$^{14}CO_2$ Emission from the Ground Surface in a Japanese Forest

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1. Introduction

Forest is one of the important interface between the atmosphere and the land biosphere, where atmospheric CO_2 is exchanged through photosynthesis and respiration processes. At present, it is considered that amounts of produced and absorbed CO_2 by land biosphere, including forest, are estimated to be almost balanced, or the land biosphere play a role of net sink of atmospheric CO_2 (IPCC, 2001). This balance should be disturbed by climate changes due to the global warming. While, the large variety and non-uniformity of the global nature make lack of our knowledge and uncertainty of predictions of the change in the balance. This study aims at quantitative understanding of mechanism of carbon cycle relating to 'soil respiration,' i.e., CO_2 productions by respiration of live roots and decomposition of organic matter in/on soil. Variations in efflux and radio- and stable carbon isotopic compositions of CO_2 emitted from the ground surface have been measured in a mountain forest in Japan. The results was analyzed by using different depth profiles of carbon isotopic ratios for CO_2 sources in forest soil.

2. Methods

2.1 Location and period of the observation

The observation site is located in a Japanese larch (*Larix leptolepis*) forest in Inabu, Toyota city, Aichi Pref. of Japan (30°12'N, 137°24'E), shown in Fig. 1, where is 60 km distant from Nagoya. It is in a mountain covered with temperate deciduous forests and cool-temperate coniferous forests, and its elevation is 1010m a.s.l. The larch trees in the site are afforested about 40 y ago, and stand with 2-3 m intervals. Their mean height at the point of the observation was 23 m. In warm season, the forest floor was covered by understory plants with c.a. 1 m height. The observation every 1 month was taken place from 2004 to 2006 except for snow covered seasons.

2.2 Measurements

Effluxes of CO_2 from the ground surface were obtained from air samples with c.a. 10 L volume collected from a 144L

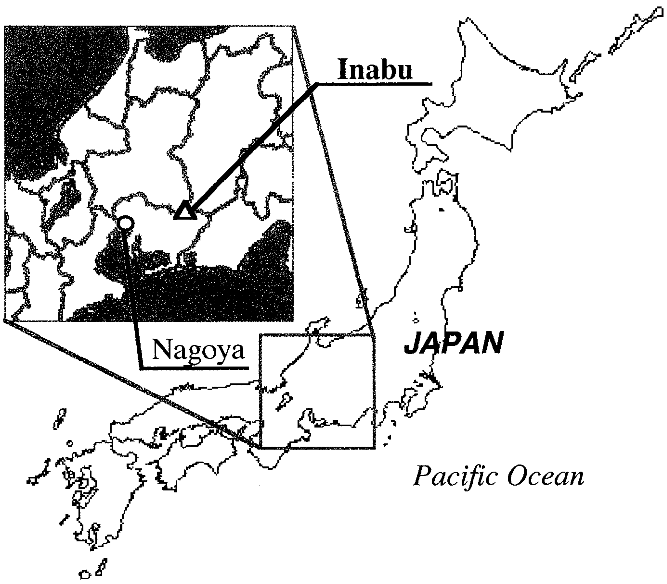

Fig. 1 The location of the observation site (Inabu).

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volume chamber with its bottom area of 1.5 m × 0.2 m, which were closed for 30 min over the ground surface in the site. Soil gas samples with their volumes of 500 cm^3 (in 2004) or 100 cm^3 (after 2005) were drawn by an air-tight syringe through stainless-steel probes with an inner diameter of 6 mm. All air samples were stored in aluminum-coated plastic bags and were brought to our laboratory for sample preparation of isotopic analysis. Flux densities of CO_2 from the ground were also measured by small closed chambers (1 L volume) with infrared CO_2 gas analyzers (LI-820 and LI-840, Li-Cor, Lincoln, NE, USA) at 5-10 points in the site. At each measured point, a pair of fluxes from normal, i.e., not-disturbed ground surface and from surface of mineral soil, i.e., where the litter layer on it was removed, were measured. These two surfaces came close within a distance of 20 cm. For both of 144 L and 1 L volume chambers, their basements had been set on the ground of their measuring points more than 1 month prior to the measurement and sampling.

Soil samples (0-10 cm depth) and cores with a 5 cm diameter (10-30 cm depth) were collected to measure depth profiles of the carbon isotopic ratios of organic carbon in soil and physical properties (Liu *et al.*, 2006). In this paper, a soil depths is expressed by distance from the surface of mineral soil, i.e., from the level where the surface litter layers were removed. Soil organic matter was converted into CO_2 by furnace at 850°C supplied by artificial air.

