June 2007
Issue No.22

AsiaFlux Newsletter

Contents

Scale-up of Flux Site Data to Regional Scale with Remote Sensing

Yoshifumi YASUOKA

National Institute for Environmental Studies, Japan
&
The University of Tokyo, Japan

Introduction

Data from flux observation sites may provide valuable information on the complex functions in terrestrial ecosystems. Net Ecosystem Productivity (NEP) is, for example, one of the most important ecosystem parameters observed at the flux site. NEP defined by gross primary productivity (GPP) and ecosystem respiration (RE) of ecosystems (NEP=GPP-RE) determines productivity and respiration of ecosystems and carbon exchange between terrestrial ecosystems and atmosphere, and their seasonal variations observed at flux sites indicate basic functional characteristics of ecosystems, in particular, dynamics in carbon exchange of the whole systems. However, flux site data is point-based, and cannot cover an extensive area. Functions and structures of terrestrial ecosystem are quite complex due to heterogeneity and diversity, and it is not easy to assess their dynamics only by a small number of point-based flux data. In order to evaluate ecosystem characteristics over the area spatial scale-up (extrapolation) of flux site data is required.

Remote sensing may provide a tool to extrapolate point based flux site data to more extensive area by combining spectral signature of flux sites with GPP or RE since GPP and RE of terrestrial ecosystems show interactions with electromagnetic radiation. In this research, a scale-up method of flux site data is investigated to extrapolate point-based observation of carbon flux (NEP, GPP and RE) with remotely sensed data. Here GPP and RE were estimated by MODerate resolution Imaging Spectroradiometer (MODIS) data. MODIS VNIR (visible and near-infrared) wavelength data was used for GPP estimation, and MODIS TIR (thermal-infrared) data was used for RE estimation. The experimental results at two flux sites in a broadleaf deciduous forest in Japan showed high correlation between seasonal variations of MODIS VNIR data and GPP, and of TIR data and RE, and it indicated that NEP may be estimated from satellite images.

This article introduces a method for spatial scale-up of flux site data with remote sensing. The research has been done as a part of the Research Theme "Scale-up Parameterization for Terrestrial Ecosystems Modeling" (Theme Leader: Prof. Yoshifumi Yasuoka, the University of Tokyo) in the RR2002 Project "Sustainable Coexistence of Human, Nature and the Earth" sponsored by the Ministry of Education, Culture, Sport, Science and Technology (MEXT). The details of the research are shown in the final report of the Project (MEXT, 2007).

Flux Site Data and Satellite Data

Flux data at two sites (Hitsujigaoka, Hokkaido and Takayama, Gifu) in the Asia Flux Network were used in this case study. Data in Hitsujigaoka was provided by the Forestry and Forest Product Research Institute (Nakai *et al*., 2003), and data at Takayama was provided by the Advanced Institute for Industrial Science and Technology (Saigusa *et al*., 2002). Daily mean NEP, GPP and RE from 2003-2004 were used after preprocessing of the original data set. Furthermore daily flux data was averaged to get 10-day mean flux data for the consistent analysis with 10 day composite MODIS data.

MODIS reflectance values at two sites were retrieved from MODIS data archive at IIS/UT (Institute of Industrial Science, the University of Tokyo; http://yasulab.iis.u-tokyo.ac.jp). Visible and near infrared (VNIR) data was used to calculate vegetation indices which represent vegetation-cover conditions of the area, and thermal infrared (TIR) was used to calculate land surface temperature. Spatial resolution of MODIS data is 250m for VNIR band and 1000m for TIR band. Time series vegetation index and land surface temperature from MODIS at two sites were statistically analyzed with NEP, GPP and RE data averaged in 10 days.

Investigation of the Relation between GPP and RE with MODIS Data

There have been several studies indicating the relations between GPP and vegetation index (VI) from remote sensing data. In this study vegetation indices including NDVI (Normalized Difference Vegetation Index) and SAVI2 (Soil Adjusted Vegetation Index 2) are statistically correlated with GPP as shown in the equation (1);

$$GPP = aVI + b \qquad (1)$$

where a and b are regression coefficients. Among several vegetation indices SAVI2 showed the highest correlation with GPP, and was selected as a VI parameter for NEP calculation.

Then, the relation between RE and thermal infrared (TIR) of MODIS data was also investigated, and RE was estimated by a regression function as shown in the equation (2);

$$RE = AQ^{(\rho_{tir}-10)/10} \qquad (2)$$

where ρ_{tir} is TIR value, Q is the temperature coefficient and A is a regression coefficient.

Satellite based NEP was finally calculated from GPP and RE obtained in the equations (1) and (2);

$$NEP = GPP - RE \qquad (3)$$

Figure 1 shows the relation between the satellite-observation based NEP and the flux-observation based NEP for two sites (2003-2004), and it is indicated that NEP observed at the flux sites may be described by the remotely sensed spectral data (MODIS data).

Scale-up of NEP with MODIS Data

Since both of Hitsujigaoka and Takayama sites belong to broadleaf deciduous forests, and since MODIS data may cover the same forest type areas as two sites it may be expected that the relation shown in the equations (1), (2) and (3) may be extended over the same forest areas in Japan. In this research, NEP, GPP and RE over broadleaf deciduous forests in Japan was estimated from MODIS VNIR and TIR data based on the equations (1), (2) and (3). Figure 2 demonstrates spatial distribution of annual NEP over broadleaf deciduous forests in Japan. In Fig.2 broadleaf deciduous forest areas were extracted from MODIS images based on time series spectral signatures in MODIS VNIR data which may reflect vegetation phenology in each pixel. The estimated annual uptake of carbon was 16.5 MtC for broadleaf deciduous forests in Japan.

This example demonstrates the possibility of the spatial scale-up of the parameters observed at flux sites to more extensive regions with remotely sensed spectral signatures observed from satellites. It should be, however, noted that the several conditions are assumed as follows in this scheme, and they should be examined carefully in the analysis;

- within one pixel of MODIS image vegetation cover condition does not vary, that is, NEP, GPP and RE have stable values in one pixel of MODIS image (250m x 250m for VNIR and 1000m x 1000m for TIR),
- ecosystem functions are similar in the same forest type (deciduous boreal forest) , and GPP and RE may be described by the same equations (1) and (2) for all deciduous broad leaf forests in Japan,

and

- atmospheric conditions are the same over the target areas in 10days, and their effect to MODIS data (spectral signature) is negligible.

Conclusions

A scale-up method from point based flux observation site data to regional scale was investigated with satellite observation data. GPP is estimated from MODIS VNIR data and RE is estimated from MODIS TIR data. The remotely sensed NEP (= GPP – RE) from MODIS images have good correlation with the flux data at flux observation sites. It indicates the possibility of scaling-up of terrestrial ecosystem parameters at flux sites to more extensive regions.

References

Ministry of Education, Culture, Sport, Science and Technology (2007): Scale-up Parameterization for Terrestrial Ecosystems Modeling, The final Report of the Project “Sustainable Coexistence of Human, Nature and the Earth”.

Nakai, Y., Kimura, K., Suzuki, S. and Abe, S. (2003) Year-long carbon dioxide exchange above a broadleaf deciduous forest in Sapporo, Northern Japan, Tellus, 55B, 305-312.

Saigusa, N., Yamamoto, S., Murayama, S., Kondo, H., and Nishimura, N. (2002): Gross primary production and net ecosystem production of a cool-temperate deciduous forest estimated by the eddy covariance method, Agricultural and Forest Meteorology, 112, 203-215.

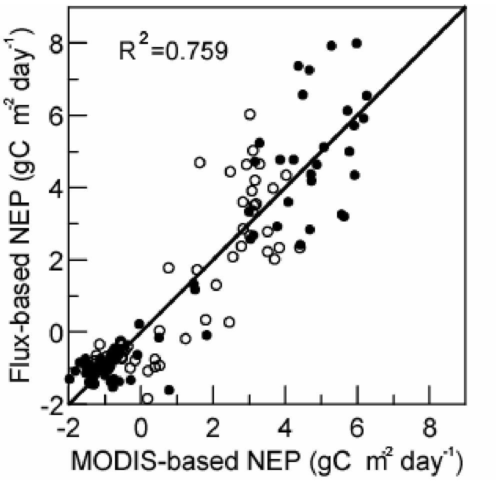

Fig. 1 Correlation between the NEP observed at two flux sites (Hitsujigaoka and Takayama) and the NEP estimated from MODIS data (Hitsujigaoka; ● and Takayama; ○).

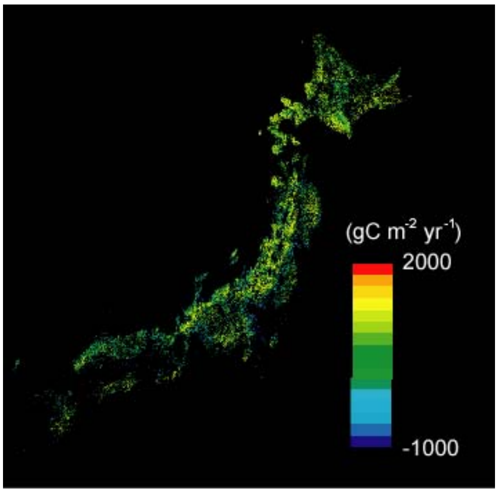

Fig. 2 Estimated spatial distribution of the annual NEP scaled up from the flux site data at Hitsujigaoka and Takayama.

Free-Air CO_2 Enrichment (FACE) Experiment for Carbon and Energy Flux Studies under Future Ecosystems

Mayumi YOSHIMOTO

National Institute for Agro-Environmental Sciences, Japan

Introduction

The atmospheric CO_2 concentration ($[CO_2]$) has risen dramatically from 280 ppm in pre-industrial times to 379 ppm in 2005, and its annual increase rate was the largest during the last ten years in continuous direct atmospheric measurements since 1960 (IPCC, 2007). The increasing $[CO_2]$ and the associated global warming have stimulated research programs to evaluate the effects of the future elevated $[CO_2]$ levels on agricultural productivity or carbon balance in agricultural/natural ecosystems.

The effects of elevated $[CO_2]$ on plant physiology have long been studied using controlled environment chambers, open-top chambers, and other enclosures to keep the CO_2 concentration elevated around the experimental plants (reviewed by e.g. Kimball, 1983; Norby *et al*. 1999; Nakagawa and Horie, 2000). However, the environment inside chambers is generally different from that outside (McLeod and Long, 1999). While the results obtained from the chamber studies may provide us with useful information regarding the *relative* plant responses to elevated $[CO_2]$, the ecosystem responses including soil-plant-atmosphere continuum to future $[CO_2]$ levels are difficult to determine. One main difficulty is well known as the, “chamber effect”, where enclosures amplify the plant response due to other environmental changes (artifacts) than the effect of $[CO_2]$. Another difficulty is the spatially and temporally small scale of chamber studies. Chambers are limited in size, which sometimes causes problems especially as growing plants in pots restricts root growth and supresses the plant response to elevated $[CO_2]$. And chamber experiments object to shorter-term response (typically one growing season at longest), and it is difficult to follow the long-term response of plant-soil system due to elevated $[CO_2]$ like soil carbon sequestration by the ecosystem.

After many attempts to solve these problems, large-scale free-air CO_2 enrichment (FACE) technology was developed, where CO_2 gas is injected into the open air without any enclosures, and $[CO_2]$ around the plant canopy is raised to 475 - 600 ppm or ambient concentration plus 200 ppm. The plants are supposed to grow under elevated $[CO_2]$ all growing-seasons long with all other environmental conditions unchanged.

In this paper, I attempt to present the meaning and the advantage of FACE studies by introducing a discrepancy between chamber- and FACE-based studies and results newly elucidated only in FACE experiments, mainly from rice FACE results related to carbon and energy flux studies. Further, I introduce one of new challenges of FACE experiments to be expected to simulate the ‘future ecosystems’ under elevated $[CO_2]$ and global warming in Asia.

History of FACE

The world’s first FACE system was developed by the Brookhaven National Laboratory (BNL) in cooperation with U.S. Department of Agriculture in 1970s. The BNL FACE system consists of a high-volume blower, a ring-shaped pipe for air distribution and vertical standing vent pipes for emitting CO_2-enriched air. Since the first FACE experiment on cotton in 1989 (e.g. Mauney *et al*., 1994), the BNL FACE system was applied to various agricultural annual plants, like wheat (C_3 grass) (e.g. Kimball *et al*., 1999), and sorghum (C_4 grass) (e.g. Ottman *et al*., 2001) in Arizona, U.S. In 1992, the BNL system was applied to grassland of perennial ryegrass and white clover in Eschikon, Switzerland, where pasture growth, soil processes and their interaction were studied (reviewed by Lüscher *et al*., 2004). Since then, various ecosystems have become subjected to the FACE experiment including forests and natural vegetations; e.g. pine forest (Hendrey *et al*., 1999), trembling aspen trees (Karnosky *et al*, 1999), desert ecosystem in Nevada (Jordan *et al*., 1999) and a range of mixed perennial grassland (Reich *et al*., 2001).

While the U.S. group had preceded the FACE experiments, this technology has spread to some European countries including Switzerland, Italy and Germany. Italian group of National Research Council (CNR) developed their original FACE system using a pure-CO_2 injection by nozzles on emission tubes, subjected to wheat (Miglietta *et al*., 1996), potato (Miglietta *et al*., 1998), grape (Bindi *et al*., 2001) in Rapolano, Italy. This pure-CO_2 injection system has been introduced to the SoyFACE in Champaign, U.S., where soybean and maize are grown (Rogers *et al*., 2004; Leakey *et al*., 2004). The SoyFACE system can elevate ozone concentration as well as [CO_2]. In New Zealand, a unique FACE experiment has been conducted targeting pasture with sheep (Edwards *et al*., 2001). In Australia, a natural grassland in the tropical savanna has been subjected to the FACE treatment, where long-term responses of plant and soil system have been investigated.

In Asia, the first FACE experiment with paddy rice started in 1998 in Shizukuishi, Japan, in a cool temperate climate. In the rice FACE, a pure-CO_2 injection method was originally designed to minimize artifacts associated with blowing CO_2-enriched air (Okada *et al*., 2001). A FACE ring consists of eight CO_2-emitting tubes placed horizontally and arranged to make an octagonal plot (Fig.1). The tubes have numerous tiny holes, from which pure CO_2 is 'sprayed' into the air above the plant canopy. Later on, a similar FACE system was set up in a rice-wheat cultivation area in Wuxi in 2001, and moved to Jiandu in 2004, both in Jiangsu Province, China, in a sub-tropical climate (Fig.2). Rice paddy fields produce the most important food crop and the submerged conditions make this agro-ecosystem quite different from the upland systems. Since 1998, many data on the physiological and agronomical responses of rice to elevated [CO_2] have been accumulated (e.g. Kim *et al*., 2003a, 2003b; Kobayashi *et al*., 2006; Yang *et al*., 2006). China FACE in Jiandu has just started to incorporate the ozone exposure treatment as in SoyFACE, which will serve as an important test-bed for the interaction between [CO_2] and ozone, the latter will likely increase to have significant impacts on agriculture in mid-western U.S. and in eastern China (Prather *et al*., 2003).

Fig.1 Overview of FACE experimental field in Shizukuishi, Japan.

Fig.2 Overview of FACE experimental field in Wuxi, China. (upper: tank and lower: FACE ring)

There are more than 30 active or planned FACE sites in the world. A map of all FACE experimental sites for the large-scale (diameter > 8m) replicated FACE trials, and links to individual websites are provided at the Carbon Dioxide Information Analysis Center website: http://cdiac.ornl.gov/programs/FACE/whereisface.html. Nearly 20 years of FACE research have produced some excellent reviews, the recent ones being published in Nosberger *et al*. (2006).

