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Soil Moisture Condition and Growth of Deciduous Tree Seedlings Native to Northern Japan Grown under Elevated CO_2 with a FACE System

By

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Summary

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To better predict the soil moisture environment of cool-temperate forests, we studied the soil moisture for stands grown under elevated CO_2 concentration ($[CO_2]$) using Free Air CO_2 Enrichment (FACE) systems (50 Pa ($[CO_2]^e$), with controls at ambient levels (37 Pa $[CO_2]^a$)), over two years. Two distinct soil conditions, brown forest soil and volcanic ash soil, were prepared in each FACE. Two-year-old seedlings of six species were planted in May 2003. The soil moisture increased under $[CO_2]^e$ in both soil conditions. Since changes of soil moisture depend on evapotranspiration from a stand, we examined the fluctuation of soil moisture in relation to the transpiration (Tr) from leaves and evaporation (Ev) from the soil surface in the FACE. The Tr per leaf area decreased under $[CO_2]^e$ for both soil conditions, although the total Tr per seedling increased because the total leaf area per seedling increased under $[CO_2]^e$. Ev decreased under $[CO_2]^e$, because the soil surface temperature fell in both soils as a result of the increase of leaf area index (LAI), which blocked incident sunlight at the soil surface. These results show that the increase of soil moisture under $[CO_2]^e$ over two years is due probably to the change in Ev. Our results also indicate that the predicted rise in atmospheric $[CO_2]$ will lead to modification of the forest ecosystem accompanied by changing soil moisture conditions.

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Introduction

Some studies have reported that forest soil moisture would increase under high CO_2 concentrations ([CO_2]) (e.g. SCHÄFER & al. 2002). The change of soil moisture under elevated [CO_2] ([CO_2]^e) depends on the change in the transpiration rate (Tr) and evaporation (Ev) from the soil surface (FREDEEN & al. 1997). To better predict the forest soil moisture environment, Tr and Ev characteristics of forest under [CO_2]^e should be determined.

Many studies have found that Tr per leaf area reduced under [CO_2]^e (DRAKE & GONZALES-MELER 1997). However, the Tr per stand under [CO_2]^e is not yet settled; some studies reported that Tr decreased (DUGAS & al. 1997, KELLOMAKI & WANG 1998), but others found that it did not (ENGEL & al. 2004, WANG & al. 2005).

Ev from the soil surface under [CO_2]^e also remains undetermined; some studies reported that Ev decreased under [CO_2]^e (JACKSON & al. 1998), but others found no such decrease (DUGAS & al. 1994). Furthermore, there have been very few studies of Ev under [CO_2]^e from the stand floor (SCHÄFER & al. 2002).

To predict the soil moisture environment of forests, the consistent response of Tr and Ev under [CO_2]^e should be determined. For this study we chose a cool-temperate forest in Hokkaido, northern Japan. The effect of global climatic change on cool-temperate forests should be quite large, because the forest is located at a climatic zone boundary between warm-temperate and boreal areas. We grew six kinds of seedling, all representative deciduous species of Hokkaido, under [CO_2]^e using a Free Air CO_2 Enrichment (FACE) system. In preliminary measurements, we found that the leaf area index (LAI) increased significantly under [CO_2]^e. OBRIST & al. 2003 reported that the increase of LAI under [CO_2]^e caused a reduction in evapotranspiration in grassland following the decrease of Ev, which offset the increased Tr. We therefore hypothesize that the soil moisture of the stand floor also increases under [CO_2]^e, duing to the decrease in Ev. The present study aimed to verify this hypothesis by determining the soil moisture, Tr, and Ev.

Material and Methods

Growth condition

Our study was conducted in Sapporo Experimental Forest, Hokkaido Univ., Sapporo, Japan (43°06'N, 141°20'E). We used a FACE (Free Air CO_2 Enrichment) system, which is able to raise [CO_2] in field conditions (HENDREY & al. 1993). Our FACE facility consisted of six circular plots, 6 m in diameter and 5 m high. Three of these were 'elevated CO_2' plots, and the other three were 'ambient' plots. CO_2 treatment began in June 2003 (TAKAGI & al. 2004). Fumigation was terminated after leaf senescence each autumn, and was re-initiated each spring before new leaves emerged. The average value of [CO_2] was 50 Pa in the [CO_2]^e plots, which is predicted to be the ambient concentration in 2040, and 37 Pa in the ambient plots ([CO_2]^a). Since the response of plants under [CO_2]^e depends on the soil nutrient conditions (OREN & al. 2001, EGUCHI & al. 2004), two soil conditions were prepared in each FACE using brown forest soil and volcanic ash soil, both of which are typical soils in Japan. The nitrogen, phosphate and potassium concentrations were higher in brown forest soil (data not shown). Two-year-old seedlings of *Betula platyphylla*, *B. maximowicziana*, *Quercus mongolica*, *Ulmus davidiana*, *Fagus crenata*, and *Acer mono* were used for the experiment, and were planted in May 2003.