Each sample CO_2 was cryogenically extracted with a vacuum glass line for their radio- and stable carbon isotopic ratio measurements with a Nagoya University AMS (Tandetron-2, HVEE, the Netherlands) (Nakamura *et al.*, 2004) and a stable isotopic ratio mass spectrometer, (Finnigan MAT 252, Thermo Fisher Scientific, Waltham, MA, USA), respectively.

3. Results and Discussions

3.1 CO_2 flux density and soil temperature

Steep increase shown in Fig. 2 of CO_2 fluxes from both normal and litter-removed surfaces with increasing temperature in surface soil was observed around 19 °C. It would be attributed to

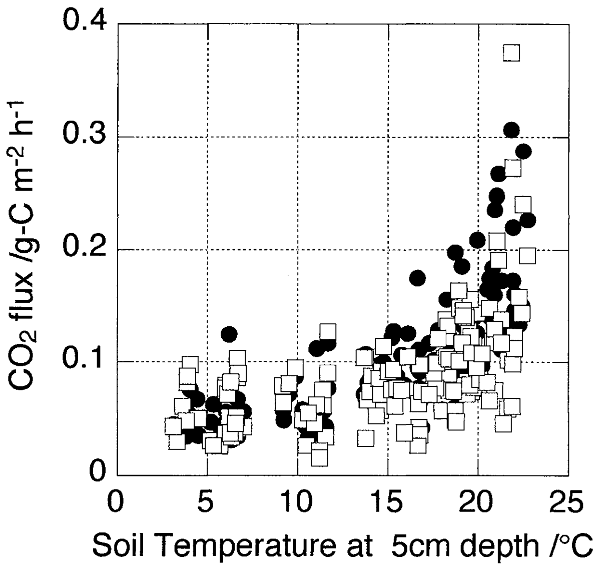

Fig. 2 The relationship between CO_2 flux densities from two types of the ground surfaces and soil temperature at a depth of 5 cm observed in 2004 and 2005. The solid circle symbols are those from normal (not disturbed) surfaces, and the open squares are those from the surfaces of mineral soil, i.e., where the litter layers on mineral soil were removed.

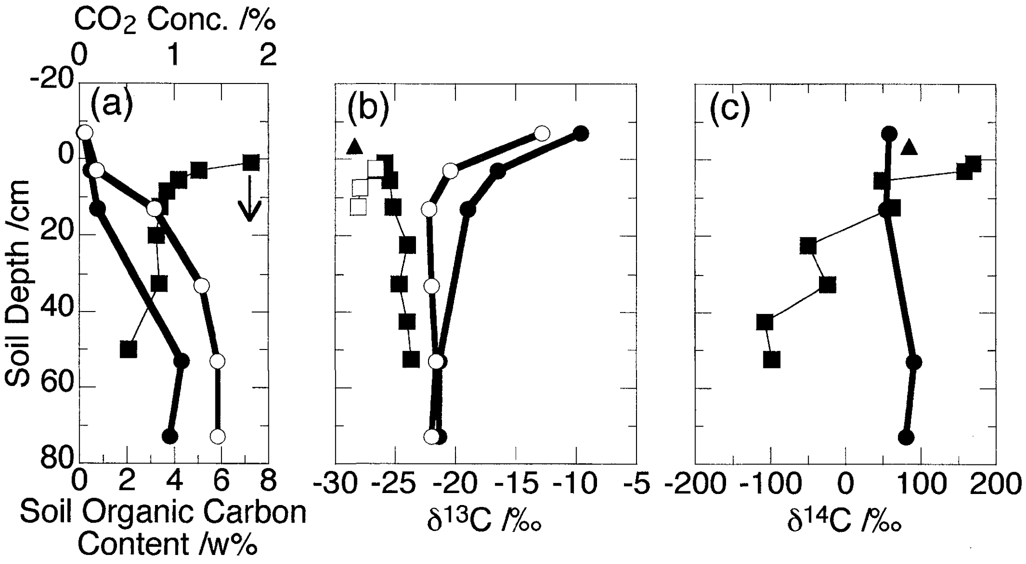

Fig. 3 The depth profiles of content, concentrations (a), stable carbon isotopic ratios (b) and radiocarbon isotopic ratios (c) of soil organic carbon (solid squares), CO_2 in soil air (soil circles for 8 Nov. 2004 and open circles for 5 Aug. 2005), living roots (open squares) and litter (solid triangle).

activation of decomposition of organic carbon in the litter layer and surface soil. This sensitivity to temperature would result in non-uniformity of CO_2 flux from forest floor heated by patchy solar radiation shaded by leaves and branches of forest plants. The fluxes from normal surfaces were likely to be larger than those from litter-removed surfaces. This discrepancy would be considered the contribution of decomposition of the litter layer to CO_2 efflux from the ground surface.