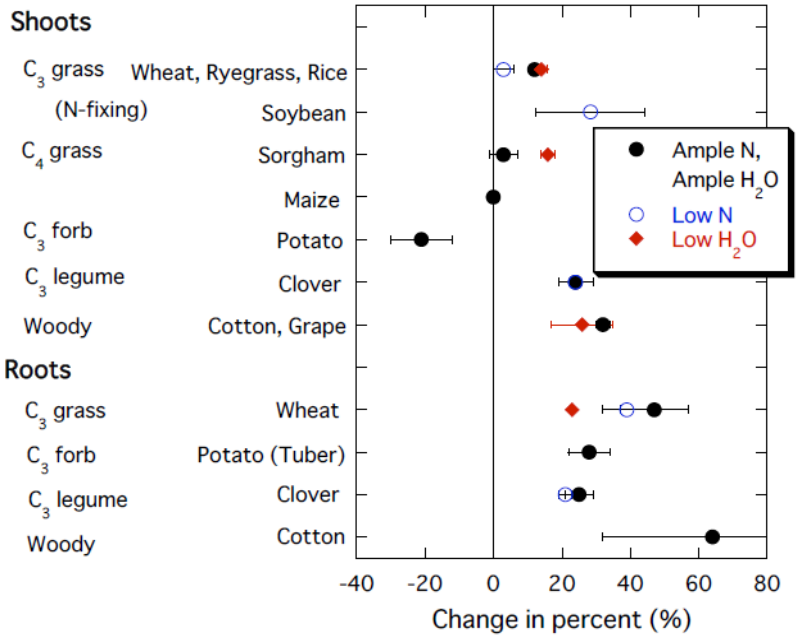

Fig.3 The percent change under elevated [CO_2] of biomass accumulation. Error bars mean standard error. All data are from result by FACE experiments (Kimball, et al., 2002; Morgan et al., 2005; Leakey, et al., 2006).

Plants biomass response to FACE

Elevated [CO_2] stimulates plant photosynthesis and enhances the biomass accumulation, which is the major process of carbon uptake by the terrestrial ecosystems. The enhanced growth of above- and below-ground biomass can in turn affect the soil carbon (C) and nitrogen (N) cycling through increased litter and root exudates.

The relative responses of biomass accumulations for shoots and roots by FACE were collected (Fig.3). As many reviewing papers have showed (e.g. Kimball *et al*., 2002), FACE increases biomass production in C_3 species, but little in C_4, and generally roots are stimulated more than shoots. Within experiments that included N availability treatments, the biomass stimulation due to elevated [CO_2] both in shoots and roots, is higher under high N availability than in low N availability.

These FACE results about biomass enhancement were almost consistent with relative responses by chamber experiments, though these tend to be stronger expressed on the enhancement of root growth relative to shoot growth in the FACE experiments than in the chamber experiments (Kimball *et al*., 2002; Gifford, 2004). In addition, there were some quantitative differences; trees were more responsive than other functional types, C_4 species showed little response, in FACE experiments than in chamber experiments, which show the need for a wide use of FACE, and most importantly side-by-side experiments to separate technique from site difference (Ainsworth and Long, 2004).

Physical response to FACE

The elevated [CO_2] causes partial stomatal closure which reduces leaf transpiration rate and raises leaf temperature because of decreased transpirational cooling. On the other hand, the leaf area change by plant growth stimulation due to elevated [CO_2] alters total transpiration and physical traits of the canopy; light transmittance and turbulent heat transfer at water surface. Such changes should alter not only the water use by plants but also the microclimate and energy balance of whole plant canopy. FACE is especially advantageous for observing and assessing the impacts of elevated [CO_2] on such canopy microclimate processes.

Yoshimoto *et al*. (2005a) conducted micrometeorological measurement in rice FACE in Japan, and clarified the effects of FACE on energy fluxes and evapotranspirational components by combining

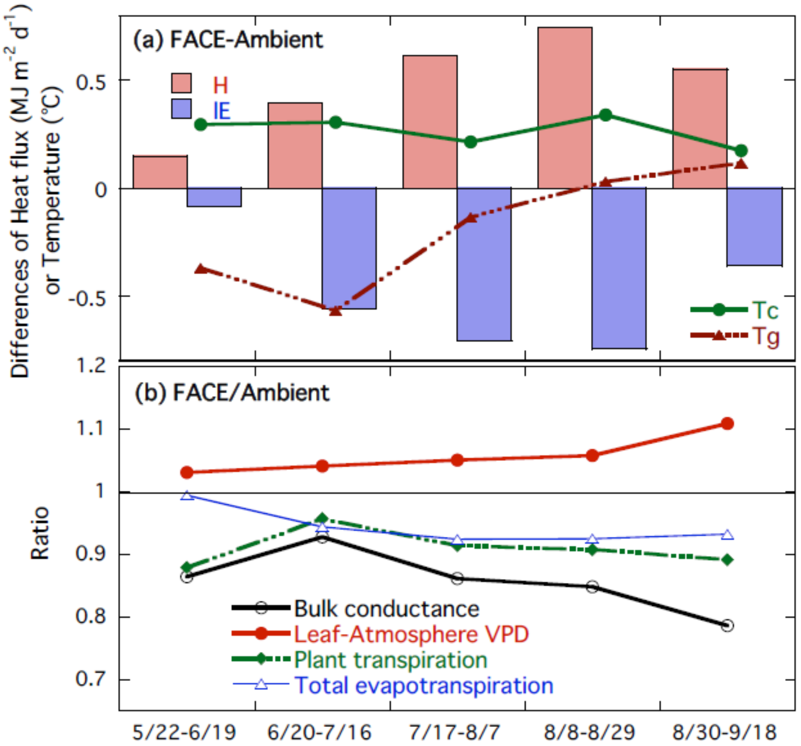

Fig.4 The effects of elevated [CO_2] on canopy microclimate and heat fluxes in rice FACE experiment in Shizukuishi, Japan. (a) The difference (FACE minus ambient) of leaf temperature (Tc) and water surface temperature (Tg), and sensible (H) and latent (lE) heat fluxes, and (b) the ratio (FACE / Ambient) of evapotranspirational components.

the observation and the heat budget model (Fig.4). The canopy temperature rose due to elevated [CO_2] in daytime average was approximately 0.2 to 0.4ºC. After the canopy surface closed in July, the latent heat flux decrease due to elevated [CO_2] was 0.4 to 0.7 MJ m^{-2} d^{-1}, which was an about 8% decrease in total evapotranspiration from ambient plot. Almost all of the decrease in the latent heat flux was balanced by the increase in the sensible heat flux (Fig.4a). The actual decrease in evapotranspiration by the FACE treatment was rather small compared to the rate of stomatal conductance decrease (by 10 to 40%) due to FACE. That is because the stomatal conductance decrease under FACE treatment was cancelled by larger LAI and the increase in the water vapor pressure deficit (VPD) between leaf and the atmosphere resulting from the leaf temperature rise due to FACE (Fig.4b).

The FACE experiment can detect the actual changes in microclimate of terrestrial ecosystems as well as its heat fluxes due to elevated [CO_2], which should not have been detected by chamber-based studies. Yoshimoto *et al*. (2005b) observed that the air temperature inside canopy was higher by 0.5 to 1ºC and the relative humidity was lower by 5 to 8% at FACE plot than at ambient plot, in rice-wheat FACE site in China. Such changes in canopy microclimate due to elevated [CO_2] have a possibility to exacerbate, especially in a warm climate area, a heat-induced spikelet sterility at flowering and cause a drastic reduction of crop yield, even in the absence of global warming.

Soil response to FACE

As mentioned above, the elevated [CO_2] stimulates the growth of plant roots and shoots, which increases carbon inputs to the soil. However, microbial activity and soil respiration are also often stimulated, although their variability is high (e.g. Zak *et al*., 2000). Therefore, it is not clear whether or not the greater growth of plants due to elevated [CO_2] will result in a greater C sequestration in the soil, that is, whether soils function as a negative or positive feedback media against the [CO_2] rise.

In the FACE experiments, the long-term measurements have been made of the changes in soil microbiology, soil respiration, and soil C

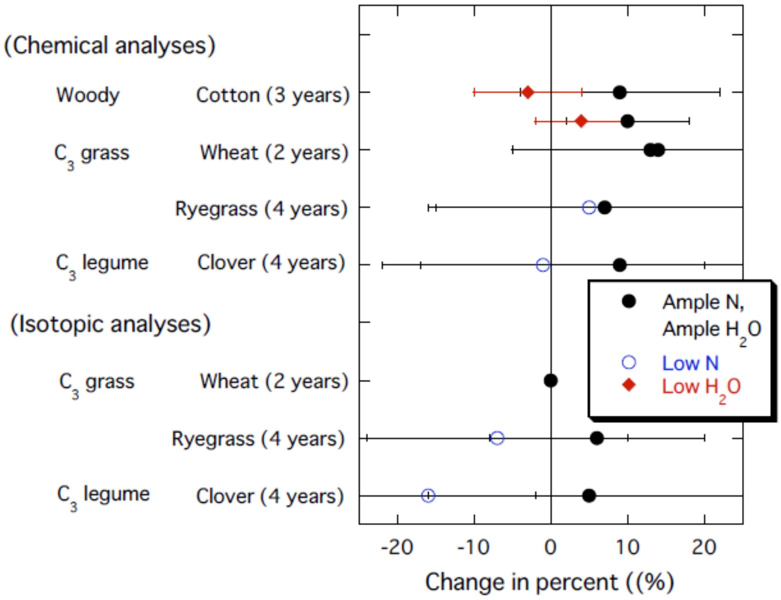

Fig.5 The percent change under elevated [CO_2] of soil carbon sequestration. Error bars mean standard error. All data are from result by FACE experiments (data are from Kimball et al., 2002).

sequestration after several seasons of FACE experiment. Due to high spatial variability and the large size of the soil C pool already present compared to soil C input, it is difficult to detect changes in soil C contents by FACE (Fig.5). Although there was no statistical significance of individual observations of soil C sequestration, it is noted that in all cases in Fig.5 there was an increase in soil C contents due to FACE at ample N. For the case of low N, the mean increase was almost zero. Thus, it appears that significant increases in soil C contents have occurred under elevated [CO_2] when N was non-limiting (Kimball *et al*., 2002; de Graaff *et al*., 2006).

Reich *et al*. (2006) showed, after a six-year FACE study of perennial grassland species grown under elevated and ambient CO_2 and N, that low N availability suppresses the positive response of plant biomass to elevated [CO_2]. The stimulation of total biomass by elevated [CO_2] was higher at ambient N than enriched N, at initial three years. In the next three years, however, the stimulation was greater at enriched N than ambient N. This response was consistent with the temporally divergent effects of elevated [CO_2] on soil and plant N availability, and the idea that C sequestration to the ecosystem is likely to be constrained over time by N availability. Also in the review by Lüscher *et al*. (2004), the ecosystem response to elevated CO_2 changed in the long-term indicating that processes in the soil that responded slowly (N cycling and sequestration, activity and mass of microorganisms etc.) gradually adapted to the new environmental conditions.

Methane (CH_4) is a particularly potent greenhouse effect gas, whose emissions from flooded rice paddies are a major source of global atmospheric CH_4. In rice FACE in Japan, Inubushi *et al*. (2003) measured CH_4 flux at elevated and ambient [CO_2] plots. The CH_4 emissions from the rice paddy increased due to FACE significantly, by 38% in 1999 and by 51% in 2000. The increased CH_4 emissions were attributed to accelerated CH_4 production potential of soils as a result of more root exudates and root autolysis products and to increased plant-mediated CH_4 emissions because of higher rice tiller numbers under FACE conditions.

Zheng *et al*. (2006) has investigated the CH_4 emissions in response to elevated [CO_2] in rice FACE in Japan (1998-2000) and rice-wheat FACE in China (2001-2003), where the N fertilization level and plant residues treatments were different. No significant effect of the elevated [CO_2] on the CH_4 emissions in the first rice season, but significant stimulatory effects (with a mean of 88% increase) were observed in the second and third rice seasons with and without organic matter addition. They investigated the correlation between stimulatory of CH_4 emissions and added decomposable organic C or the rates of N fertilization. Then, they found that the soil N availability was an important regulator for CH_4 emissions, and that not only the N supply in the current growing season but also that in the previous seasons may regulate the CH_4 emissions from rice paddy ecosystem. Also, they implied the possibility of accelerating the increase of atmospheric CH_4 both in N-poor and N-rich paddy fields by feedback mechanisms for the elevated [CO_2] on CH_4 emissions from rice paddy ecosystems.

Challenge for new FACE and inter FACE

The global warming concurrent with the elevated [CO_2] also has a great impact on ecosystem carbon balance. Since warming affects all chemical and biological processes, the direct and indirect effects of warming on ecosystem C and N cycles should be more complex than the effects of elevated [CO_2] (Shaver *et al*., 2000). In order for their understanding and predicting the ecosystem responses in the future, ecosystem warming experiments have been conducted at various ecosystems in the world: http://www.umaine.edu/teracc/ The CO_2 enrichment will add complexity to the relationship between the ecosystem C and N cycles and warming, because of interactions by both two factors (temperature and [CO_2]), which leads to the necessity of multifactor (temperature × [CO_2]) experiments in ecosystem-scale (Norby and Luo, 2004).

Taking the initiative in the world, in 2007, a free-air warming experiment combined with FACE has started in rice FACE site in Shizukuishi, Japan, as a cooperative research project of National Agricultural Research Center for Tohoku Region and National Institute for Agro-Environmental Sciences (Fig.6). The treatment plots of the ambient water temperature and the warmed water temperature (ambient plus 2ºC) are provided in each ambient [CO_2] and elevated [CO_2] plot, which enables to observe the interactive temperature × [CO_2] responses of rice paddy ecosystem. The responses of plants physiology and soil processes will be investigated, related with C and N cycles like leaf photosynthesis and respiration, soil respiration, N immobilization, N availability, CH_4 flux and soil microbes, etc. as well as agricultural responses. It is expected to clarify the whole rice paddy ecosystem responses in warming FACE experiment as a 'future ecosystem'.

Fig.6 Overview of warming experiment in the FACE experimental field in Shizukuishi, Japan. There are both of ambient water temperature and warmed water temperature areas in each ambient [CO_2] and elevated [CO_2] plot.

In addition, a group of Japanese and Chinese rice FACE research including the Institute of Soil Science, Chinese Academy of Science, Yangzhou University and the National Institute for Agro-Environmental Sciences has initiated an "Inter-FACE results analysis" to identify the commonality and differences between the two sites. This analysis will be an important step toward better understandings of the future CO_2 effects on diverse Asian rice agriculture.

References

Ainswoth, E.A. and Long, S.P., 2004: What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol*. **165**, 351-372.

Bindi, M., Fibbi, L., Lanini, M. and Miglietta, F., 2001: Free air CO_2 enrichment (FACE) of grapevine (*Vitis vinifera* L.): I Development and testing of the system for CO_2 enrichment. *Eur. J. Agron*. **14**, 135-143.

de Graaff, M-A., van Groenigen, K-J., Six, J., Hungate, B. and van Kessel, C., 2006: Interactions between plant growth and soil nutrient cycling under elevated CO_2: a meta-analysis. *Global Change Biol*. **12**, 2077-2091.

Edwards, G.R., Clark, H., Newton, P.C.D., 2001: The effects of elevated CO_2 on seed production and seedling recruitment in a sheep-grazed pasture. *Oecologia* **127**, 383-394.

