Topographical variations of soil respiration in the deciduous forest -In the case with extremely immature soil from weathered granite-

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Abstract
This study considers the time series data of soil respiration and its spatial variation in a small mountainous catchment which is located on complex terrain in Japan. Soil respiration rate was measured for 96 soil collars in the small mountainous catchment (1.6ha) in this study. The relationships between soil temperature, soil moisture content and measured soil respiration rate could be expressed by one function in spite that measured places were located at different topographical locations. The relative difference between calculated and measured soil respiration rate was 23%. The time series data of daily soil respiration was estimated by this function used with the monitoring data of soil temperature and soil moisture content ratio at 5 places in this cachment. These daily soil respiration rates fluctuated at almost the same time and relative variation ranges between 73-122% in one year.

Key Words
Soil respiration, complex terrain, time series data, soil temperature, soil moisture content ratio.

Introduction
In recent years, the eddy correlation method for measuring CO_2 flux has been used increasingly to evaluate the carbon uptake capacity of forests (e.g., Nakai *et al.* 2003). This method, however, is generally used for forests growing on flat terrain. Evaluating the carbon fixing of forests on the more topographically complex terrains typical of Japan requires measuring tower CO_2 flux, and comparing the value obtained with CO_2 flux measurements from both foliage and at the forest floor. For example, Kominami *et al.* (2003) measured CO_2 flux at night (CO_2 efflux measured from foliage and at the forest floor using the chamber method), when wind speed is low and atmospheric stability is high, and compared the results to tower flux using the eddy correlation method. Their results indicated that the estimated flux in the former case was only 40% of the latter, which suggests that CO_2 gas migrated down inclined surfaces due to its being denser than air. Thus, it is necessary to compare data on CO_2 flux at the forest floor with tower-flux data from above the forest canopy using the eddy correlation method. To do so, the evaluation of soil respiration rate as 1) time series data and 2) spatial representative data at the scale of small watersheds in mountainous terrains is required. This study focused on providing time series data on soil respiration rate, and on spatial variation in those data, by determining the relationships between soil respiration rate, soil temperature, and soil moisture content, based on multipoint year-round observations in a small mountain watershed. Soil temperature and soil moisture content can be monitored easily and nondestructively.

Methods
Site description
Measurements were conducted in the 1.6-ha Yamashiro Experimental Watershed (34°47'N, 135°50'E; 180–250 m ASL) in Japan. A broadleaf secondary forest covers the watershed and is dominated by *Quercus serrata*. In 1999, the total basal area occupied by stems larger than 3 cm diameter at breast height (DBH) was 20.7 m^2/ha, and the aboveground biomass was 105.05 t /ha. From 1999 to 2002, the average litter fall was 5.16 t/ha/y, the average air temperature was 15.5 ^{o}C, the average monthly temperature was 5.1–26.1 ^{o}C, the warmth index was 125.6 ^{o}C ·month, and the average annual precipitation was 1,449.1 mm (Goto *et al.* 2003). Bedrock underlying the site is weathered granite, and the soil is generally sandy, immature, and thin (Araki *et al.* 1997).

Measurements of soil respiration rate, soil temperature, and soil moisture content
The relationships among soil respiration rate (F_c; mg CO_2/m^2/s), soil temperature (T_s; ^{o}C), and soil moisture content ratio (θ; m^3/m^3) are expressed by Equation (1):

$$F_c = a\mathrm{EXP}(bT_s)\left(\frac{\theta}{c+\theta}\right)$$

(1)

where '*a*', '*b*' and '*c*' are constants.

