 Unit CO₂ emission by carbonization system.

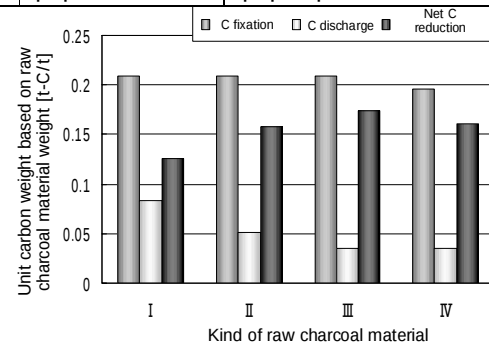


Fig. 6 Net reduction in CO₂ emissions from each raw

charcoal material using the carbonization system.

4.6 Calculated results

The unit CO₂ emission rate was the largest for the raw charcoal material I, which requires forestation and cutting, and the smallest for type III, which does not require the construction and operation of the dryer. A significant amount of CO₂ is emitted during the process of construction and operation of the carbonization factory and facilities, while the emission during transportation is relatively small.

5. Net Reduction in CO₂ Emissions Using the Carbonization System

Figure 6 shows the net reduction in CO₂ emissions from each raw charcoal material^{A4)}, which was calculated based on carbon fixation rate estimated in Chapter 3 and the unit CO₂ emission calculated in Chapter 4. It shows that the carbonization system has a CO₂ reduction effect, although the amount of reduction differs depending on the type of raw material. The CO₂ reduction rate from the raw charcoal material III is the highest, while the raw charcoal material I exhibited the lowest rate.

Using the available WBP estimated in Chapter 2, the net reduction in CO₂ emissions when carbonization is performed amounts to 16.34 million t-C/year. This corresponds to 5% of the anthropogenic CO₂ emission in Japan, 328 million t-C/y (as of 2002) [12], and 31% of the Japanese reduction goal as per the Kyoto protocol, 53 million t-C/y (as of 2002).

6. Prediction of the Reduction in Atmospheric CO₂ Concentration

To understand the influence that the CO₂ reduction by carbonization would have on the atmospheric CO₂ concentration, an extended model that integrates the carbonization process into the well-known CO₂ prediction model [13], [14] was proposed. The calculated atmospheric CO₂ concentration when carbonization is performed was compared to a scenario without carbonization analyzed using the proposed model.

6.1 Surface Biomass Carbon Circulation Model Combined with Carbonization

The previously proposed model [13], [14] predicts the CO₂ concentration from time 0 to t, using a convolution integral considering the net CO₂ emission at time t and CO₂ absorption by the ocean. The net emission is calculated using CO₂ emission data from industrial activities and changes in CO₂ accumulation of surface biomass. The latter is given by a carbon circulation model of the surface biomass^{A5)}.

Since the proposed carbonization process involves biomass resources as a raw material, it will influence the carbon circulation of the surface biomass. Therefore, the carbon circulation model was extended to consider CO₂ fixation by carbonization by adding the model (Fig. 7).

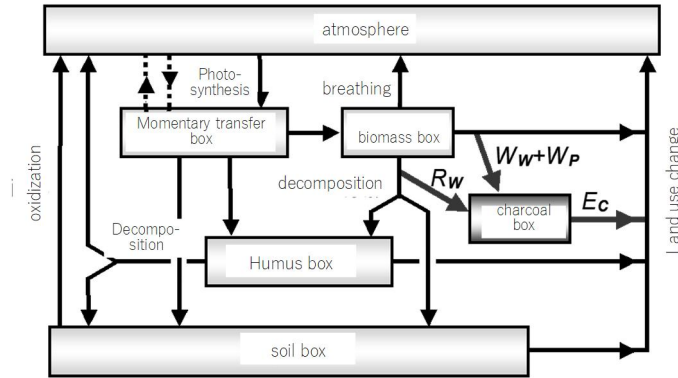
Because the raw charcoal materials I and II, which were to be resolved into humic substances or soil without utilization, are removed from the forestland, the corresponding amount of carbon, R_w , is deducted from decomposition flux of plants. The amount of CO₂ from the raw charcoal materials III and IV was represented by W_w and W_p , respectively, and deducted from the carbon flux from the plants to the atmosphere caused by the changes in land use (mainly deforestation), because these materials were utilized before incineration and reclamation. The carbon content of the raw charcoal materials, R_w , W_w , and W_p , was evaluated based on the carbon contents of the air-dried materials (types I to III: 42.7%, type IV: 43.1%). The carbon flux from charcoal box to the atmosphere, E_C , in the form of emitted carbon gas which was transformed from the carbon contained in the raw charcoal material without being changed into charcoal is given by the following equation.

$$E_C = (R_w + W_w)(1 - CR_w) + W_p(1 - CR_p)$$

where CR_w and CR_p represent the remaining carbon fractions [t-C/t-C] of the charcoal and paper charcoal, respectively, and $CR_w = 0.491$ and $CR_p = 0.456$.