Gifford, R.M., 2004: The CO_2 fertilising effect - does it occur in the real world? *New Phytol.* **163**, 221-225.

Hendrey, G.R., Ellsworth, D.S., Lewin, K.F. and Nagy, J., 1999: A free-air enrichment system for exposing tall forest vegetation to elevated atmospheric CO_2. *Global Change Biol.* **5**, 293-309.

Inubushi, K., Cheng, W., Aonuma, S., Hoque, M.M., Kobayashi, K., Miura, S., Kim, H.Y. and Okada, M., 2003: Effects of free-air CO_2 enrichment (FACE) on CH_4 emission from a rice paddy field. *Global Change Biol.* **9**, 1458-1464.

IPCC 2007 *Climate Change 2007: The Physical Basis - Summary for Policymakers,* Accessed at http://www.ipcc.ch/SPM2feb07.pdf

Jordan, D.N., Zitzer, S.F., Hendrey, G.R., Lewin, K.F., Nagy, J., Nowak, R.S., Smith, S.D., Coleman, J.S. and Seeman, J.R., 1999: Biotic, abiotic and performance aspects of the Nevada Desert free-air CO_2 enrichment (FACE) facility. *Global Change Biol.* **5**, 659-668.

Karnosky, D.F., Mankovska, B., Percy, K., Dickson, R.E., Podila, G.K., Sober, J., Noormets, A., Hendrey, G.R., Coleman, M.D., Kubiske, M., Pregitzer, K.S. and Isebrands, J.G., 1999: Effects of tropospheric O_3 on trembling aspen and interaction with CO_2: results from an O_3-gradient and a FACE experiment. *Water Air Soil Pollut.* **116**, 311-312.

Kim, H.Y., Lieffering, M., Kobayashi, K., Okada, M., Mitchell, M.W. and Gumpertz, M., 2003a: Effects of free-air CO_2 enrichment and nitrogen supply on the yield of temperate paddy rice crops. *Field Crops Res.* **83**, 261-270.

Kim, H.Y., Lieffering, M., Kobayashi, K., Okada, M. and Miura, S., 2003b: Seasonal changes in the effects of elevated CO_2 on rice at three levels of nitrogen supply: a free-air CO_2 enrichment (FACE) experiment. *Global Change Biol.* **9**, 826-837.

Kimball, B.A., 1983: Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. *Agron. J.* **75**, 779-788.

Kimball, B.A., LaMorte, R.L., Pinter, P.J., Jr., Wall, G.W., Hunsaker, D.J., Adamsen, F.J., Leavitt, S.W., Thompson, T.L., Matthias, A.D. and Brooks, T.J., 1999: Free-air CO_2 enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. *Water Resour. Res.* **35**, 1179-1190.

Kimball, B.A., Kobayashi, K. and Bindi, M., 2002: Responses of agricultural crops to free-air CO_2 enrichment. *Adv. in Agron.* **77**, 293-368.

Kobayashi, T., Ishiguro, K., Nakajima, T., Kim, H.Y., Okada, M. and Kobayashi, K., 2006: Effects of elevated atmospheric CO_2 concentration on the infection of rice blast and sheath blight. *Phytopathol.* **96**, 425-431.

Leakey, A.D.B., Bernacchi, C.J., Dohleman, F.G., Ort, D.R. and Long, S.P., 2004: Will photosynthesis of maize (*Zea mays*) in the US Corn Belt increase in future [CO_2] rich atmospheres? An analysis of diurnal courses of CO_2 uptake under free-air concentration enrichment (FACE) *Global Change Biol.* **10**, 951-962.

Leakey, A.D.B., Uribelarrea, M., Ainsworth, E.A., Naidu, S.L., Rogers, A., Ort, D.R. and Long, S.P., 2006: Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. *Plant Physiol.* **140**, 779-790.

Lüscher, A., Daepp, M., Blum, H., Hartwig, U.A. and Nosberger, J., 2004: Fertile temperate grassland under elevated atmospheric CO_2 - role of feed-back mechanisms and availability of growth resources. *Eur. J. Agron.* **21**, 379-398.

McLeod, A.R. and Long, S.P., 1999: Free-air carbon dioxide enrichment (FACE) in global change research: A review. *Adv. Ecol. Res.* **28**, 1-56.

Mauney, J.R., Kimball, B.A., Pinter, P.J., Jr., LaMorte, R.L., Lewin, K.F., Nagy, J. and Hendrey, G.R., 1994: Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. *Agric. For. Meteorol.* **70**, 49-68.

Miglietta, F., Giuntoli, A. and Bindi, M., 1996: The effect of free-air carbon dioxide enrichment (FACE) and soil nitrogen availability on the photosynthetic capacity of wheat. *Photosyn. Res.* **47**, 281-290.

Miglietta, F., Magliulo, V., Bindi, M., Cerio, L., Vaccari, F.P., LoDuca, V. and Peressotti, A., 1998: Free air CO_2 enrichment of potato (*Solanum tuberosum*, L.): development, growth and yield. *Global Change Biol.* **4**, 163-172.

Morgan, P.B., Bollero, G.A., Nelson, R.L., Dohleman, F.G. and Long, S.P., 2005: Smaller than predicted increase in aboveground net primary production and yield of field-grown soybean under fully open-air [CO_2] elevation. *Global Change Biol.*, **11**, 1856-1865.

Nakagawa, H. and Horie, T., 2000: Rice responses to elevated CO_2 and temperature. *Global Environ. Res.* **3**, 101-113.

Norby, R.J. and Luo, Y., 2004: Evaluating ecosystem responses to rising atmospheric CO_2 and global warming in a multi-factor world. *New Phytol*. **162**, 281-293.

Norby, R.J., Wullschleger, S.D., Gundersonm, C.A., Johnson, D.W. and Ceulemans, R., 1999: Tree responses to rising CO_2 in field experiments: implications for the future forest. *Plant Cell Environ*. **22**, 683-714.

Nosberger, J, Long, S.P., Norby, R.J., Stitt, M., Hendrey, G.R. and Blum, H. eds. 2006: Managed ecosystems and CO_2: case studies, processes, and perspectives. Springer, Berlin Heidelberg New York, (Ecological studies, vol. 187), 87-104.

Okada, M., Lieffering, M., Nakamura, H., Yoshimoto, M., Kim, H.Y. and Kobayashi, K., 2001: Free-air CO_2 enrichment (FACE) using pure CO_2 injection: system description. *New Phytol*. **150**, 251-260.

Ottman, M.J., Kimball, B.A., Pinter, P.J., Jr., Wall, G.W., Vanderlip, R.L., Leavitt, S.W., LaMorte, R.L., Matthias, A.D. and Brooks, T.J., 2001: Elevated CO_2 effects on sorghum growth and yield at high and low soil water content. *New Phytol*. **150**, 261-273.

Prather, M., Gauss, M., Berntsen, T., Isaksen, I., Sundet, J., Bey, I., Brasseur, G., Dentener, F., Derwent, R., Stevenson, D., Grenfell, L., Hauglustaine, D., Horowitz, L., Jacob, D., Mickley, L., Lawrence M., von Kuhlmann, R., Muller J-F., Pitari, G., Rogers, H., Johnson, M., Pyle, J., Law, K., van Weele, M. and Wild, O., 2003: Fresh air in the 21st century? *Geophys. Res. Lett*. **30**, 1100.

Reich, P.B., Hobbie, S.E., Lee, T., Ellsworth, D.S., West, J.B., Tilman, D., Knops, J.M.H., Naeem, S. and Trost, J., 2006: Nitrogen limitation constrains sustainability of ecosystem response to CO_2. *Nature*, **440**, 922-925.

Reich, P.B., Tilman, D., Craine, J., Ellsworth, D. Tjoelker, M.G., Knops, J., Wedin, D., Naeem, S., Bahauddin, D., Goth, J., Bengtson, W. and Lee, T.D., 2001: Do species and functional groups differ in acquisition and use of C, N and water under varying atmospheric CO_2 and N availability regimes? A field test with 16 grassland species. *New Phytol*. **150**, 435-448.

Rogers, A., Allen, D.J., Davey, P.A., Morgan, P.B., Ainsworth, E.A., Bernacchi, C.J., Cornic, G., Dermody, O., Dohleman, F.G., Heaton, E.A., Mahoney, J., Zhu, X.-G., Delucia, E.H., Ort, D.R. and Long, S.P., 2004: Leaf photosynthesis and carbohydrate dynamics of soybeans grown throughout their life-cycle under Free-Air Carbon dioxide Enrichment. *Plant Cell Environ*. **27**, 449-458.

Shaver, G.R., Canadell, J., Chapin III, F.S., Gurevitch, J., Harte, J., Henry, G., Ineson, P., Jonasson, S., Melillo, J., Pitelka, L. and Rustad, L., 2000: Global warming and terrestrial ecosystems: a conceptual framework for analysis. *BioScience* **50**, 871-882.

Yang, L.X., Huang, J.Y., Yang, H.J., Dong, G.C., Liu, G., Zhu, J.G. and Wang, Y.L., 2006: Seasonal changes in the effects of free-air CO_2 enrichment (FACE) on dry matter production and distribution of rice (*Oryza sativa* L.). *Field Crops Res*. **98**, 12-19.

Yoshimoto, M., Oue, H. and Kobayashi, K., 2005a: Energy balance and water use efficiency of rice canopies under free-air CO_2 enrichment. *Agric. For. Meteorol*. **133**, 226-246.

Yoshimoto, M., Oue, H., Takahashi, N. and Kobayashi, K., 2005b: The effects of FACE (Free-Air CO_2 Enrichment) on temperatures and transpiration of rice panicles at flowering stage. *J. Agric. Meteorol*. **60**, 597-600.

Zak, D.R., Pregitzer, K.S., King, J.S. and Holmes, W.E., 2000: Elevated atmospheric CO_2, fine roots and the response of soil microorganisms: a review and hypothesis. *New Phytol*. **147**, 201-222.

Zheng X.H., Zhou, Z.X., Wang, Y.S., Zhu, J.G., Wang, Y.L., Yue, J., Shi, Y., Kobayashi, K., Inubushi, K., Huang, Y., Han, S.G., Xu, Z.J., Xie, B.H., Butterbach-bahl, K. and Yang, L.X., 2006: Nitrogen-regulated effects of free-air CO_2 enrichment on methane emissions from paddy rice fields. *Global Change Biol*. **12**, 1717-1732.

Science Topic: Field Measurement of CO_2 Efflux from Roots –the Importance in Forest Carbon Cycle-

Masako DANNOURA*, Yuji KOMINAMI**, Koji TAMAI**,
Mayuko JOMURA*** and Yoichi KANAZAWA*

*Kobe University, Japan
** Forestry and Forest Products Research Institute, Japan
*** National Institute for Agro-Environmental Sciences, Japan

The importance of root respiration at flux sites

Belowground processes play an important role in the carbon cycle of the biosphere. Soil respiration (R_s) is the main pathway for carbon moving from an ecosystem into the atmosphere (Ryan and Law, 2005) and its variations likely affect the net ecosystem products (NEP). The NEP is defined as the difference between the gross primary products (GPP) and total ecosystem respiration (the sum of autotrophic respiration (R_a) and heterotrophic respiration (R_h)). The net ecosystem exchange (NEE) is equivalent to －NEP and is measured mainly using the eddy covariance methods. Measurements of the NEEs of various forests have been conducted worldwide. It is estimated that about 80% of GPP are returned to the atmosphere from ecosystems, using the data obtained from the flux measurement (Law *et al.*, 2002).

However, since the eddy covariance method requires adequate mixing of air and measurements of storage CO_2 flux require conditions when horizontal advection can be ignored; eddy fluxes sometimes underestimate respiration at night in calm winds (Baldocchi *et al.*, 1997; Goulden *at al.*, 1996; Black *et al.*, 1996). This means that alternative method to validate nighttime respiration and a method to detect period are necessary to confirm the carbon flux when using the eddy covariance method.

The R_a is an important factor to understand the NEP variation (Valentini *et al.*, 2000), and 70% of the R_a is effused from the soil (Goulden *et al.*, 1996; Law *et al.*, 1999). R_s has been measured in many ecosystems (Crill, 1991; Lavigne *et al.*, 1997). To compare the NEE measured using the eddy covariance method with the NEP estimated with biometric measurements, and to understand the CO_2 budget of a forest ecosystem, it is important to accurately evaluate both the R_a and R_h. However, the efflux from a soil surface is an assemblage of multiple belowground processes, such as decomposition respiration and root respiration (R_r). According to Hanson *et al.* (2000), about half of soil respiration is derived from metabolic activity to support and grow roots and their associated mycorrhiza. Since there are many technical difficulties in the measurement of R_r, R_r has been assumed to form constant proportion of R_s, i.e. $R_r = 0.5R_s$ (Curtis. *et al.*, 2002), in many studies. However, since the ratio of R_r to R_s also changes in the seasonal variation or in the response to the environmental factors (Tang *et al.*, 2005), this kind of assumption causes misunderstanding of its contribution to the carbon budget, and direct measurements of R_r are needed for the accurate evaluation. The influence of various root-related processes must be quantified, there have been very few reports of the direct measurement of R_r. Thus, we report here a direct measurement of R_r.

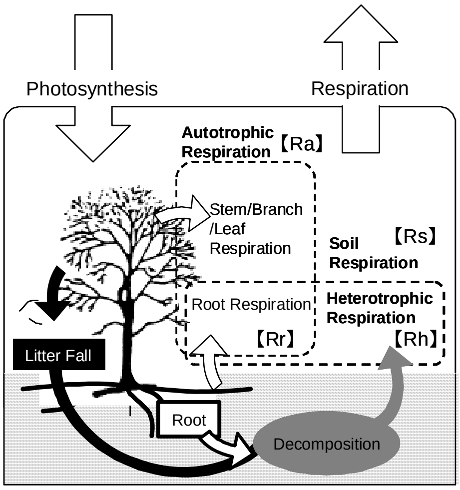

Fig.1 Forest carbon cycle

Contributions to root dynamics

First, we explain root dynamics, because the R_r rate is thought to depend on this factor. Roots constitute a large stock of carbon, because about 25% of a tree is underground. Roots accumulate in the soil as carbon, and living roots emit CO_2 due to respiration activity. Moreover, parts of living roots die and CO_2 goes back into the atmosphere from the decomposition process. The heterogeneity of dead roots influences the density of microorganisms and the spatial variation of the CO_2 efflux from the soil surface. The litter fall on the surface has been investigated in detail, including the amount, elements, seasonal variations, and yearly changes, because it is possible to gather litter in a trap. However, it is very difficult to measure root litter, because the flow of death-decomposition CO_2 emission all takes place in the soil. It has been reported that 35-80% of the GPP can be allocated underground as a result of root production, root respiration, mycorrhiza, and exudation (Raich and Nadelhoffer 1989; Davidson *et al*., 2002; Giardina *et al*., 2003; Ryan *et al*., 2004). Particularly fine roots have a higher turnover rate than larger roots, and 30-54% of the NPP of trees in forests is consumed in fine root turnover (Vogt *et al*., 1982). Therefore, the turnover cycle of fine roots is very important in the forest carbon cycle, although the fine roots themselves do not have a large biomass. A current method used for studies of long-term root dynamics, the minirhizotron method, involves a transparent observation system in the soil (Johnson and Mayer, 1998; Satomura *et al*., 2001). Satomura *et al*. (2007) compared studies on fine root turnover that used the minirhizotron method, and found that the definition of root turnover is important, and the turnover speed depends on the definition of turnover, the methods of calculation, and other factors. In any case, a high turnover rate of fine root has been reported.

