Influence of Environmental Changes and Forest Management Practices on CO_2 Sequestration of Conifer Plantations (Abstract of the Final Report)

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1. Introduction

The first commitment period for reduction of green house gas has started this year. Article 3.4 of the Kyoto Protocol offers the option of including additional human induced activities in the agricultural soils, land-use change, and forestry categories for the meeting national commitments. In the second commitment period that will start after 2013, however, more severe rules with scientific foundation will be required to precisely account forest CO_2 sequestration. CO_2 uptake in forest stands would be affected by both forest management (anthropogenic factor) and environmental conditions such as global warming (non-anthropogenic factor). Prior to the second commitment period, therefore, a prerequisite research is immediately needed for setting scientific and objective bases to evaluate forest CO_2 sequestration. Particularly, we should distinguish the effects of anthropogenic and non-anthropogenic factors on CO_2 uptake in forest stands of conifer plantation forests of *Cryptomeria japnica* and *Chamaecyparis obtusa*.

2.Research Objectives

This research addresses scientific bases and simulation models to be developed for evaluating carbon sequestration into forest stands with thinning practices, which will be required for the second commitment period. The study focuses on man-made forests of Japanese cedar (*Cryptomeria japonica*) and cypress (*Chamaecyparis obtusa*). It is reported that such plantation forests contribute to a large amount of forest CO_2 uptake in all of the forested area in Japan.

We will develop a biochemical process model of CO_2 sequestration in plantation forests, which involves interactions between environmental factors and forest management practices, and evaluate photosynthesis response against environmental changes. Also, integrating with forest growth models based on forest structure and tree architecture, we will develop a CO_2 budget model that enables us to separately evaluate the effects of forest management (e.g. thinning intensity and interval) and climate factors (e.g. changes of temperature, solar radiation).

3. Results and Discussion

(1) Physiological response of forest canopy to thinning operation

In order to distinguish carbon fixation benefited from forest management from non-human factors, we studied the changes in photosynthesis after thinning and analyzed its relation to leaf nitrogen. The study site was a 10-year-old *Chamaecyparis obtusa* stand (36˚3'N, 140˚7'E) with 4.24 m high. The forest density was 3000 trees ha^{-1}. Every other tree was cut in the thinned treatment in May 2004. The photosynthetic responses to CO_2 concentration were measured *in situ* in leaves from July to estimate V_{cmax} in both thinned treatment and non-thinned control and fine root dynamics were traced by images obtained from installed minirhizotron tubes every month.

Thinning improved irradiance in the lower and middle crowns but not in the upper crown. V_{cmax} in both the lower and middle crowns of the thinned stand increased significantly in comparison with the same crown positions of the control stand three months after thinning. Needles in the lower crown in the control stand senesced in the autumn of the second year and defoliated branches spread up to 2 m above ground in the autumn 2007. In contrast, leaves maintained high V_{cmax} even in the summer 2007 in the thinned stand. In addition, the increase in V_{cmax} became significant even in the upper crown in October of the second year after thinning. Thinning did not influence on leaf nitrogen concentration (N_a) at any crown position in the first year, whereas increased N_a at both lower and middle crowns from the second year. These results indicate that thinning improved irradiance in the lower and middle crowns of *C. obtusa*, leading to photosynthetic acclimation. Photosynthetic acclimation mainly occurred via redistribution of *N* within leaves in the first year and via leaf nitrogen increases in the second year after thinning. Both aboveground and fine root biomass had similar seasonal growing pattern with two peaks in spring and autumn. Thinning did not affect on this seasonal pattern. The biomass of fine roots was lower in the thinned treatment than in the non-thinned control. Annual fine root production rate at individual level, estimated from the biomass of fine roots, was 570 and 870 g tree^{-1} yr^{-1} in the non-thinned control and thinned stand respectively. These results indicate that thinning may have a tendency to enhance the fine root production rate and allocation of assimilated carbon to fine roots at individual level.

(2) Effects of water stress and nutrient supply on forest tree growth

To reveal the effect of environmental changes related with water conditions on the growth of sugi and hinoki trees, we conducted three experiments (1) to compare water characteristics for both tree species, i.e., whole tree water hydraulic resistance or leaf photosynthesis rate and stomatal conductance under water stress, (2) to quantitatively analyze the effect of water stress on photosynthesis using “the water characteristics mediated photosynthesis model”, and (3) to formulate the relationship between tree growth and growing site condition or physiological characteristics in different sites of forest slope.