Measurements

The soil moisture was measured every hour using a Dielectric Aquameter (Decagon Devices, Inc. NE, USA) and an average for each month was calculated. To evaluate Tr under $[CO_2]^e$, we determined Tr per unit leaf area and total Tr per seedling. The Tr per unit leaf area was determined using a gas analysis system (LI-6400, Li-Cor, Lincoln, NE, USA) in the morning in early August 2004, targeting leaves at the crown canopy having sensitive stomatal function. The PPFD in the leaf chamber (measured with a LI-6400 device Li-Cor, Lincoln , NE, USA) was 1500 μmol m^{-2} s^{-1}, which was saturation level for every species according to a preliminary study (data not shown). The temperature in the leaf chamber was 25 °C and the water vapor deficit in the leaf chamber was about 1.5 KPa. After Tr determination, we measured the total leaf area of seedlings so as to calculate the total Tr per seedling. Ev was determined from the change in soil weight; see TAMAI 1999. The soil was sampled from the stand floor using soil sampling cylinders (6cm diameter, 200cm^3 volume) and weighed at 13:00. We then put the soil with the cylinder back into the stand floor. We then weighed it again four hours later. The Ev value was determined on 14th October 2004, on which day the weather was sunny, the average temperature was 14.8 °C, the average atmospheric moisture content was 55.4% and the average wind speed was 0.89 m s^{-1}. We also monitored the soil surface temperature using a Thermo Recorder (Especmic, Aichi, Japan), monitored the LAI with a LAI 2000 (Li-Cor, Lincoln, NE, USA), and the amount of sunlight on the stand floor using a light sensor (LI-190SA, Li-Cor, Lincoln, NE, USA) in August 2004. The effect of $[CO_2]$ was evaluated by one-way analysis of variance (ANOVA) for each condition of the soil. Differences were considered significant at $p < 0.05$.

Results and Discussion

The soil moisture increased in both soils (Fig. 1). This increase has also been detected in a temperate forest by SCHÄFER & al. 2002. They pointed out that the increase of soil moisture owing to a reduction in soil Ev was caused by a larger litter build-up in the $[CO_2]^e$ plot. However, in the study there was little build-up of litter on the plot. We therefore persevered in finding why the soil moisture increased under $[CO_2]^e$ in our study.

The Tr per leaf area decreased under $[CO_2]^e$ in both soil conditions, but the total Tr per seedling increased under $[CO_2]^e$ (Table 1). This increase is attributed to the increase in total leaf area per seedling (data not shown). ENGEL & al. 2004 and WANG & al. 2005 reported that the Tr per stand increased under $[CO_2]^e$, owing to a large increase in foliage area. These reports support our results. Although the total Tr per seedling in our study was an estimated value, our results indicate that the change in Tr might not have a significant impact on the increase in soil moisture under $[CO_2]^e$.

Ev decreased significantly under $[CO_2]^e$, though discontinuous capillarity at the soil surface was a possible cause (Table 2). We attribute this decrease to the reduction in soil surface temperature owing to an increase in LAI that blocked direct sunlight at the stand floor (Table 2). OBRIST & al. 2003 reported a similar tendency: the Ev from the soil decreased under $[CO_2]^e$ following the increase of LAI.

Did the decrease of Ev have a significant effect on soil moisture? FREDEEN & al. 1997 reported that the change of soil moisture under $[CO_2]^e$ depends on the change of Ev and Tr. In the present study, the value of Ev did not differ notably from that of the total Tr per seedling. Also, Ev decreased significantly under $[CO_2]^e$, but the total Tr per seedling did not. The increase of soil moisture in our study might therefore be due to the decrease of Ev. OBRIST & al. 2003 reported that the increase of Tr under $[CO_2]^e$ was offset by the decrease of Ev. These reports find similar results to our own. Incidentally, since Ev in our study was determined in October, rather than in August when Tr was determined, we cannot compare Ev and Tr directly. Temperature and sunlight were greater in August than October, so that the differences of temperature and sunlight on the forest floor between $[CO_2]^e$ and $[CO_2]^a$ would be greater in August than in October. Therefore, Ev would have a greater effect on soil moisture in August than in October.

We conclude that the soil moisture of the forest floor at $[CO_2]^e$ is higher than at $[CO_2]^a$. It is possible that this increase is caused by the decrease in Ev under $[CO_2]^e$. This result is same as that found for grassland (OBRIST & al. 2003). The coming increase in atmospheric $[CO_2]$ will modify the forest ecosystem and be accompanied by changes in soil moisture conditions.