Based on these considerations, a new prediction model of atmospheric CO₂ concentration incorporating carbonization was proposed by changing the surface biomass carbon circulation model

and adding the CO₂ emissions from the carbonization process to those emitted from industrial activity (Fig. 7).



R_w : carbon weight of raw charcoal material (I and II) directly taken out from forestland [Gt-C/yr]

W_w : carbon weight of carbonized wooden waste (III) [Gt-C/yr]

W_p : carbon weight of carbonized paper waste (IV) [Gt-C/yr]

E_c : carbon weight liberated from raw charcoal material without being carbonized [Gt-C/yr]

Fig. 7 Surface biomass carbon circulation model incorporating carbonization.

6.2 Predicted reduction in CO₂ concentration

The predicted reduction in CO₂ concentration caused by carbonization, i.e., the difference in CO₂ concentration between the basic (without carbonization) and carbonization scenarios, is shown in Fig. 8. It was assumed that carbonization started in the year 2000, and that the annual amount was constant. The annual decrease rate of CO₂ concentration was determined to be approximately 0.0032 ppmv/y, and the total reduction amounts to 0.338 ppmv by 2100. These values represent a global reduction in CO₂ concentration when carbonization is performed only in Japan.

Figure 9 shows the unit CO₂ concentration reduction for each raw charcoal material^{A6)}. Similar to the unit net CO₂ reduction of each raw charcoal material in Fig. 6, it is largest for the type III materials, and smallest for the type I materials. The reduction efficiency is high 5 to 10 years after carbonization started in types I and II (raw wood), while it immediately jumps for carbonization of types III and IV (wastes).

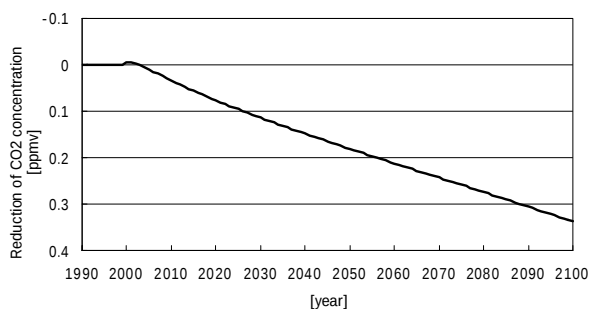


Fig. 8 Reduction in CO₂ concentration attributed to carbonization.

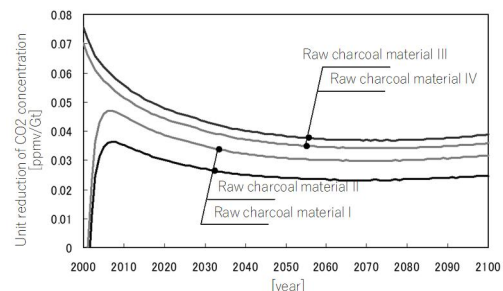


Fig. 9 Unit reduction of CO₂ concentration for each type of raw charcoal.

7. Prediction of the Decrease in Air Temperature

7.1 Calculation Method

The influence of CO₂ concentration on global climate has been discussed by comparing the temperatures at equilibrium for different atmospheric CO₂ concentrations, which are computed by climate models [15] assuming constant CO₂ concentrations. The temperature increase when the CO₂ concentration is

doubled (temperature sensitivity) is predicted to be 2.0 ± 0.5 °C by the one-dimensional radiation-convection equilibrium model, and 3.0 ± 1.0 °C (global average) by three-dimensional atmosphere-ocean combined global circulation model. In this study, the temperature reduction effect caused by carbonization was roughly estimated using these models.

Since the temperature in the troposphere is nearly proportional to the logarithm of the CO₂ concentration [16], the temperature increase ΔT [°C] when the CO₂ concentration changes from C_0 [ppmv] to C [ppmv] is described by the following equation using a temperature sensitivity ΔT_{2X} [°C] factor.

$$\Delta T = \Delta T_{2X} \log_2(C/C_0)$$

This is the predicted asymptotic value of the temperature increase at a constant CO₂ concentration, C . Because it takes several decades for this transient change to equilibrate, the temperature response is complicated when the CO₂ concentration continuously changes. To examine this response delay, the temperature change calculated using CO₂ concentration history was compared with the observed values. It was concluded that the above mentioned prediction model assumes a response delay of 30 years when $\Delta T_{2X} = 2$ [°C], 60 when $\Delta T_{2X} = 3$ [°C], and 80 years when $\Delta T_{2X} = 4$ [°C].