The whole tree hydraulic resistance of young sugi and hinoki trees was compared in wet and dry soil water conditions. The hydraulic resistance of hinoki was larger than that of sugi in both of wet and dry water conditions. This result shows that the leaf water potential of hinoki is always lower than that of sugi when they are grown in the same soil water conditions. Photosynthesis and transpiration changes in the course of soil drying were compared in young sugi and hinoki trees. Stomatal conductance and photosynthesis of hinoki began to decrease at more negative values of leaf water potential than those of sugi. This result shows that hinoki can continue to open stomata and maintain photosynthesis until low leaf water potentials.

The effect of decrease of soil water potential and increase of air temperature were evaluated by using photosynthesis model. Photosynthesis of sugi did not decreased by the increase of air temperature in wet soil conditions, and began to decreased at less than -40kpa soil water potential. However, photosynthesis of hinoki decreased by air temperature increment even in wet soil conditions. These results indicate that the effect of environmental changes is stronger to hinoki tree than sugi tree.

In order to compare the growth characteristics of sugi and hinoki, we studied growth conditions, tree sizes, and leaves physiological functions at top and bottom sites of an inclined plantation. Besides, we constructed a simulating model in crowns to reveal the response of photosynthesis to environmental factors. The constant soil moisture shortage was observed in top site of the slope. Tree sizes were larger in sugi than that of hinoki in both sites of the plantation. Measured leaves photosynthesis in daytime was lower in top site of the plantation compared with bottom site. The low photosynthesis rate induced by shortage of soil moisture was suggested as a cause of the small tree sizes in top site of the plantation. The leaves photosynthesis measured in field was able to reproduce with sufficient accuracy using the model. Adding relative light intensity to the model, the crown photosynthesis of each tree crown was able to be calculated. Calculated crown photosynthesis was corresponded to the growth of sugi and hinoki in the inclined plantation.

(3) Growth dynamics and environmental responses of old-aged hinoki plantations

Little information is available on the growth-dynamics in the old-aged conifer plantations. The practices of forest management should be established to promote the amount of the carbon fixation in the plantations. The main objectives of this study are to elucidate the factors of forest site and environmental conditions limiting the growth of the old-aged conifer plantations, focusing on the difference in the growth among the slope positions. Two experimental plots were established in the plantations of 90-year-old Hinoki cypress (*Chamaecyparis obtusa*) on the slope of Mt.Hiei, Ohtsu, where thinning has been treated twice, and of Kyoto Prefectual University "Ohno" Forest, Nantan, which has never been thinned. In the Hiei site, both DBH and height of Hinoki cypress increased from upper to lower slope position. However, the rate of change in relation to slope position was the same between 2004 and 2008. This suggested that adequate thinning mitigated differences in growth rate between upper and lower slope. The concentrations of nitrogen in the leaves were not affected by the heterogeneitic concentrations of soil nitrogen within the slope. However, the leaf N concentrations were generally higher than those in the previous reports of Hinoki cypress, suggesting that nitrogen in the soil is not a limiting factor for the growth in this site. In the Ohno site, there were marked differences in the growth of Hinoki cypress between the upper and lower slope. The leaves of Hinoki cypress in the upper slope were more vulnerable to the water deficiency in the soil than those in the lower parts. This behavior of leaves can be induced a lower growth rate of Hinoki cypress in the upper slope sites. These results suggest that the factors of slopes must be taken into consideration when designing future silvicultural treatments and management plans in the old-aged conifer plantations.

(4) Long-term permanent study

The objectives of the study were (1) to clarify the effects of site conditions and thinning practices on carbon sequestration, and (2) to validate the process-based forest growth model which was developed in the present project, utilizing the long-term monitoring data of the permanent study sites of conifer plantations, located all over Honsyu region.

The effect of thinning on the stand volume growth was examined. The data from a long-term thinning experiment of Japanese cypress plantations was analyzed. Total net volume yields of light or moderate thinning treatment were larger than those of intensive thinning or control (un-thinned) plots. Thus, light or moderate thinning was the most advantageous for carbon sequestration. The data from 41 long-term monitoring sites in Japanese cedar stands was analyzed. Large mean annual net volume increments were found in the range between 10 and 30 % in cumulative thinning rate, indicating that the optimal thinning rate for carbon sequestration might exist.

The effects of tree species and site productivity on the volume growth of dominant trees were examined using the data obtained 66 long-term monitoring sites. The mean volume of dominant trees (MVD) for Japanese cedar was more than twice the amount for Japanese cypress. Age-related decline in growth of MVD was recognized in Japanese cedar stands, but not in Japanese cypress. Culmination age of current annual increment in MVD was negatively correlated with site productivity for Japanese cedar. The effect of site productivity varied with different species.