3.2 Depth profiles of isotopic ratios of soil organic carbon and soil CO_2

Forest soil at the observation site contains litter layer (surface organic layer) with c.a. 7 cm thickness from the ground surface and mineral soil under it. In the mineral soil, microorganisms, which decompose soil organic matter as nutritive substances, and live roots of the plants are considered to produce CO_2 by their respiration. As shown in Fig. 3(a), the content of soil organic carbon decreased steeply with increase in the depth, in contrast, CO_2 concentrations increased. Seasonally increased CO_2 concentrations in Aug. 2005 would result from activated CO_2 production by both of organic decomposition and root respiration under higher temperatures.

As shown in Fig. 3(b), the $\delta^{13}C$ of soil organic carbon slightly increased with increase in the depth, in contrast, that of live roots decrease. The $\delta^{13}C$ of CO_2 in soil air were larger than both soil organic carbon and roots. This profile would be caused by difference in diffusion coefficients of $^{12}CO_2$ and $^{13}CO_2$, i.e., their isotopic fractionation. Slower $^{13}CO_2$ would be likely to remain in deeper soil. This result suggests that evaluation of contributions of CO_2 sources in soil to CO_2 efflux with $\delta^{13}C$ values needs precise analysis of transport of two isotopic gases in soil.

Soil depth profile of radiocarbon ratio in soil organic carbon illustrated in Fig. 3(c) decreased with soil depth, and showed a spike maximum at a depth of 0-4 cm under the bottom of the organic layer. This maximum is attributed to enriched ^{14}C by nuclear weapon testing in 1950s-60s. The range of variation in $\delta^{14}C$ of soil organic carbon with the depth were significantly larger than that in $\delta^{13}C$. In contrast, the profile $\delta^{14}C$ of soil CO_2 was nearly constant or rather increase slightly in deeper layer. It is suggested that ether soil organic carbon in shallow layer (including litter) or live root in deeper layer, or both of them, would result in this $\delta^{14}C$ profile of soil CO_2, since they have "modern" $\delta^{14}C$ values which are larger than 0 ‰. Large discrepancy of $\delta^{14}C$ values among CO_2 sources in soil comparing to that of $\delta^{13}C$ among the sources suggests feasibility of estimation of contributions of CO_2 sources in soil to CO_2 efflux with $\delta^{14}C$ values.

3.3 Contribution of Soil CO_2 Sources to CO_2 Flux

By adoption of $\Delta^{14}C$ values, which is normalized $\delta^{14}C$ values by the $\delta^{13}C$ values corresponding to the same subject materials to $\delta^{13}C$ = -25 ‰, influence of unknown isotopic fractionation in CO_2 production from its substances and CO_2 diffusion from deep soil to surface can be canceled (Stuiver and Polach, 1977). By using the difference in CO_2 fluxes mentioned above and the difference in radiocarbon isotopic ratio of substances used for respiration of live roots and microorganisms, the contribution ratios of three CO_2 sources, i.e., the decomposition of litter (R_{litter}), that of soil organic carbon (R_{org}) by microorganisms and respiration of live roots (R_{root}) to total CO_2 efflux were estimated by mass balance of $^{12}CO_2$ and $^{14}CO_2$ as following equation:

$$\Delta^{14}C_{res} = R_{root}\,\Delta^{14}C_{root} + R_{org}\,\Delta^{14}C_{org} + R_{litter}\,\Delta^{14}C_{litter},$$

where $\Delta^{14}C_{res}$ is of observed for CO_2 efflux. The other subscripts of $\Delta^{14}C$ correspond to the same as Rs, assuming $R_{root}+R_{org}+R_{litter}=1$ (no other CO_2 sources and sinks exist). The values of R_{litter} were