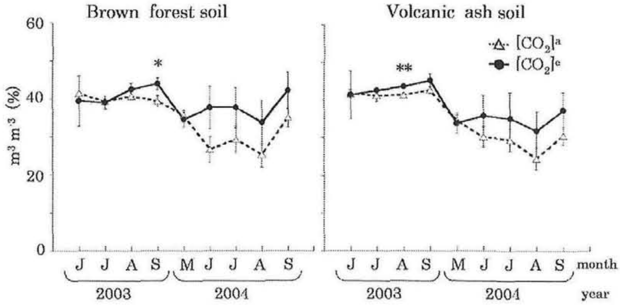

Fig. 1. Percentage of the soil moisture in FACE. Vertical bars indicate S.E.. * denotes $P<0.05$, ** denotes $P<0.01$. n = 6. $[CO_2]^a$: ambient $[CO_2]$, $[CO_2]^e$: elevated $[CO_2]$.

Table 1. Transpiration per unit leaf area (mmol m^{-2} s^{-1}). Values are means (S.E.). * denotes $P<0.05$, ** denotes $P<0.01$. NS denotes non-significant. n = 6. Bp: *Betula platyphylla*, Bm: *Betula maximowicziana*, Qm: *Quercus mongolica*, Ud: *Ulmus davidiana*, Fc: *Fagus crenata*, Am: *Acer mono*. $[CO_2]^a$: ambient $[CO_2]$, $[CO_2]^e$: elevated $[CO_2]$.

	Brown forest soil			Volcanic ash soil		
Sp.	$[CO_2]^a$	$[CO_2]^e$	*p*	$[CO_2]^a$	$[CO_2]^e$	*p*
Bp	2.31 (0.06)	2.45 (0.04)	NS	2.28 (0.25)	1.75 (0.10)	**
Bm	3.51 (0.27)	2.14 (0.36)	**	2.92 (0.15)	2.64 (0.33)	NS
Qm	2.14 (0.13)	2.31 (0.19)	NS	2.00 (0.26)	1.77 (0.18)	NS
Ud	1.59 (0.12)	1.37 (0.04)	NS	1.77 (0.10)	1.20 (0.17)	*
Fc	1.76 (0.11)	1.22 (0.22)	*	1.08 (0.04)	1.09 (0.07)	NS
Am	1.77 (0.20)	1.07 (0.15)	*	2.17 (0.09)	1.59 (0.21)	*

Table 2. Total transpiration rate per seedling (mm h^{-1}). Values are calculated from the average value of transpiration per unit leaf area (Table 1), multiplied by the average value of total leaf area per seedling (n=4, data not shown). Bp: *Betula platyphylla*, Bm: *Betula maximowicziana*, Qm: *Quercus mongolica*, Ud: *Ulmus davidiana*, Fc: *Fagus crenata*, Am: *Acer mono*. $[CO_2]^a$: ambient $[CO_2]$, $[CO_2]^e$: elevated $[CO_2]$.

	Brown forest soil		Volcanic ash soil	
Sp.	$[CO_2]^a$	$[CO_2]^e$	$[CO_2]^a$	$[CO_2]^e$
Bp	0.19	0.31	0.22	0.20
Bm	0.23	0.27	0.32	0.64
Qm	0.14	0.19	0.35	0.56
Ud	0.11	0.20	0.08	0.41
Fc	0.01	0.02	0.01	0.03
Am	0.12	0.09	0.08	0.17

Table 3. Evaporation (Ev) from the soil, soil surface temperature, leaf area index (LAI) and amount of sunlight on the soil surface. Values are means (S.E.) * denotes $P<0.05$, ** denotes $P<0.01$. NS denotes non-significant. n = 6. $[CO_2]^a$: ambient $[CO_2]$, $[CO_2]^e$: elevated $[CO_2]$.

	Brown forest soil			Volcanic ash soil		
	$[CO_2]^a$	$[CO_2]^e$	*p*	$[CO_2]^a$	$[CO_2]^e$	*p*
Ev (mm h^{-1})	0.13 (0.04)	0.04 (0.01)	*	0.26 (0.04)	0.11 (0.01)	**
Temp. of soil surface (℃)	23.5 (0.20)	21.9 (0.20)	**	23.4 (0.20)	22.4 (0.20)	**
LAI (m^2 m^{-2})	3.17 (0.14)	4.67 (0.25)	*	4.35 (0.17)	4.85 (0.17)	*
Amount of the sun light on soil surface (W m^{-2})	229 (28.2)	84 (14.2)	**	147 (11.7)	91 (13.4)	**

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