In the Yamashiro Experimental Forest (YMS, an Asia Flux site in Kyoto Prefecture), meteorological data from flux tower observation (Kominami *et al*., 2005) were compared with biometric data such as an annual presumed Rs (Tamai *et al*., 2005), litter amount, and biomass (Goto *et al*., 2003). The carbon supplied into the soil as litter fall was estimated to be approximately 30% lower than the annual amount of Rs, suggesting that a large carbon source remains unknown and the detailed investigation on the carbon cycle below the ground are needed

Separating root respiration from soil respiration

In this context, the R_a is means the R_r. Many reports have dealt with the separation of R_s into the R_a and R_h. Hanson *et al*. (2000) concluded in a review that the contribution of CO_2 efflux from roots (R_r) to the total soil CO_2 efflux (R_s) averages approximately 48.5% in a forest ecosystem, but this ratio varies widely (between 10% and 90%) depending on the measurement method, forest type, season, and location. Among the various methods to separate the R_r from the R_s, direct measurement of CO_2 fluxes from sample roots using a chamber (Dannoura *et al*., 2005) has advantage that the R_r can be measured exclusively, without the complicating influence of the presence of soil. However, in this sampling method, the roots used are excavated from soil and cut to fit within the chamber. As a result, continuous measurements are impossible and the results may be biased due to the impact of cutting. The main alternative to this approach involves the indirect measurement of the R_r. In this approach, the R_r is calculated as the difference in the total R_s and the Rs from the root exclusion plot by means of root removal, trenching, gap creation, and other methods (Nakane *et al*., 1996; Ohashi *et al*., 2000). This indirect approach permits continuous measurements (Lee *et al*., 2003; Tang *et al*., 2005), but includes the influence of dead roots. This is a significant problem because dead roots can be a major source of R_h. The isotope-labeling method for estimating the R_r exploits variations in the $^{13}C/^{12}C$ ratio (Andrews *et al*., 1999; Rochette *et al*., 1999). This method permits continuous measurements (Bhupinderpal-Shing *et al*., 2003) with minimum disturbance to the soil and roots. However, this method generally yields lower rhizosphere contributions than those obtained using other methods, and there are uncertainties in quantitative results obtained by applying this method under natural environment (Hanson *et al*., 2000).

Measurements of the R_r at a flux site

In this paper, we present some measurements of R_r that has been taken at the YMS from 2000. The YMS is a mixed deciduous and evergreen broad-leaved forest that includes some conifers. The area has a very thin immature soil layer derived from granite.

Direct measurement of the R_r for the estimation of the R_r per unit area in the YMS: relationship between root diameter and R

To quantify the root biomass in the YMS, we excavated 16 root systems and measured their root volumes and diameters in detail. We estimated the allometric relationship between the DBH and the root biomass for several root diameter classes. Using data on the tree DBH in the YMS (Goto *et al.*, 2003), we estimated the biomass of roots larger than 2 mm in diameter. For fine roots (< 2 mm), we sampled soil blocks and calculated the fine root biomass per unit area. We estimated the root biomass by defining five diameter classes: 0-2, 2-5, 5-20, 20-50, and greater than 50 mm（Dannoura *et al.*, 2006a: Fig.2）. Next, the R_r of each diameter class was measured using a sampling method. Root samples of various diameters were collected from typical deciduous and evergreen tree species in the YMS. The CO_2 fluxes were measured from root samples of each diameter class using a closed-chamber system with an infrared gas analyzer (IRGA). Measurements were conducted in April (temperature: 20.6ºC), July (32.4-34.0ºC), September (24.6-31.7ºC), November (18.9-21.2ºC), and December (6.8-7.9ºC). Combining the data with the root biomass of each size allowed the estimation of the diameter distribution of the R_r in the YMS. Moreover, on 9 and 11 September, the R_s and R_r were measured simultaneously in the YMS (Tamai *et al.*, 2005; Dannoura *et al.*, 2006b).

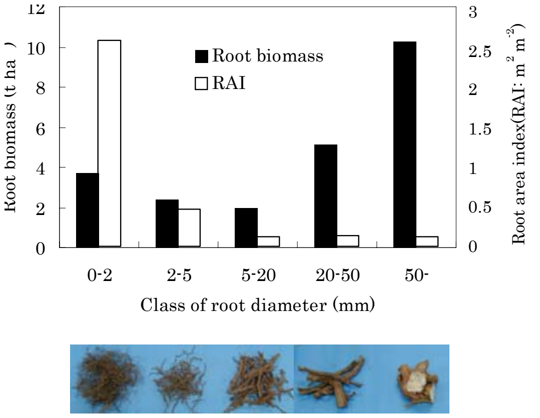

Fig.2 Root biomass and surface area according to size (modified from Dannoura *et al.*, 2006a).

Independent of the tree species and tree size, we found that the smaller the root diameter, the higher the CO_2 flux per unit weight. The R_r in fine roots (< 2 mm) per unit weight was remarkably high, a tendency that was present throughout the year. The CO_2 flux per unit area was calculated using the CO_2 flux per unit root weight and the root biomass of each diameter class. The data revealed that fine roots, which constituted only about 16% of the total root biomass, provided more than half of the respiration. This result shows that it is necessary to consider root size, especially fine roots, in estimating the forest R_r. We also compared the estimated R_r and R_s. The R_s was measured at 256 points on 9 and 11 September (Tamai *et al.*, 2005). The effect of any uneven spatial distribution was eliminated because of the multi-point simultaneous measurements. The mean R_s rate on 9 and 11 September in the YMS was 0.91 mg CO_2 $m^{-2}s^{-1}$and the rate of contribution of the R_r to the R_s during this time was 37.2%.

Temporal measurement of the R_r using an automatic chamber system

We have developed an automatic chamber system for measuring the CO_2 flux from fine roots (Dannoura *et al.*, 2006c). The system consists of an IRGA, a pump, and five chambers that are operated alternately (Fig. 3). To measure only the R_r, layer A of the forest soil, including the organic matter, was removed, and only living roots remained. The resulting space was filled with decomposed granite soil. An acrylic board was placed between layers A and B to remove the influence of CO_2 flux from layer B (mineral soil). We set up three chambers for the R_r. At the same time, the *Rs* was measured and the CO_2 flux was measured at 35-min intervals. The soil temperature and water content were also measured continuously in each chamber from April 2004 to May 2005.

The R_r and R_s showed different responses to the soil water content: the *Rs* decreased with decreasing soil water content, whereas the R_r peaked at relatively low soil water content. The R_r/R_s ratio decreased from 64.8% to 27.3% as the soil water content increased from 0.075 to 0.225 m m^{-3}. The relationship between respiration and temperature appeared to change seasonally in response to phenological and biological factors. During the growing period, the R_r was higher at the same soil temperature

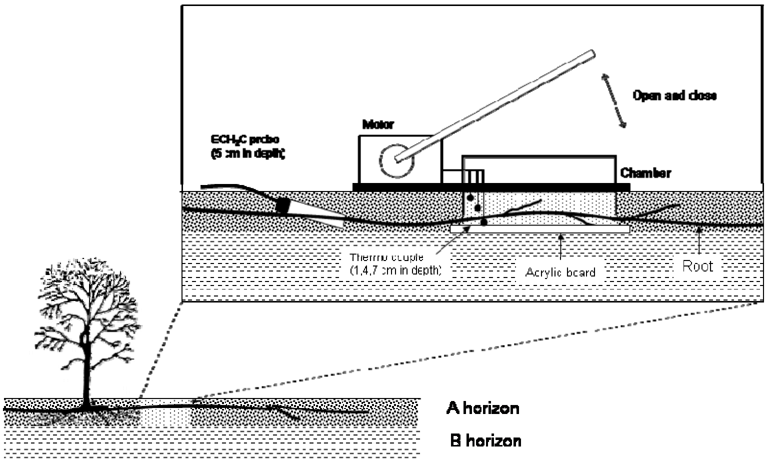

Fig.3 The chamber system for measurement of root respiration only (Dannoura et al., 2006c)

as during other periods, which may be due to phenological influences such as fine root dynamics. On the other hand, R_s decreased during the late summer (August) despite the high soil temperatures, although many researchers found the acceleration of the R_s by high soil temperature. One possible explanation is that the most litter had decomposed in the rainy season (June-July) just before the late summer, when both the soil temperature and water content are favorable condition. The seasonal variation in R_r/R_s ranged between 25% and 60% over the course of the year. We suspect many factors have an effect on variation of R_s, not only change of environmental factors, but also change of biological factors and these affect each other in short and long term because R_s consist of R_r and R_h basically. These results demonstrate the importance of the analysis of long-term measurements in examining the role of R_r in forest ecosystems.

Conclusions

The estimation of the *Rr* per unit area clearly showed the importance of fine roots respiration. Fine root turnover is a factor that must be included in analyses estimating the underground carbon cycle. A compositive method to measure the CO_2 is necessary for evaluations of the R_r. From temporal measurements of the R_r, the contribution of the R_r shows seasonal variations that mean that it cannot easily be predicted from the R_s, and should be evaluated independently. The results of the present study show that an accurate evaluation of the R_r and the clarification of its properties are indispensable for understanding the carbon budget of forest ecosystems.

Acknowledgements

This study was supported in part by a Grand-in-Aid for Research from JSPS (numbers 15380107 and 18380095) and the Asahi Breweries Foundation. We deeply appreciate many valuable suggestions from editor and reviewers. We are grateful to Dr. Yoshiaki Goto and Dr. Takafumi Miyama for their helpful advice in biometric research and establishment of the chamber system. We also thank the members of the laboratory of forest resources at Kobe University, especially Hitoshi Kimura, Taizo Sasaki, and Shogo Hamada, for providing field support.

References

Andrews, J. A., Harrison, K. G., Matamala, R., and Schlesinger, W. H. 1999. Separation of root respiration from total soil respiration using carbon-13 labeling during free-air carbon dioxide enrichment (FACE). *Soil Sci. Soc. Am. J.* **63**, 1429-1435.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., and *co-authors*. 2001. A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bull. Am. Meteorol. Soc. For.* **82**, 2415-2434.

Bhupinderpal-Shingh, Nordgren, A., Lofvenius, M. O., Hogberg, M. N., Mellander, P. E., and Hogberg, P. 2003. Tree root and soil heterotrophic respiration as revealed by girdling of boreal Scots pine forest: extending observations beyond the first year. *Plant Cell Environ.* **26**, 1287-1296.

Crill, P. M. 1991. Seasonal patterns of methane uptake and carbon dioxide release by a temperate woodland soil. *Glob. Biogeochem. Cycles* **5**, 319-334.

Curtis, P. S., Hanson, P. J., Bolstad, P., Barford, C., Randolph, J. C., Schimid, H. P. and Wilson, K. B. 2002. Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Agri. For. Met.* **113**, 3-19.

Dannoura, M., Kominami, Y., Hirano, Y., Kanazawa, Y., and Goto, Y. 2005. Measurement of root respiration using potted Japanese cedar. *Mem. Grad. School Sci. & Techonol., Kobe Univ.* **23-A**, 67-73.

Dannoura, M., Kominami, Y., Goto, Y., and Kanazawa, Y. 2006a. Estimation of root biomass and root surface area of a broad-leaved secondary forest in the southern part of Kyoto prefecture. *J. Jpn For. Sci.* **88**, 120-125. (In Japanese with English summary.)

Dannoura, M., Kominami, Y., Tamai, K., Goto, Y., Jomura, M., and Kanazawa, Y. 2006b. Short-term evaluation of the contribution of root respiration to soil respiration in a broad-leaved secondary forest in the southern part of Kyoto Prefecture. *J. Agric. Meteorol.* **62**, 15-20. (In Japanese with English summary.)

Dannoura, M., Kominami, Y., Tamai, K., Jomura, M., Miyama, T., Goto, Y., and Kanazawa, Y. 2006c. Development of an automatic chamber system for long-term measurements of CO_2 flux from roots. Tellus B **58**, 502-512.

Davidson, E. A., Savage, K., Bolstad, P., Clark, D. A., Curtis, P. S., Ellsworth, D. S., Hanson, P. J., Law, B. E., Luo, Y., Pregitzer, K. S., Randolph, J. C., and Zak, D. 2002. Belowground carbon allocation in forests estimated from litterfall and IRGA-based soil respiration measurement. *Agric. For. Meteorol.* **113**, 39-51.

Giardina, C. P., Binkley, D., Ryan, M. G., Fownes, J. H., and Senock, R. S. 2004. Belowground carbon cycling in a humid tropical forest decreases with fertilization. *Oecologia* **139**, 545-550.

Goto, Y., Kominami, Y., Miyama, T., Tamai, K., and Kanazawa, Y. 2003. Aboveground biomass and net primary production of a broad-leaved secondary forest in the southern part of Kyoto prefecture, central Japan. *Bull. For. and For. Prod. Res. Inst.* **387**, 115-147. (In Japanese with English summary.)

Goulden, M. L., Munger, J. W., Fan, S. M., Daube, B. C., and Wofsy, S. C. 1996. Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. *Science* **271**, 1576-1578.

Hanson, P. J., Edwards, N. T., Garten, C. T., and Andrews, J. A. 2000. Separating root and soil microbial contribution to soil respiration: a review of methods and observations. *Biogeochemistry* **48**, 115-146.

Johnson, M. G. and Mayer, P. F. 1998. Mechanical advancing handle that simplifies minirhizotron camera registration and image collection. *J. Environ. Qual.* **27**, 710-714.

Kominami, Y., Miyama, T., Tamai K., Jomura M., Dannoura M., Goto, Y. 2005. Evaluation of nighttime eddy CO_2 flux using automated chamber measurements. *J. Agric. Meteorol.* **60**, 745-748.

Lavigne, M. B., Ryan, M. G., Anderson, D. E., Baldocchi, D. D., Crill, P., Fitzjarrald, D. R., Goulden, M. L., Gower, S. T., Massheder, J. M., McCaughey, J. H., Rayment, M., and Striegl, R. G. 1997. Comparing nocturnal eddy covariance measurements to estimates of ecosystem respiration made by scaling chamber measurements at six coniferous boreal sites. *J. Geophys. Res. Atmos.* **102**, 28977-28985.

Law, B. E., Falge, E., Gu, L., Baldocchi, D. D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A. J., Falk, M., Fuentes, J. D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I. A., Jarvis, P., Jensen, N. O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw, K. T., Thorgeirsson, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S. 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agric. For. Meteorol.* **113**, 97-120.

Law, B. E., Ryan, M. G., and Anthoni, P. M. 1999. Seasonal and annual respiration of a ponderosa pine ecosystem. *Global Change Biology* **5**, 169-182.

Lee, M., Nakane, K., Nakatsubo, T., and Koizumi, H. 2003. Seasonal changes in the contribution of root respiration to total soil respiration in a cool temperate deciduous forest. *Plant Soil* **255**, 311-318.

Nakane, K., Kohno, T., and Horikoshi, T. 1996. Root respiration rate before and just after clear felling in a mature, deciduous, broadleaved forest. *Ecol. Res.* **11**, 111-119.

Ohashi, M., Gyokusen, K., and Saito, A. 2000. Contribution of root respiration to total soil respiration in Japanese cedar (*Cryptomeria japonica* D. Don) artificial forest. *Ecol. Res.* **15**, 323-333.

Raich, J. W., and Nadelhoffer, K. J. 1989. Belowground carbon allocation in forest ecosystems: global trends. *Ecology* **70**, 1346-1354.

Rochette, P., Angers, D. A., and Flanagan, L. B. 1999. *In situ* measurements of maize residue decomposition using natural abundance of $^{13}CO_2$. *Soil Sci. Soc. Am. J.* **113**, 1385-1393.