7.2 Predicted temperature decrease

Figure 10 shows the temperature decrease caused by carbonization and the difference between the temperatures calculated using the CO₂ concentrations estimated for the basic and carbonization scenarios in Chapter 6. When $\Delta T_{2X} = 3$ [°C], the temperature reduction appears in 2060, 60 years after the start of carbonization. The reduction of the global average temperature was estimated as 0.0022 °C by 2160. Although with larger temperature sensitivity, larger temperature reductions were observed along with larger response delays.

Figure 11 shows the estimated unit temperature reduction per unit of raw charcoal materials when $\Delta T_{2X} = 3$ [°C] ^{A7)}. The unit temperature reduction increases between 2065 and 2070 for raw material types I and II (raw wood) due to the CO₂ concentration reduction effect 5 to 10 years after the start of carbonization. For types III and IV (waste) materials, a large effect is observed at 2060, because the carbon reduction appears immediately after the start of carbonization, and subsequently, the effect decreases and approaches 0.

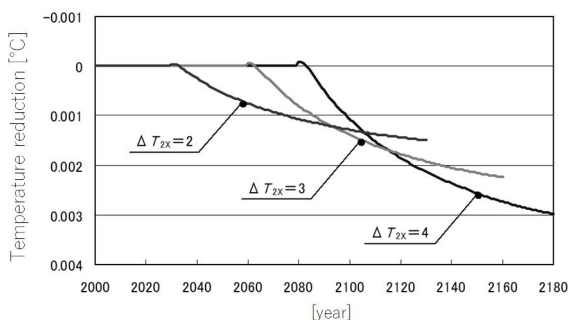


Fig. 10 Temperature decrease attributed to carbonization.

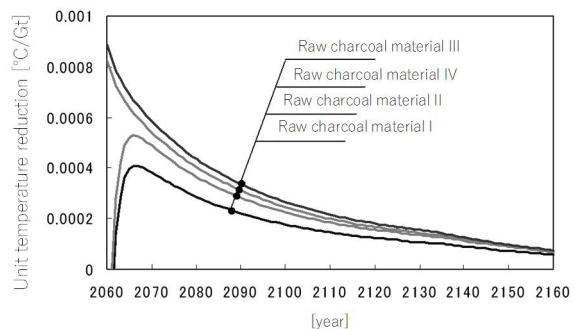


Fig. 11 Unit temperature reduction for each raw charcoal material when $\Delta T_{2X} = 3$.

8 Conclusions

(1) Carbonization fixes CO₂ corresponding to approximately 20% of the weight of the raw charcoal material (carbon-based weight). Since CO₂ corresponding to 4 to 8% of the raw materials is emitted during the carbonization process, the net reduction of CO₂ emissions amounts to 13 to 17% of the raw materials. The reduction efficiency strongly depends on the moisture content of the raw charcoal materials, and wooden wastes with low moisture content show the highest efficiency.

(2) To examine the influence of the carbonization of wood base products on the carbon circulation of surface biomass, a prediction model for the atmospheric CO₂ concentration integrated with

carbonization was developed. The reduction in the atmospheric CO₂ concentrations caused by continuous carbonization amounts to 0.024–0.037 ppmv/Gt per air-dried weight of raw charcoal material. The reduction efficiency becomes the highest 5 to 10 years after the start of carbonization for raw wood, while it occurs immediately after the start for the waste materials.

(3) If the available forest resources in Japan are fully utilized, 16 million t-C/y of net CO₂ can be removed, which corresponds to 5% of the anthropogenic CO₂ emissions of Japan. This corresponds to 31% of the Japanese goal of CO₂ reduction declared in the Kyoto protocol. This would decrease the global CO₂ concentration at a rate of approximately 0.0032 ppmv/y. By continuing this carbonization process for 100 years, the global CO₂ concentration would decrease by 0.338 ppmv, and the temperature by 0.0015–0.0030 °C. The effect on temperature reduction would appear 30–80 years later.

It should be noted that these conclusions are based on a limited consideration using models with uncertain assumptions, and the carbonization has its merits and demerits from a wider point of view.

Appendix

A1) Production efficiency of charcoal: air-dried weight of charcoal/air-dried weight of raw charcoal material

A2) Carbon fixation rate: carbon content of the charcoal/air-dried weight of the raw charcoal material

A3) Remaining ratio of carbon: carbon content of the charcoal/carbon content of the raw charcoal material

A4) Unit net CO₂ reduction = (fixed CO₂ – emitted CO₂) /air-dry weight of raw charcoal material

A5) 4-box model, whose surface biomass is composed of momentary transfer box, biomass box, humus box, and soil box

A6) Unit CO₂ concentration reduction = reduction rate of CO₂ concentration/air-dry weight of raw charcoal material

A7) Unit temperature reduction = reduction rate of temperature/air-dry weight of raw charcoal material

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