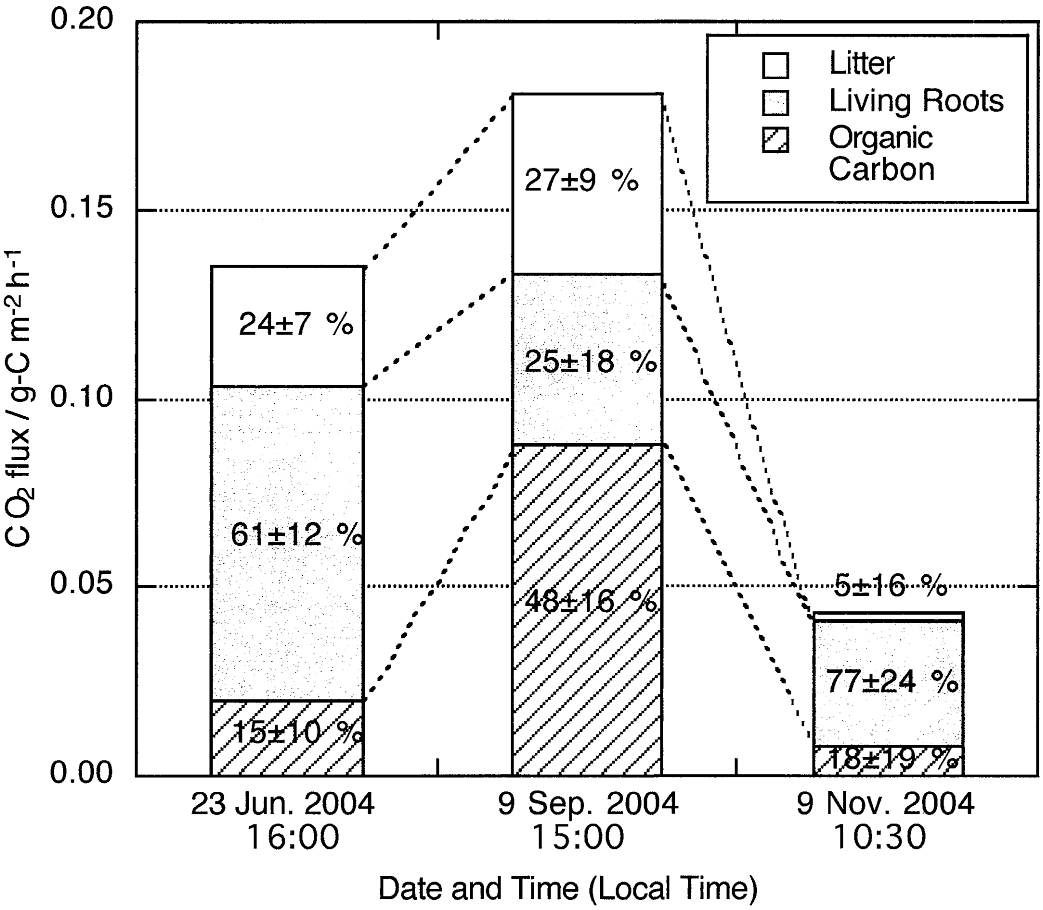

Fig. 4 The contributions of three CO_2 sources in soil to CO_2 efflux from the ground surface estimated by using $\Delta^{14}C$ of CO_2 efflux and three sources. The value in each column is corresponding ratio of the contribution to the total flux with its error (1σ).

calculated from the mean difference of fluxes between the 5-10 pairs of the normal and litter-removed surfaces mentioned in Section 3.1. The values of $\Delta^{14}Cs$ were given from observations; 83.2 ‰ for $\Delta^{14}C_{root}$ (sampled in 0-15 cm depth), 85.1 for $\Delta^{14}C_{litter}$. The value of 131.2 ‰ for $\Delta^{14}C_{org}$ was obtained from a laboratory measurement for CO_2 emitted from soil at 10 cm depth and 15°C.

The results of the estimation is showed in Fig. 4. The contribution of decomposition of soil organic carbon seems to depend on the variation in temperature. The air temperature varied 21.0, 24.0 and 10.0 °C and the soil temperature at 5 cm depth varied 19.6, 22.7 and 9.2 °C at the times of the observation on 23 Jun. 2004, 9 Sep. 2004 and 9 Nov. 2004, respectively. The living roots produces more than half of CO_2 flux in early summer, while its contribution decreases in summer. This suggests that CO_2 production by root respiration showed correlation with seasonal activity of trees' growth rather than soil temperature. The CO_2 from the organic carbon increase in summer, when the soil temperature has maximum. The litter has little contributions in winter, when surface temperature becomes low. These are consistent with meteorological seasonality.