Ryan, M. G., Binkley, D., Fownes, J. H., Giardina, C. P., and Senock, R. S. 2004. An experiment test of the causes of forest growth decline with stand age. *Ecol. Monog.* **74**, 393-414.

Ryan, M. G., and Law, B. E. 2005. Interpreting, measuring, and modeling soil respiration. *Biogeochemistry* **73**, 3-27.

Satomura, T., Nakane, K., and Horikoshi, T. 2001. Analysis of fine root net primary productivity of trees using the minirhizotron method. *Root Res.* **10**, 3-12. (In Japanese.)

Satomura, T., Fukuzawa, K., and Horikoshi, T. 2007. Consideration in the study of tree fine-root turnover with minirhizotron. *Plant Root*, **1**.34-45.

Tamai, K., Kominami, Y., Miyama, T., and Goto, Y. 2005. The estimation of time series data for soil respiration based on soil temperature and soil moisture content ratio and its special variation in a small mountainous catchment: the case of a weathered granite region in southern Kyoto prefecture. *J. Jpn. For. Soc.* **87**, 331-339.

Tang, J., Misson, L., Gershenson, A., Cheng, W., and Goldstein, A. H. 2005. Continuous measurements of soil respiration with and without roots in a ponderosa pine plantation in the Sierra Nevada Mountains. *Agric. For. Meteorol.* **132**, 212-227.

Valentini, R., Matteucci, G., Dolman, A. J., Schulze, E.-D., Rebmann, C., Moors, E. J., Granier, A., Gross, P., Jensen, N. O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A. S., Vesala, T., Rannik, U., Berbigier, P., Loustau, D., Gudmundsson, J. Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., and Jarvis, P. G. 2000. Respiration as the main determinant of carbon balance in European forests. *Nature* **404**, 861-8565.

Vogt, K. A., Grier, C. C., Meier, C. A., and Edmonds, R. L. 1982. Mycorrhizal role in net primary production and nutrient cycling in *Abies amabilis* ecosystems in western Washington. *Ecology* **63**, 370-380.

Measurement and Analysis of Free Water Evaporation

Buyong LEE

Catholic University of Daegu, Korea

I. INTRODUCTION

Class A evaporation pan has been used throughout the world to measure free water evaporation once a day. Penman-Monteitch method was carried out by comparing daily evaporation (Chiew *et al*., 1994).

This study use new technique which measures the weight of buoyance bar in water with high accuracy and resolution by every ten minutes. Field observations of evaporation were made in the forest at Catholic University of Daegu located in southeastern part Korea from 5 to 16 August 2006 for 14 days were used for this analysis

The purpose of this study is making one empirical equation of evaporation combined by meteorological elements from the observation data.

II. OBSERVATION

2.1. Observation site

This study was carried out August 2006 in a small forest in Catholic University of Daegu(E128:48, N35:54) located north side of Depart of Science building. The main trees of area is made in a 10 to 30 year old stand of a pine and an oak tree around 10 meter tree height (Fig. 1).

Fig. 1 Evaporation measurement in the Forest at Catholic University of Daegu.

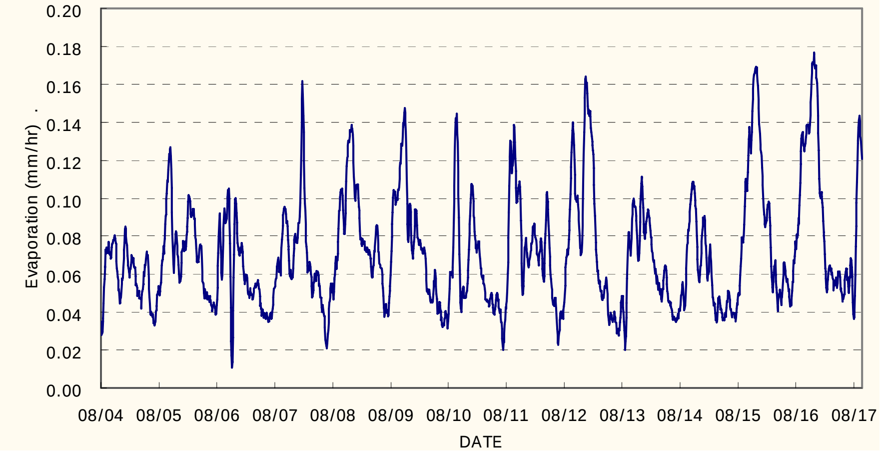

Fig. 2 The observed evaporation from 4 to 16 August 2006.

2.2 Evaporation measurements

Measurement of pan evaporation rate, E, were performed in the Class A Pan. The water level measured by water level meter (Entec (Korea), BYL-EV250) with below then 0.1mm resolution set inside of Class A Pan. To minimize water level wave change by wind influence and to enhance the measurement resolution the signal of water level meter was sampled every 30 second using a CR10X datalogger and was subsequently averaged to 10 min value.

We carried out measurements on 14 days from 4 to 17 in August 2006 with clear days. Wind speed (R.M. young Wind Monitor, Campbell Scientific Inc., U.S.A.) and air temperature and humidity (HMP 45C, Campbell Scientific Inc., U.S.A.) were measured at 1 m height same observation interval. We also measured water temperature (107 Campbell scientific Inc., U.S.A.) in Class A evaporation pan.

III. RESULT

Figure 2 shows the evaporation of Class A evaporation pan from 4 to 17 August 2006. In this observation period there is no rain. Hourly evaporation recorded only from 0.02 mm/h to 0.18 mm/h. Daily total evaporation recorded from 2.2 to 1.5 mm a day. It is small amount of evaporation compare then open site data.

There is strong relation between wind speed and evaporation. It is well known as high wind speed derives much evaporation. This study analysis observation data based on this principle to understand relation between evaporation and meteorological elements data of 5 to 16 August.

Make a graph very 0.1 meter wind speed step and calculated the relation between evaporation and vapor pressure deficit. Figure 3 shows 4 cases of relation at condition of 0.0, 0.2-0.3, 0.4-0.5, 0.7-0.8 meter/sec. At 0.0 m/s the slope coefficient 0.0058 and 0.2-0.3 m/s then 0.0059 and 0.4-0.5 m/s then 0.0066 and 0.7-0.8 m/s then 0.008. The slope coefficient increases by the wind speed.

Figure 4 shows relationships between wind speed and the slope coefficient from 0 to 0.8-0.9 m/s range. After a linear fit with experimental results, it adjusted the above coefficients, resulting empirical equation (1).

$$\mathrm{Evap} = (0.0034\times U + 0.0054)(\mathrm{Ew}-\mathrm{Ea}) \qquad (1)$$

Evap: Evaporation of Class A Pan (mm/h)
U: Wind speed 1 meter height (m/s)
Ew: Vapor pressure of water at Class A Pan (hpa)
Ea: Vapor pressure at 1 meter (hpa)

Figure 5 shows observed evaporation data and estimation evaporation from observation data of meteorological elements using equation (1). There is very similar evaporation pattern between two line. Table 1 shows the daily evaporation data of observation and estimated from 5 to 16 August there is only 0.35 mm of total 20.87. Also daily difference recorded from 0.00 to 0.3 mm. Most of cases recorded below than 0.13 mm difference of evaporation this means equation (1) estimate evaporation very correctly from meteorological elements.

The observation study of Han and Lee (2005) at open site HaeNam showed equation (2)

$$\mathrm{Evap} = (0.0063\times U + 0.0146)(\mathrm{Ew}-\mathrm{Ea}) \qquad (2)$$

Comparing equation (1) and (2) then there is difference between the slope coefficient and intercept. The value of coefficient value of equation (2) is bigger than (1). This means the empirical evaporation equation has different coefficient by the observation location. The observation site of open area can make much more evaporation compare then in side of forest. We need more study and field observation for well understanding of evaporation in free water surface.

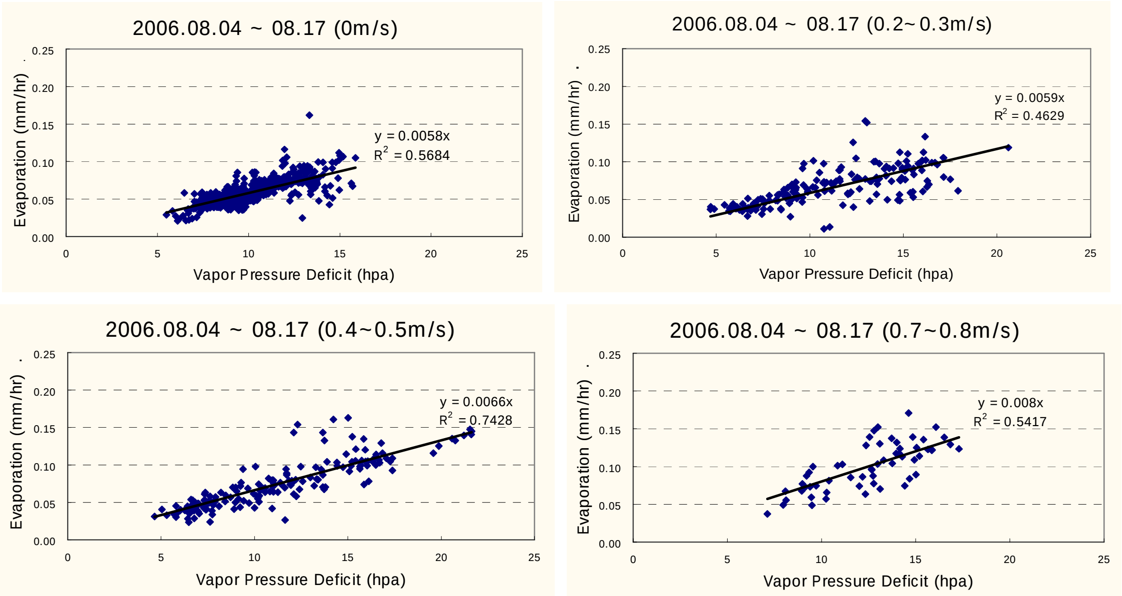

Fig. 3 Relation between observed evaporation and the vapor pressure deficit under different wind conditions. From top, wind speed is 0m/s, 0.~0.3m/s, 04~0.5m/s and 07~0.8m/s.

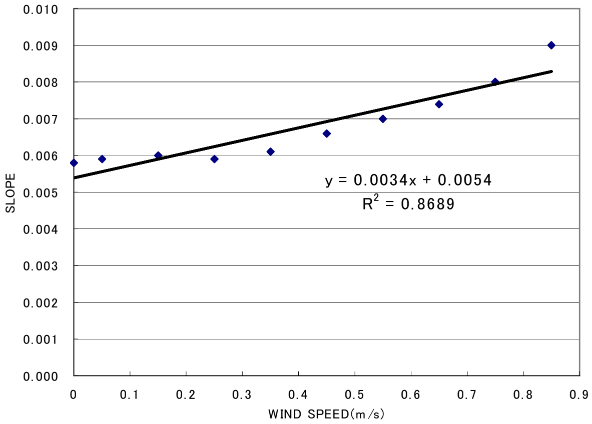

Fig. 4 Relationships between wind speed and the slope coefficient from the relationship between Evaporation and Vapor Pressure.

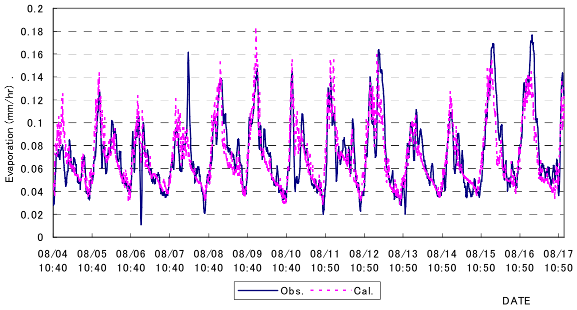

Fig. 5 The observed and estimated evaporation.

Table 1. Comparison of evaporation observation and calculation data.

	Obs.	Cal.	Diff.
08/05	1.63	1.74	-0.11
08/06	1.58	1.61	-0.03
08/07	1.58	1.59	-0.01
08/08	1.80	1.72	0.08
08/09	1.95	1.87	0.08
08/10	1.52	1.62	-0.10
08/11	1.63	1.74	-0.11
08/12	2.05	1.92	0.13
08/13	1.50	1.48	0.02
08/14	1.50	1.53	-0.03
08/15	1.94	1.81	0.13
08/16	2.19	1.89	0.30
Total	20.87	20.52	0.35

IV. Reference

Chiew, F.H.S., N.N. Kamaladasa, H.M. Malano and T.A. McMahon, 1995 : Penman-Monteith, FAO-24 reference crop evapotranspiration and class-A pan data in Australia. *Agricultural Water Management* 28, 9-21.

Han, J. S., and B. Y. Lee, 2005: Measurement and analysis of free water evaporation in HaeNam Paddy Field. *Korean Journal of Agricultural and Forest Meteorology* 7, 91-97. (in Korean with English abstract)

Site Presentation

Rubber Flux, CO_2, Water and Energy Budget of Rubber Plantations in Thailand

Philippe THALER* and Poonpipope KASEMSAP**

* Cirad, France
** Kasetsart University, Thailand.

Rubber area and rubber plantation in Thailand

Rubber tree (*Hevea brasiliensis*) is a major tree crop in Southern and South-eastern Asia. It is the only commercial source of natural rubber, a polymer widely used in industrial products such as tyres, joints, shock-absorbers, and latex goods such as condoms and gloves. Although natural rubber competes with synthetic polymers, its specific properties make it irreplaceable for many applications. Moreover, during the last decades rubber wood has become an important product, and rubber wood industry (furniture, toys) has developed significantly.

World rubber area has grown at a rate of 1.67% annually, showing almost three times increase during the last four decades from 3.88 million ha in 1961 to 10.07 million ha in 2004. Though rubber is grown in more than 20 countries now, four major countries, including Thailand, Indonesia, Malaysia and India who were the pioneers to take up rubber cultivation at a commercial scale, continue to dominate the global rubber production sector with a relative share of 77% in rubber planted area and 79% of the global rubber production. These four countries have also experienced substantial transformation in the production structure with the entry of the native peasantry, eventually leading to the proliferation of smallholder systems under various socio-economic, political and institutional contexts. Therefore, the smallholder sector dominates the rubber plantation agriculture in these countries to the extent of 90% in Thailand, followed by 89% in India and Malaysia, and 83% in Indonesia (Viswanathan and Shivakoti, 2006).

The total rubber planted area in Thailand has increased from 0.4 million ha in 1961 to more than 2.0 million ha in 2003, with a concentration of area in the Southern region of the country occupying 80% (RRIT, 2003) (table 1). In 2003, a major proportion of the total area of agricultural holding in the Southern region was covered by rubber (54.1 %), followed by permanent crop/forest (29.0%) and rice (11.1%) (National Statistics Office 2003). Thus, apart from natural forest remaining in national parks, rubber plantations represent the major forest ecosystem in southern Thailand. Assessing the carbon budget of rubber plantation is thus a prior requirement to quantify local and regional carbon budgets. It is also worthy of estimating the carbon sequestration potential of rubber plantations and the possible implementation of related Clean Development Mechanism (CDM). Carbon sequestration potential of rubber plantations may provide opportunities to increase the profitability and acceptability of plantations.

Table 1. Rubber plantation area (ha) by region in Thailand (source RRIT, 2003).

	1996 (kilo-ha)	2003 (kilo-ha)	% of total area in 2003
South	1,471	1,602	79.4
East	241	210	10.4
Northeast	64	94	4.7
Other	234	113	5.6
Total	2,010	2,019	

Land use changes.

Currently two major evolutions about rubber cultivation are underway.