The effects of thinning and site productivity on stand biomass growth were examined using the data obtained 66 long-term monitoring sites. The correlations of site index (SI) and cumulative thinning rate (CTR) with culmination age of mean annual net increment (MAI) and its maximum value of MAI (max MAI) were analyzed. Max MAI was increased with increasing SI, but did not change with CTR for Japanese cedar. Culmination age was decreased with increasing SI, and increased with increasing CTR for Japanese cedar. Therefore, thinning extends the culmination age without changing Max MAInet for Japanese cedar. The positive correlation of SI with max MAI was found for Japanese cypress, but other correlations were not found. Since most of the plots for Japanese cypress have not reached a maximum value of MAI, we must continue to observe stand growth of Japanese cypress to examine the correlation of SI and CTR with culmination.

Finally, the effect of site productivity, thinning, and growth stage on stand growth for Japanese cedar were examined. The modified Richards growth function was fitted the data from 29 plots in Japanese cedar stands in Akita district. We predicted total volume yield at varying levels of thinning and site productivity, using this regression model. The predictions indicated that the total yield in lightly or moderately thinned stand was larger than unthinned stand at the older growth stage under high site productivity, although the total yield in thinned stand was smaller than unthinned stand at the early growth stage or under low site productivity. Therefore, light or moderate thinning increases total net yield in sites with high productivity based on a long-term perspective. These results contributed to the validation of the process-based forest growth model.

(5) Modeling carbon sequestration in plantation forests

The final goal of this study project is to develop a process-base model to evaluate carbon sequestration as affected by anthropogenic activities (e.g. thinning practice) and naturally changing climatic conditions (e.g. global warming and increasing atmospheric CO_2 concentration). Since the start of the project, we have developed a forest growth model to simulate stand growth of man-made plantations. Also we are still continuing making modifications for the parameters in the simulation model, examining the data sets of plantation forests of sugi (*Cryptomeria japonica*) and hinoki (*Chamaecyparis obtusa*).

To develop a simulation model to factor out the effects on C sequestration, we adopt the following two procedures to formulate ecophysiological processes of forest growth as affected by environmental factors and anthropogenic factors. That is, the first approach is to evaluate C sequestration linking with structural changes in plantation forests accompanying thinning practices. The second one is to evaluate C sequestration linking with physiological processes to respond to environmental factors, employing the biochemical-process model by Farquhar et al. (1982).

As a part of the simulation model for C sequestration in plantation forests, a sub-model of natural thinning of forest trees was included, which is required to adequately predict stand growth, particularly in un-thinned and light-thinned stands in which natural thinning should take place. Several thinning patterns were chosen to simulate stand growth and total carbon gain during the growth period of 100 years. The simulation model shows excellent performance to model biomass growth and structural changes in a forest stand with various thinning regimes. It is suggested that there is little difference in the total carbon sequestration of forest stands that includes all organs of dead and thinned trees among thinning regimes. Using a tree architectural model, a simplified mathematical method was devised to estimate total surface area of woody organs of individual trees. This enables to scale up woody respiration to whole tree level. Ecophysiological parameters for photosynthesis and respiration were obtained through the cooperative work by the researchers of this project, and used to conduct the simulation analyses particularly for C sequestration as affected by environments and thinning regimes.

In order to validate the simulation model of canopy photosynthesis developed in this study, several revision have been made to improve the model performance, i.e., spatial distribution of leaf mass in a forest canopy. Using the meteorological data observed in Tsukuba city, the effects of climate change (i.e., warming and drying) on canopy photosynthesis and respiration were examined. In mid-summer under the condition of higher air temperature, canopy photosynthesis was markedly reduced as the air humidity lowers. Through the simulations of environmental changes, it is likely that slight warming up to 4ºC may increases carbon sequestration into forests, although extreme warming over 4ºC reversely leads to the decrease of carbon fixation.

Further examinations should be needed to understand the properties of environmental and structural responses on C sequestration in plantation forests. The temporal findings of the research project were summarized as follows. Leaf mass distribution in a forest canopy could vary reflecting thinning regimes, which affects C budget of the related forests. On the contrary, however, environmental factors such as temperature and relative humidity seem less effective on C sequestration. This implies that because crown size and its spatial location should be determined by thinning intensity and tree density, spatial structure of a forest could take a large role in determining growth potential through the photosyntheric performances. The modeling approach for factoring-out on C sequestration of plantation forests were developed and practical applicability was verified for various data sets obtained in long-term monitoring forest sites. Although further examinations and modifications are needed, we can predict the growth process, structural change, and environmental response of plantation forests as related to thinning practices.