3.4 Diurnal variation in $\delta^{14}C$ of CO_2 efflux

Not only seasonal but also wide and complicate diurnal variations, shown in Fig. 5, were observed for $\delta^{14}C$ of CO_2 emitted form the ground surface. They seem to have positive correlation with temperature in the surface soil. Especially in November, the largest amplitude was observed, and the highest $\delta^{14}C$ values were observed in daytime. This would be caused by characteristic depth profile of $\delta^{14}C$ of soil organic matter, which showed a maximum in shallow soil shown in Fig. 3(c), and that of soil temperature, which typically has the largest amplitude of temporal variation at the surface. The temporal variation in soil temperature is generally transfered to deeper layer with delay of its phase and decrease of its amplitude. In case that just surface soil becomes higher temperature

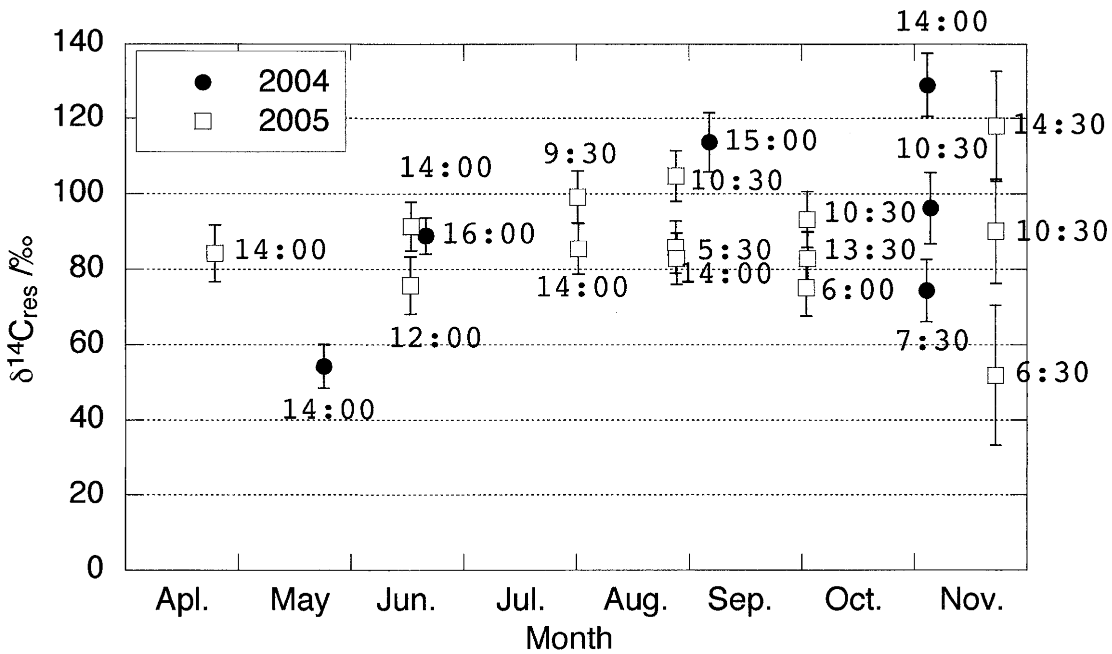

Fig. 5 The seasonal and diurnal variation in $\delta^{14}C$ of CO_2 efflux from the ground surface. The solid circle symbols were measured in 2004 and open squares were in 2005. The time notated close to each symbol in the figure is time of its observation (local time), and the error bar of each symbol corresponds to 1σ.

by sunlight but deeper soil remains cold, such as in daytime in winter, the contribution of CO_2 production by surface soil with the highest $\delta^{14}C$ would be the largest.

The wide diurnal variation of $\delta^{14}C$ of efflux of CO_2 means both difficulty of seasonal representativeness of the estimation mentioned in Section 3.3 and usefulness for analysis of detail characteristics of CO_2 production in shallow soil, at which soil organic carbon is abundant.

4. Conclusion

The observations in a Japanese Larch forest in a mountain of central Japan showed some characteristics about flux and radiocarbon isotopic composition of CO_2 released from the forest floor. Steep increase of CO_2 flux with increasing temperature was obtained around 19 °C, and it suggest the sensitivity of CO_2 production to temperature of surface soil. The depth profile of ^{14}C ratio in soil organic carbon decreased with soil depth. Its spike maximum was obtained at a depth of 0-4 cm under the bottom of the litter layer, attributed to nuclear weapon testing in 1950s-60s.

By using $\Delta^{14}C$ values of source substances of CO_2 in soil, the seasonal contributions of soil organic carbon, litter and living root respiration to CO_2 efflux were estimated. The decomposition of organic carbon including litter showed their correlation with temperature. While, the root respiration seems to be correlated with plant activity rather than temperature.

The complicate diurnal variations in $\delta^{14}C$ of CO_2 efflux were also found with their ranges of 20-70 ‰, and they seems to be related to the variation in depth profile of soil temperature. It is considered that ^{14}C is useful to analyze detail mechanism of soil respiration rather than simple CO_2 flux measurement, especially in shallow soil with rich organic carbon.

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