1. In the traditional region, almost all the appropriate land for rubber has been used. Natural forest felling is no more possible and neither desirable. In the current agricultural area, rubber cultivation has to compete with other crops, particularly with oil palm cultivation. During the last decade, the trend was toward the expansion of oil palm, replacing rubber to some extent. However, the recent increase in rubber price, and encouraging prospects, make rubber attractive again. The future share of land use between rubber and oil palm is a major issue in Thailand and in other South-eastern Asian countries. As such choice involves long term investments and perennial ecosystems, environmental issues are particularly important. Among these issues, the impact of climatic changes on the relative competitiveness of rubber and oil palm requires appropriate knowledge about the ecophysiology of both tree crops.
2. Meanwhile, rubber cultivation expands to new areas, mainly Northern and North-eastern Thailand, where it has to face less favourable climatic conditions, such as a long and dry season (up to 6 months) and relatively cold temperature in winter (in the North). In these new planting areas, the expansion of rubber occurs on previous crop area such as cassava and sugarcane, with a possible substitution of eucalypt by rubber too.

Currently there is about 209,000 ha and 95,000 ha rubber plantation in the Eastern region and North East region, respectively. Government's plans are for 1 million ha to be planted in Northern and North-eastern Thailand. Thailand aims to increase its rubber planted area by 960000 ha in 2012. Thus, it is important not only to evaluate rubber performance in such areas, but also to assess impact of rubber plantations on environment and particularly on water balance.

The Rubber Flux project

Rubber flux aims at providing a complete picture of CO_2, water and energy budget of a rubber plantation in Eastern Thailand. A synthetic presentation of the site information is available at http://www.asiaflux.net/network.html.

Beyond the evaluation of the fluxes, our purpose is to partition them among the different components of the plantation ecosystem (canopy, trunks, roots, under storey, soil) and the different functions (photosynthesis, respiration evapotranspiration) in order to understand the factors controlling the carbon, water and energy budgets of the ecosystem.

Site Description

The experiment is situated at the Chachoengsao Rubber Research Station located in Phanom Sarakham district (13° 41' N, 101°04' E, 69 m above sea level). The site is about 140 km east of Bangkok (Fig.1).

This location, although close to the Eastern region where rubber has been cultivated for a long time, is considered as climatically not optimal for rubber. The dry season last usually 4 months, from December to April (Fig. 2). Within this district, the landscape changes from the flat lands of the central plain (alluvial terrains from Chaopraya River and other rivers) to a more hilly landscape. However, the station itself is located on a relatively flat area. It covers 350 ha plantation with rubber trees of different clones and different ages, supporting experiments devoted mainly to breeding, agronomy, tapping systems.

Soils are sandy-clay-loam (Kabin Buri series) characterized by a compact lateritic layer with ferralitic concretions at around 1 m deep, which prevents most roots developing further downward.

The observation site is located in a plot at the center of the station. It is thereby surrounded by other rubber tree plots in all directions with different ages. The plot itself is 6 ha large and is planted with a monoclonal stand (clone RRIM 600, the major clone in Thailand). Trees were 12 years old in 2006. The average height was 20 m and average girth at 1.7 m was 60 cm (Fig. 3). The usual planting design is 7 m by 2.5 m (571 trees/ha) but in the considered plot inter-row distance varies between 5 to 11 m, initial planting density was 500 trees/ha and actual stand density was 454 trees/ha in June 2006. Trees are tapped for latex production for 4 years.

Rubber CO_2 Flux Experiment Design

Carbon fluxes of rubber plantation ecosystem are continuously measured by the eddy covariance method (ED). Evapo-transpiration (ET) is measured by ED and water balance together. Meanwhile, amounts of carbon (C) stored in the trees will be evaluated by measuring biomass increment of the plantation, in combination with estimations of the carbon content at the different compartments. The flux tower is a 25

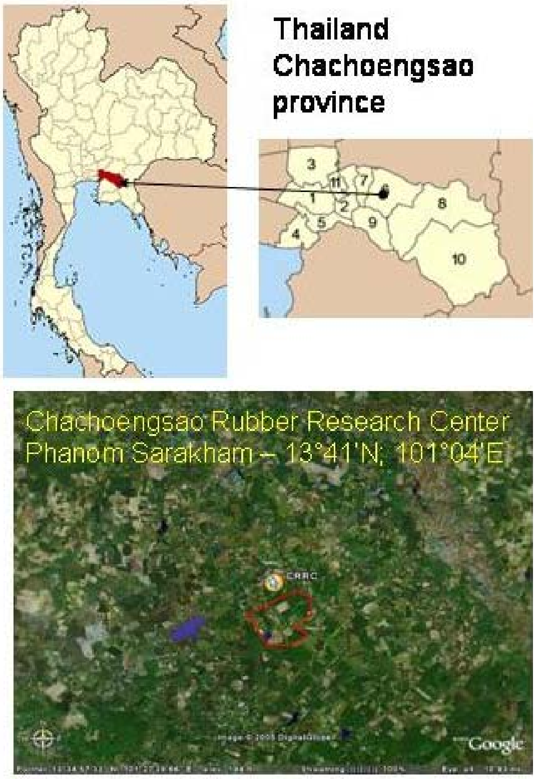

Fig. 1. Location of Rubber Flux Chachoengsao.

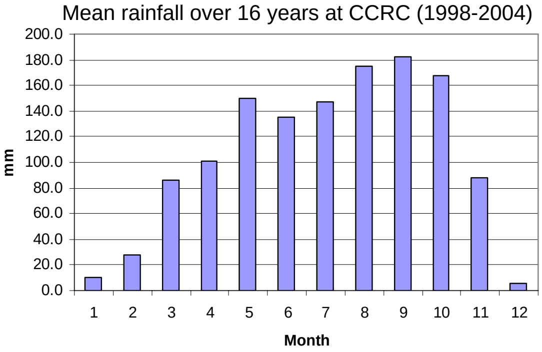

Fig. 2. Monthly mean rainfall during 1989-2004 at CRRC.

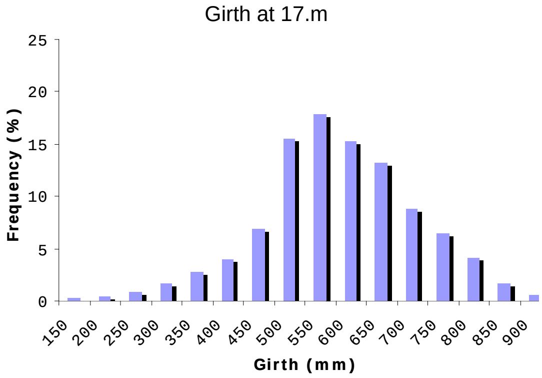

Fig 3. Distribution of trunk girth in June 2006 in Rubber Flux plot.

m high self-standing triangular structure. On the top of the tower, a hexagonal platform is used as working area and to support data loggers and power supply. The measurement height for ED is 27 m. A sheltered coaxial cable carries both power and data which can be recorded online onto a PC (personal computer) located in a shed 10 m away from the tower. An alternative way, to avoid technical problems associated with the data transfer, is to record the data on a laptop located in a water proof box on top of the tower. Electric power for the tower and equipments is supplied from the shed.

Measurements will provide the annual balance of C within plantations at different ages. Energy balance will be assessed by measurements of net radiation (Rn) and estimation of the energy partitioning among heat fluxes and heat storage.

Results obtained at the ecosystem scale by these methods will be compared to gas exchanges measured at the level of the different compartments (canopy, trunk, root system, soil, etc). Thereby, the validated CO_2 and H_2O fluxes will be used to model gas exchanges of rubber plantation ecosystem according to climate and other environmental parameters as well as crop management.

Sub-components

Eddy-covariance (ED)

ED methodology was adapted from a similar experiment developed by our research group on another tropical tree crop plantation, coconut tree, in Vanuatu islands. Details of the methods are described in Roupsard *et al* (2006). Three-demensional (3-D) sonic anemometer Young 81000V 20 Hz is used together with an open path gas analyser (LI-7500; LI-COR, Inc., Lincoln, Nebraska, USA). Raw data are collected and pre-processed by the "Tourbillon" software (INRA-Bioclimatologie, Bordeaux, France) for a time-integration period of 300 s. Raw data are post-processed using EdiRe software (University of Edinburgh, UK) into half-hourly values. All data are despiked according to variance filters, planar fit is applied (parameters are calculated monthly), and vapour is corrected for buoyancy.

For short periods (2 months), a double ED systems will be installed, above and below the canopy, to estimate contribution from the understorey to fluxes.

Climate

Weather station measures semi-hourly net radiation (Rn), photosynthetically active radiation (PAR), diffuse PAR (PAR_{diff}), reflected PAR ($PAR_{reflected}$), global radiation (Rg), air temperature (Ta), relative humidity (Rh), wind speed, wind direction, rainfall, vertical profile of air temperature (TCs).

Net Primary Productivity (NPP)

Standing biomass dynamics will be assessed by tree survey in the plot. As we are in a monoclonal plantation, DBH and height measurements, monitored on a large sample (± 500 trees), will provide an accurate estimation of biomass, based on existing allometric relationships.

Litter-traps are used to assess fall of leaf, branches, flowers and fruits. There are currently 20 litter-traps. Litter-bags will be used to compute the time-course of litter mass remaining (LMR) and the decomposition constants (k). Phenology of leaf, flowers and fruits is surveyed. In our conditions complete leaf-shedding occurs in January-February, followed by a rapid re-foliation. Together with the use of hemispheric photography, this will allow good assessment of leaf area index (LAI) dynamics. A specific sub-programme aims at comparing several methods and software for the acquisition of canopy parameters (including LAI) from hemispheric pictures.

Fine root biomass dynamics will be assessed from the growth measurement in cores or trenches, whereas root lifespan and turnover will be obtained from root observation glasses. Allometric rules from previous data will be used to calculate biomass increment.

Water balance, water status in soil and trees

16 home-made Granier probes (heat dissipative) are installed on a representative sample of the tree stand, selected according to trunk diameter, to measure sap-flow. Sap-flow is computed semi-hourly in order to provide calculation of transpiration that could be compared with evapo-transpiration measured by ED. Leaf water potential (predawn and diurnal time-course) is assessed periodically throughout the canopy in relation to climate and soil water content. Hydraulic conductance will be computed thereby. We particularly focus on contrasting periods, such as beginning of rainy season (May) and end of rainy season (November).

Soil temperature profiles are measured in three trenches located according to planting design, using copper-constantan thermocouple probes buried down to 1 m, and a 10TCRT thermocouple reference thermistor (Campbell Scientific, Inc., Logan, Utah, USA). Soil volumetric water content (θ) is measured using 21 water content reflectometers (CS615 probes, Campbell Scientific), buried horizontally in the vertical walls of the same trenches and calibrated against the gravimetric method, using the measured soil dry bulk density.

Energy balance

Soil heat flux (G) will be assessed using soil water content, soil temperature profile and soil mineral and organic composition (from previous data). Heat storage in trunks (Qt) is measured using thermocouples. Heat storage in air (Qa) is measured using thermocouples (air profile). Sensible heat flux (H) and latent heat flux (LE) are obtained from the ED measurement

Leaf photosynthesis

An important related topic is the parameterization of Jarvis and Farquhar models of stomatal conductance and leaf photosynthesis, using the LI-6400 photosynthesis system (LI-COR). This is performed on trees of different ages, including those of the flux tower plot. Measurements within the canopy are processed from a crane cradle along a vertical transect (Fig. 4, 5 and 6). At the same time, leaf nitrogen content, leaf chlorophyll content, leaf water potential, light interception and LAI are measured along this transect. This would finally be integrated to model canopy CO_2 and water exchanges.

Soil respiration

This important component of carbon budget assay will be implemented in 2008. We plan to transfer a system and expertise that we developed to measure continuously trunk respirations for this soil respiration measurement. In order to unravel heterotrophic respiration from root respiration we will compare soil respiration from undisturbed soil and from trenched plots.

Partnership

This operation is a component of a project under Thai-French cooperative programme for higher education and research, namely ‘Improving the Productivity of the Rubber tree’.

Fig. 4. The 25 m high, self standing tower, view at leaf-shedding.

Fig. 5. View of rubber canopy from the tower.

Fig. 6 Leaf gas exchanges measurements with a crane.

There are two main Thai partners and two main French partners.

Kasetsart University, Bangkok Thailand, is the main Thai University in agriculture and environment. Coordinator of the project is Sornprach Thanisawanyangkura, faculty of Science, Department of Botany. Main scientist involved in the project is Poonpipope Kasemsap, Faculty of Horticulture. Several PhD and MS students are doing their research work within the Rubber Flux project.

Chachoengsao Rubber Research Center (CRRC), where the experiment is located, is one of the two largest research stations of the Department of Agriculture (DOA) devoted to rubber in Thailand. The main scientist involved is Arak Chantuma.

CIRAD, French Agricultural Research Centre for International Development, is an agency specialized in cooperative research in agriculture and environment. The main scientist involved is Philippe Thaler, Functioning of Plantation Ecosystem research unit, helped by Dr Olivier Roupsard, currently responsible for the Coco Flux site in Vanuatu.

INRA, French National Centre for Agricultural Research provides expertise thanks to Jean-Marc Bonnefond, a key member of the INRA-Ephyse research unit already involved in several flux research sites within the Euroflux network.

Schedule

The flux tower has been built in January 2006. The site is still under installation and setting up. Processed flux data cannot be provided yet. However, complete weather, soil water content and sap flow are already monitored.

References

Farquhar, G.D., S. Caemmerer von and J.A. Berry. 1980. A biochemical model of photosynthetic CO_2assimilation in leaves of C3 species. Planta. 149: 78-90.

Jarvis P.G. 1976. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field. Phil. Trans. R. Soc. London B. 273: 593-610.

National Statistics Office 2003. Agriculture Census. Southern Region. Ministry of Information and Communication Technology, Bangkok, Thailand. 21pp.

Roupsard O., Bonnefond J.M., Irvine M., Berbigier P., Nouvellon Y., Dauzat J., Taga S., Hamel O., Jourdan C., Saint-André L., Mialet-Serra I.,Labouisse J.P., Epron D., Joffre R., Braconnier S., Rouzière A., Navarro M., Jean-Pierre Bouillet J.P. 2006. Partitioning energy and evapo-transpiration above and below a tropical palm canopy. Agricultural and Forest Meteorology 139, 252–268.

RRIT 2004. http://www.rubberthai.com/statistic/stat_index.htm

Viswanathan P.K. and G. P. Shivakoti. 2006. Changing Dimensions of Monoculture Rubber in the Era of Globalization: A Comparative Study of Smallholder Rubber Production Systems in India and Thailand. Workshop on Rubber Development in Lao PDR: Exploring Improved Systems for Smallholder Production. 9 – 11 May 2006 Vientiane, Lao PDR.

Site Info

Continuous Observation at a Sub-Arctic Black Spruce Forest in Interior Alaska

Masahito UEYAMA and Yoshinobu HARAZONO

International Arctic Research Center, University of Alaska Fairbanks

Introduction

Climate change in northern high latitude was remarkable in past few decades (Hinzman *et al.*, 2005). To improve our understanding how the arctic ecosystems would respond to the recent arctic warming, we started year-round continuous observation at a sub-arctic black spruce forest in interior Alaska since fall 2002 (Nojiri *et al.*, 2003). Fluxes of energy, water, and CO_2 were measured by the eddy covariance method, whereas CH_4 flux was measured by using the modified gradient method (Ueyama *et al.* 2006a, b). Since the black spruce is a climax forest of boreal biome in North American continent, it is particularly important to estimate the carbon fluxes of black spruce forests for evaluating the regional carbon budget.

Site description

The research site is located at a typical taiga forest in Fairbanks Alaska (64°52'N, 147°51'W, elevation 120 m; Figure 1). Since the climate in interior Alaska is continental, there is a long cold winter; the snow accumulation typically starts in early October and the snowmelt is usually in late April. The mean monthly temperature for Fairbanks is the lowest in January, at –19.3^{o}C, and highest in July, at 17.4^{o}C, with an annual mean of –1.4^{o}C (Fairbanks National Weather Service, 1980-2000). The average annual precipitation was 270 mm, in which approximately 37% falls as snow, and the rest as rain.

Black spruce (*Picea mariana*) is dominant tree species, and the canopy is sparse with the average height of about 1.5 m, but there are taller trees of up to 6 m, sporadically. Understory vegetation is low and dwarf shrubs, such as *Ladum groenlandisum*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, and *Betula glandulifera*, and some *Carex* species. The forest floor is almost completely covered by mosses, such as *Sphagnum capillifolium*, *Sphagnum magellanicum*, *Sphagnum riparium*, *Calliogon stramineum* and *Aulacomnium palustre*, and patchily lichens, such as *Cladonia* species. The list of the dominant species is shown in Table 1. The forest around the observation tower is old growth, with a mean age of 120 years (Vogel *et al*., 2005). The forest dominates on the discontinuous permafrost, where the active layer depth seasonally changes with the maximum depth of about 50 cm.

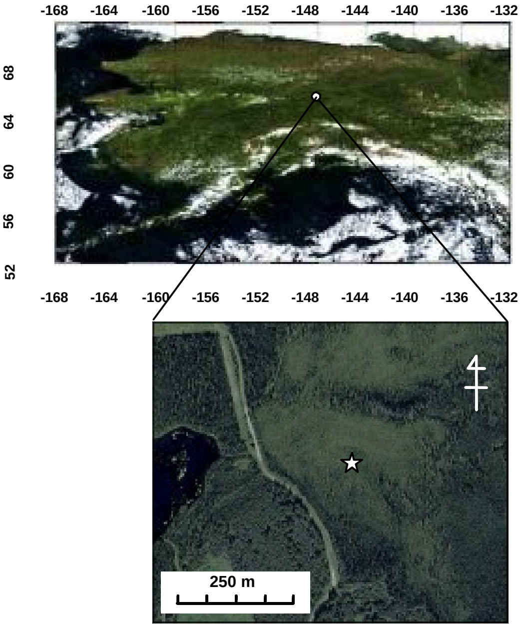

Fig.1 Location of the observation site. The upper image is a 8-day composite image of surface reflectance by MODIS for 7/20-27/2006. The lower image is a photograph by Google Earth.

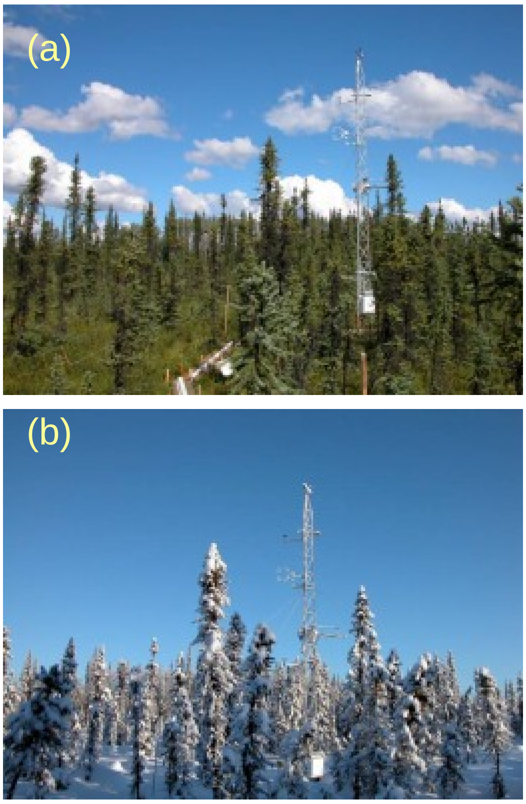

Photo 1 Photographs showing the observation site in the black spruce forest during the mid-growing season (a) and mid-winter (b).

Field observation

The measurements were made from a 10 m tower over a reasonably flat area since November 2002 (Figure 2; Photo 1). Fluxes of CO$_2$, water vapor, heat and momentum has been measured at 6.0 m above ground, using the eddy covariance method with a sonic anemometer (CSAT3, Campbell Scientific inc.) and an open-pass gas analyzer (LI-7500, Li-Cor). The data have been recorded at 10Hz and averaged for 30-minute periods.

To measure CO$_2$ and CH$_4$ concentration, ambient air samples at 4 heights (8, 4, 2, and 1 m) are switched every 3 minutes by solenoid valves. The CO$_2$ and CH$_4$ concentration at each height have been measured by a NDIR-CO$_2$ gas analyzer (LI-840, Li-Cor) and a FID-CH$_4$ gas analyzer (FIA-510, Horiba). The gas concentration data are collected between 120 and 180 seconds after the line switched at 5-second intervals, and 30-minute averages are recorded by a data logger (CR10X, Campbell Scientific Inc.). The FID-CH$_4$ analyzer is

Table 1 Dominant vegetations at the observation site.

Common Name	Family	Species
Trees		
Black spruce	*Pinaceae*	*Picea mariana*
Tamarack	*Pinaceae*	*Larix laricina*
Low Shrubs		
Green alder	*Betulaceae*	*Alnus crispa*
Dwarf birch	*Betulaceae*	*Betula glandulosa*
Common labrador tea	*Ericaceae*	*Ledum groenlandicum*
Bog blueberry	*Ericaceae*	*Vaccinium uliginosum*
Tealeaf willow	*Salicaceae*	*Salix pulchra*
Dwarf Shrubs		
Bunchberry	*Cornaceae*	*Cornus canadensis*
Lingonberry	*Ericaceae*	*Vaccinium vitis-idaea*
Red fruit bearberry	*Ericaceae*	*Arctostaphylos rubra*
Bearberry	*Ericaceae*	*Arctostaphylos uva-ursi*
Crowberry	*Ericaceae*	*Empetrum nigrum*
Small cranberry	*Ericaceae*	*Oxycoccus oxycoccos*
Cloudberry	*Rosaceae*	*Rubus chamaemorus*
Graminoids		
Spruce muskeg sedge	*Cyperaceae*	*Carex lugens*
Other angiosperms		
Round leaf sundew	*Droseraceae*	*Drosera rotundifolia*
Mosses		
Small red peat moss	*Sphagnaceae*	*Sphagnum capillifolium*
Midway peat moss	*Sphagnaceae*	*Sphagnum magellanicum*
Streamside sphagnum	*Sphagnaceae*	*Sphagnum riparium*
Squarrose peat moss	*Sphagnaceae*	*Sphagnum squarrosum*
Calliergon moss	*Amblystegiaceae*	*Calliergon stramineum*
Ribbed bog moss	*Amblystegiaceae*	*Aulacomnium palustre*
Lichens		
Horsehair lichen	*Parmeliaceae*	*Bryoria simplicior*
Ring lichen	*Parmeliaceae*	*Evernia mesomorpha*
Tube lichen	*Parmeliaceae*	*Hypogymnia physodes*
Reindeer lichen	*Cladoniaceae*	*Cladina mitis*

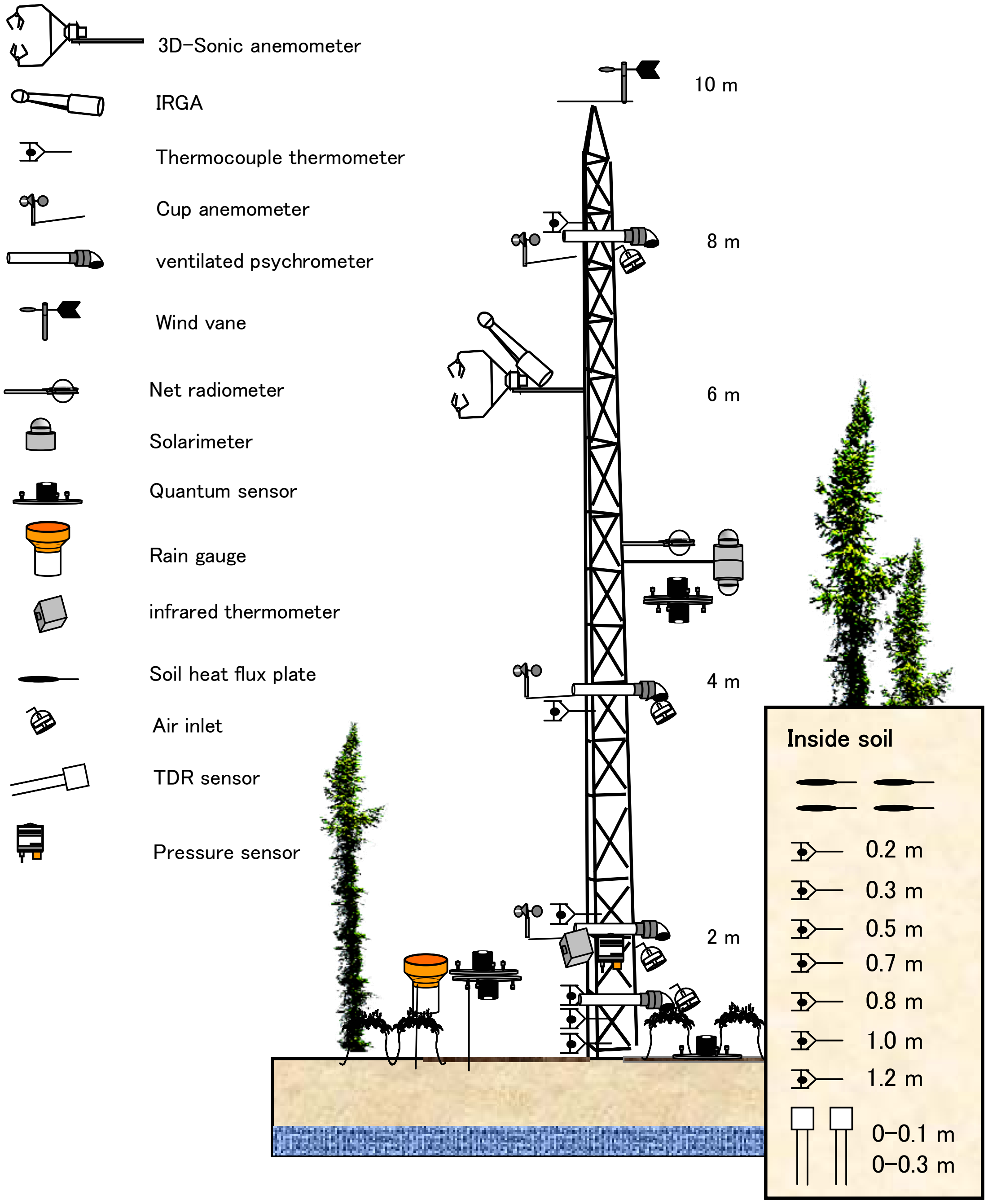

Figure 2 Installation of the instruments at the black spruce forest site between 2003 and 2006.

Table 2 Measured meteorology, their sensors, their heights and terms.

Meteorology	Sensors	Height (m)	Term
Above ground			
air temperature	Vaisala, HMP45D	8, 2	2003. 1. 1 ~ 2006. 6. 9
	Vaisala, HMP45C	8, 4, 2, 1	2006. 6. 9 ~ 2006.12.31
	thermocouple thermometer	8, 4, 2, 1, 0.5, 0.1	2003. 1. 1 ~ 2006.12.31
wind direction	Young, 03301	10	2003. 1. 1 ~ 2006.12.31
wind speed	Young, 03101	8, 4, 2	2003. 1. 1 ~ 2005. 6.27
	Makino, VF016	8, 4, 2	2005. 6.27 ~ 2006.12.31
surface temperature	Minolta, Model505	2	2003. 1. 1 ~ 2006.12.31
upward and downward solar radiation	Kipps & Zonen, CPM3	4.7	2003. 1. 1 ~ 2006.12.31
upward and downward PAR	Li-Cor, LI-190	4.7	2003. 1. 1 ~ 2006.12.31
downward PAR inside canopy	Li-Cor, LI-190	1	2005. 5. 5 ~ 2006.12.31
upward PAR inside canopy	Li-Cor, LI-190	1	2006. 5.16 ~ 2006.12.31
downward PAR in forest floor	Li-Cor, LI-190	0	2004. 8. 5 ~ 2006.12.31
net radiation	REBS, Q7.1-L	4.9	2003. 1. 1 ~ 2006.12.31
	Texas Electronics, TE525-L	1	2003. 1. 1 ~ 2006.12.31
Barometric Pressure	Vaisala, CS105	2	2003. 1. 1 ~ 2006.12.31
below ground			
soil temperature	thermocouple thermometer	-0.05, - 0.1, - 0.2, - 0.3 - 0.5, - 0.8, - 1.3	2003. 1. 1 ~ 2006.12.31
ground heat flux	REBS, HFT3-L	-0.1	2003. 1. 1 ~ 2006.12.31
volumetric water content	Campbell, CS616	-0.0 ~ -0.1	2006. 5.22 ~ 2006.12.31
	Campbell, CS616	-0.0 ~ -0.3	2006. 6.28 ~ 2006.12.31

calibrated once a day, around 0800 hour using two reference standard gases (0ppm and 3.0ppm).

Micrometeorological data, such as wind speed, temperature, humidity, radiation, and precipitation are measured at the tower (Table 2). Wind speed was measured at 3 heights (8, 4, and 2 m) by three cup anemometers (Young, 03301) since June 2005, but changed to three cup anemometers (Makino, VF016). Wind direction is measured by wind vane (Young, 03301). Air temperature and humidity are measured at 4 heights (8, 4, 2, and 1 m) by ventilated psychrometers with sensors (Vaisala, HMP45C). Upward and downward shortwave radiations are measured at 4.7 m by two radiometers (PCM3, Kipps & Zonen). The incoming and outgoing photosynthetically active radiations (PAR) are measured at 4.7 m by quantum sensors (LI-190SZ , Li-Cor), whereas the transmitted PAR are measured at 1 m and on the moss surface. Net radiation is measured at 4.9 m by a net radiometer (Q7, REBS). Rainfall is measured by a rain gauge (TE525MM, Texas electronics). Air pressure is measured by a pressure sensor (Vaisala, CS105). Soil temperatures are measured at 7 depths (0.05, 0.1, 0.2, 0.3, 0.5, 0.8, and 1.3 below the ground level) by thermocouple thermometers. The ground heat flux is measured at 4 locations by soil heat plates (REBS, HFT3-L).Soil volumetric water content is measured at two depths (0-0.1 m and 0-0.3 m below the ground) by TDR sensors (CS616, Campbell Scientific Inc.). The micrometeorological data are sampled through a multiplexer (AM16/32, Campbell Scientific Inc.) and data loggers (CR10X and CR23X, Campbell Scientific Inc.) at 10-second intervals and each 30-minute averages are recorded.

Thaw depths at 10 points are measured by inserting a brass rod into the frozen soil once or twice a week. LAI is measured at 8 points using a plant canopy analyzer (LAI-2000, Li-Cor) once a week during the growing season and once a month during winter. The soil moisture is measured at 10 points around the tower by a TDR sensor (Campbell, CD620) once or twice a week. In winter period, snow depth is measured by using 3 fixed ruler bars at every week.

Findings from the observations

To partition observed NEE (Net Ecosystem Exchange) to GPP (Gross Primary Production) and RE (Ecosystem Respiration), we applied the CBAT (Carbon Budget Analysis Tool), where the potential photosynthetic rate, the light use efficiency, and the suppression factors on photosynthesis were empirically evaluated (Ueyama *et al*., 2006a). 2-year mean (2003 and 2004) of calculated GPP, RE, and NEE by CBAT are shown in Figure 3 as 7-day running mean, where the cumulative carbon fluxes are also drawn. The results showed that the early growing season acted as an important sink period in the sub-arctic black spruce forest, because RE did not increase rapidly due to the thin active layer. During the late growing season, on the other hands, RE overwhelmed GPP, and thus the forest acted as a carbon source. Since the understory senescence and decreased daylight limited GPP during this period, RE was more sensitive to temperature than was GPP. The average GPP and RE between 2003 and 2004 were 2.35 and 2.28 kg CO_2 m^{-2} y^{-1}, respectively, and thus the forest acted as a small carbon sink of 70 g CO_2 m^{-2} y^{-1}. Since the characteristic of GPP, such as potential photosynthetic rate and the light use efficiency, were related with the understory LAI in our site, contributions of the understory could be important to the canopy CO_2 exchange.

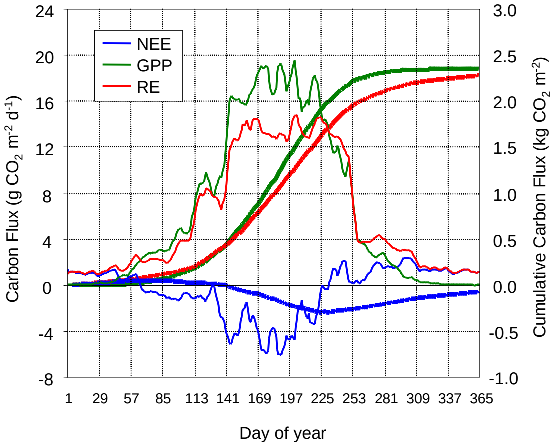

Figure 3 2-year mean of calculated carbon fluxes of GPP, RE, and NEE by CBAT between 2003 and 2004. The data were shown as 7-day running mean. Thin and bold lines are daily mean and cumulative fluxes, respectively.

Future directions

The observed results indicated that the black spruce forest acted as a carbon sink in some years, but as a source in other years. The carbon budget was small differences between two large terms (GPP and RE), and that there was large inter-annual variability in the sink-source relationships. Considering the observed results, we will incorporate the dataset to process-based model, such as BIOME-BGC (Running and Coughlan, 1988), to simulate the carbon cycle under historical, current, and potential future climate. Observed data are also applying to improve TEM model (McGuire *et al*., 2000) for better understanding of arctic ecosystem responses. The model results may explain the ecosystem responses to current global change by validate the simulation output with the ongoing field observation and other collaborative measurements, such as winter fluxes (Kim *et al*., 2007). We are developing the scheme to scale-up the eddy covariance dataset to regional carbon fluxes by using satellite dataset, such as AVHRR and MODIS (Harazono *et al*., 2007; Ueyama *et al*., 2007; Kitamoto *et al*. in review). In order to accurately estimate the regional fluxes with satellite derived reflectance, we are distributing PAR sensors for the APAR and albedo measurements of black spruce stands in Fairbanks as collaborative ground truth measurements with Okayama University (P.I. T. Iwata). The spectral reflectance of canopy, trees and understory species are also measured by using the spectraradiometer (FieldSpec, Analytical Spectral Devices Inc.).

We have great nature here in Alaska. During the winter, air temperature drops down to below –40°C (Photo 2a), but beautiful lights brighten the sky in mid-night (aurora borealis Photo 2b). Ice sculptures decollate the town of Fairbanks (Photo 2c). Once spring comes, Alaska has “breakup”; arrival of migratory birds (Photo 2d), blooming of flowers (Photo 2e), and birth of animal newborns (Photo 2f). Under the mid-night sun in summer, plants and wildlife show the lively state, where thousands of fireweeds bloom on the ruins of forest fire (Photo 2g), caribous migrate on the arctic tundra (Photo 2h), and non-migratory animals, such as bears and moose, eat as much as they can to prepare for the harsh winter (Photo 2i, j).

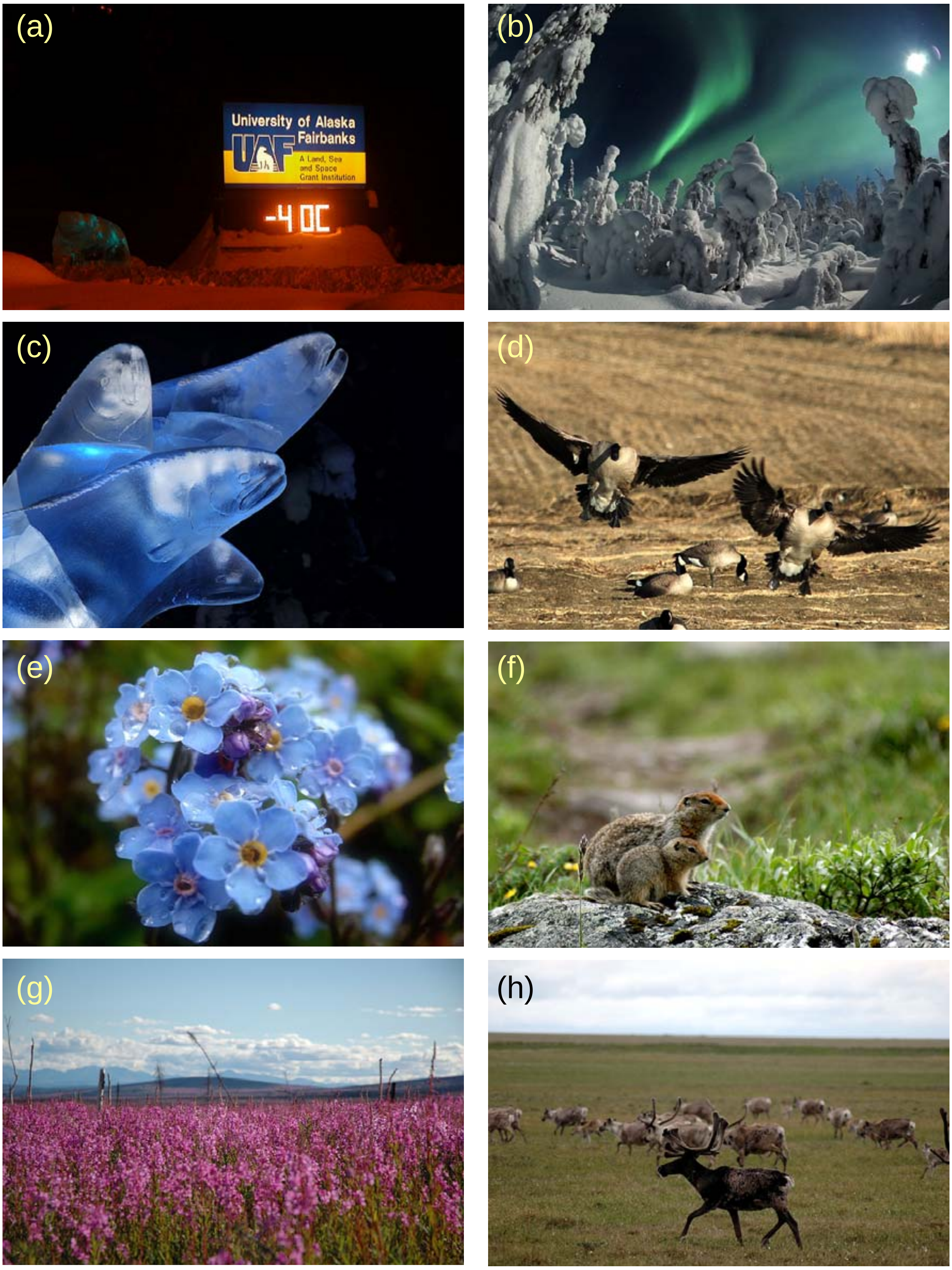

Photo 2 Photographs showing the extreme low temperature in Fairbanks (a), northern lights over silver frost (b), the ice sculpture carving spawning salmons at 2007 World Ice Art Championships (c), migratory birds of Canada geese (d), state flower of Alaska, forget-me-not (e), arctic ground squirrels (f), fireweed on the ruins of forest fire (g), caribous on the arctic tundra (h)

Photo 2 Continued. Photographs showing grizzly bears on the tundra ground (i), male moose in the boreal forest (j), the foliage season on the alpine tundra (k), and northern lights over International Arctic Research Center (IARC) (l).

When northern lights return to the sky, short autumn turns plants yellow and red (Photo 2k). International arctic research center (IARC) is located in interior Alaska surrounded by such wilderness with beauty (Photo 2l). In IARC, IARC-JAXA information system (IJIS) was established in 1999 as the satellite data analysis system (http://www.ijis.iarc.uaf.edu/en/index.htm), and has supported our research activities in the arctic through the state-of-the-art computational hardware and software systems. The Arctic welcomes all visitors for either vacation or research.

Acknowledgements

The observation site was established by supports of former JST International Collaborative Study Program (P.I. Y. Harazono) and CO_2/CH_4 Observation Program (P.I. Y. Harazono) of IARC/NSF (the U.S. National Science Foundation), and continued by supports of the IJIS (IARC/JAXA Information systems) and the Carbon Cycle Program of IARC/NSF by the U.S. National Science Foundation. We are grateful to Dr. Akira Miyata of National Institute for Agro-Environment Sciences, Dr Eiji Ohtaki, Dr. Tohru Iwata and Dr. Susumu Yamamoto of Okayama University for their helps of the establishment and their effective advice regarding field observations. We thank Mr. Ryo Okada of Tsukuba University, Mr. Atsushi Nojiri of Okayama University, and Mr. Tohru Saito and others of IARC for their contributions to field observations.

References

Harazono, Y., Nishida, N., Kitaya, Y., Ueyama, M. and Oechel, W. C. 2007. Application of greenery ratio (visible trichromatic strengths) to estimate stand scale CO_2 budget. In *2nd Edition Proceedings of the Seventh International Conference of Global Change: Connection to the Arctic (GCCA7)*, 19-29 February 2007, Fairbanks USA, pp. 312-315.

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P. Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M., Tweedie, C. E., Vourlitis, G. L., Walker, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K. S. and Yoshikawa, K. 2005. Evidence and implications of recent climate change in northern Alaska and other arctic region. *Climate Change* **72**, 251-298.

Kim, Y., Ueyama, M., Nakagawa, F., Tsunogai, U., Harazono, Y. and Tanaka, N., 2007. Assessment of winter fluxes of CO_2 and CH_4 in boreal forest soils of central Alaska estimated by the profile method and the chamber method: A diagnosis of methane emission and implications for the regional carbon budget. *Tellus* **59B**, 223-233.

Kitamoto, T., Ueyama, M., Harazono, Y., Iwata, T. and Yamamoto, S. Applications of NOAA/AVHRR and observed fluxes to estimate the carbon budget at Alaska black spruce forests, *J. Agric. Meteorol. under review*.

McGuire, A. D., Clein, J. S., Melillo, J. M., Kicklighter, D. W., Meier, R. A. Vorosmaty, C. J. and Serreze, M. C. 2000. Modelling carbon responses of tundra ecosystems to historical and projected climate: sensitivity of pan-arctic carbon storage to temporal and spatial variation in climate. *Global Change Biol.* **6**, 141-159.

Nojiri, A., Harazono, Y., Ohtaki, E. and Iwata, T. 2003. Seasonal change of CO_2 flux at tundra vegetation in interior Alaska. Proceedings of the AGU fall meeting, AC52C-0817.

Running, S. W. and Coughlan, J. C. 1988. A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecol. Modelling* **42**, 125-154.

Ueyama, M. and Harazono, Y. 2007. Satellite observation of ecosystem productivity over Alaskan black spruce forests. In *2nd Edition Proceedings of the Seventh International Conference of Global Change: Connection to the Arctic (GCCA7)*, 19-29 February 2007, Fairbanks USA, pp. 351-354.

Ueyama, M., Harazono, Y., Ohtaki, E., and Miyata, A. 2006a. Controlling factors on the inter-annual CO_2 budget at a sub-arctic black spruce forest in interior Alaska. *Tellus* **58B**, 491-501.

Ueyama, M., Harazono, Y., Okada, R., Nojiri, A., Ohtaki, E. and Miyata, A. 2006b. Micrometeorological measurements of methane flux at a boreal forest in central Alaska. *Mem. Natl Inst. Polar Res., Spec. Issue* **59**, 156-167.

Vogel, J. G., Valentine, D. W. and Ruess, R. W. 2005. Soil and root respiration in mature Alaskan black spruce forests that vary in soil organic matter decomposition rates. *Can. J. For. Res.* **35**, 161-174.

AsiaFlux Workshop 2007

AsiaFlux Workshop 2007 will provide a perfect opportunity to address mass and energy exchanges and the related hydrometeorological and biogeochemical processes in Asian terrestrial ecosystems. Reports on various related topics such as new approaches from measurement, remote sensing, modeling and other methodologies will be also discussed. In addition to general sessions, we are now planning a special session “Fluxes and biogeochemical cycles under the humid climate in Asia”. Presentations on findings under the humid or rainy climate influenced by Asian monsoon are especially welcome to the special session.

Date: Friday 19 - Sunday 21 October 2007

Venue: Aspire Park, Taoyuan, Taiwan

The second announcement will be released and online registration will be opened on 2 July 2007.

www.asiaflux.net/ws2007

Youth AsiaFlux meet the forefront

- Meeting of Young Researchers in AsiaFlux -

We are pleased to announce that we have established “Young Researchers in AsiaFlux” and that we are going to have its very first assembly on the 2nd day of AsiaFlux Workshop 2007. It will be a perfect opportunity for young flux researchers to come together across borders to know each other, discuss the current issue, think about future of flux research and talk about our carrier. In this first meeting entitled “Youth AsiaFlux meet the forefront”, we are going to invite frontiers in our study field to join us to give us talk while recalling back in their younger days, and share their treasurable experience with us.

DATE & TIME: 20th October 2007, 18:00-20:00
(2nd night of WS2007)

Any young AsiaFlux members are welcome to participate.
Please refer www.asiaflux.net/youth for details.

Promoters of this event:
Takagi, Kentaro (Hokkaido University, Japan), Li, Ming-Hsu (National Central University, Taiwan), Hirata, Ryuichi (National Institute for Environmental Studies, Japan), Ono, Keisuke (University of Tsukuba, Japan), Mano, Masayoshi (National Institute for Agro-Environmental Sciences, Japan) and Takanashi, Satoru (Forestry and Forest Products Research Institute, Japan)

AsiaFlux Newsletter
June 2007, Issue No.22

Editorial board:
AsiaFlux Editorial Sub-workgroup

AsiaFlux Secretariat:
c/o Center for Global Environmental Research
National Institute for Environmental Studies
16-2 Onogawa, Tsukuba, 305-8506 Japan
TEL: +81-29-850-2971 FAX: +81-29-858-2645
E-mail: secretary@asiaflux.net

AsiaFlux Newsletter is only available on the AsiaFlux Website: www.asiaflux.net

Editor's Note

Rainy season has arrived in Japan but we do not have much rain this year. I am paying attention to how this phenomenon is affecting the ecosystem of our forest site.

Registration for AsiaFluxWS2007 will be opened soon. I'm looking forward to seeing you all in Taiwan!!

The editor of AsiaFlux Newsletter No.22:
Ryuichi HIRATA
(National Institute for Environmental Studies, Japan)

The editors of AsiaFlux Newsletter No.23 will be Poonpipope Kasemsap (Kasetsart University, Thailand) and Philippe Thaler (Cirad, France).