Various methods have been proposed for measuring F_c, including the dynamic closed-chamber method, the static closed-chamber method, the open-top chamber method, and the measurement of eddy correlation on the forest floor. The advantages and disadvantages of these methods have been compared by Norman *et al.* (1997). The present study used a manual chamber with an enclosed IRGA sensor, which is a highly portable system developed by Nobuhiro *et al.* (2003). This is a variation of the static closed-chamber method, and uses an IRGA sensor (GMT-222; VAISALA, Helsinki, Finland) inserted into a cylindrical chamber (diameter 9.1 cm, height 13.5 cm). The concentration of CO_2 in the chamber is measured every 10 s. F_c is calculated from the increased CO_2 concentration, based on Irvine *et al.* (2002), although these studies did not use identical dynamic closed-chamber methods or static closed-chamber methods. After confirming that the CO_2 concentration in the chamber increased linearly, the soil respiration rate was calculated from the rate of increase. Actively photosynthesising plants were not present in all of the soil collars.

Measurements to identify variables
In order to obtain data for identifying the constants a, b, and c used in Equation. (1), measurements were made at four plots (each 3 m × 0.5 m) on a ridge, a north-facing slope, a valley bottom and a south-facing slope (plots 1–4; Figure. 1) in the Yamashiro Experimental Forest. Each plot from 1 to 4 has Twenty-four soil collars (total of 96 collars). Spacing between soil collars was about 10–20 cm. Soil respiration was measured 74 times, with a frequency of one to four times per month between June 2002 and May 2003. Each measurement consisted of one respiration rate measurement for each of the 24 soil collars. Chamber attachment time was 32 min in the winter months (December 2002–April 2003), and 12 min for measurements during the rest of the year. The shorter time for chamber attachment is better. Because more frequent observation is possible. However, the digit of the CO_2 concentration rate is 10ppm with the system in this study. Thus longer attachment time was needed to obtain the linear increased data of CO_2 concentration when F_c was low in winter (Nobuhiro *et al.* 2003). The soil respiration rate was calculated using the values measured 2 min after chamber attachment.

One soil moisture/temperature sensor (HYDRA; Stevens Vitel, Chantilly, VA, USA) was buried near the center of each plot, and soil temperature and soil moisture content at a depth of 5 cm were measured at 10-min intervals from June 2002 to June 2003.
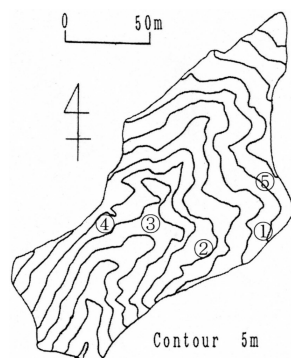

Figure 1. Topography and location of observation sites, Numbers show the location of the observation sites.

Results and discussion
Data used in identifying variables
F_c, T_s, and θ were used in identifying the variables to minimize the relative error indicated by Equation. (2):

$$\text{RRSE} = \frac{\sqrt{\Sigma(F_{cal} - F_c)^2}}{\Sigma(F_c)} , \tag{2}$$

where F_{cal} is the calculated value for F_c and Σ is the sum of all applicable data.
The results yielded by Equation. (3), are: a = 0.0566, b = 0.0717, and c = 0.1089, with a RRSE of 23%:

$$F_c = 0.0566 EXP(0.0717 T_s)\left(\frac{\theta}{0.1089 + \theta}\right). \tag{3}$$

F_c and F_{cal} are indicated in Figure 2. A satisfactory result was obtained, with data plotting roughly along a 1:1 line. This supports the validity of using the functions given by Equation. (1) for this study.
The soil respiration rate is affected not only by soil temperature and soil moisture content ratio, but also by a

variety of other factors, including the amount of organic matter and roots in the soil, and the tree species present. The standard deviation of the soil respiration rate in the plots was large (roughly 20–40% of the average value), which was probably due to factors other than soil temperature and soil moisture content ratio. However, the F_c for all plots roughly matched the F_{cal} estimated from the soil temperature and moisture content ratio, as indicated in Equation. (3). This may indicate that effects due to factors other than soil temperature and soil moisture content ratio were canceled by averaging the measurements from the 24 soil collars. This issue will need to be investigated further.
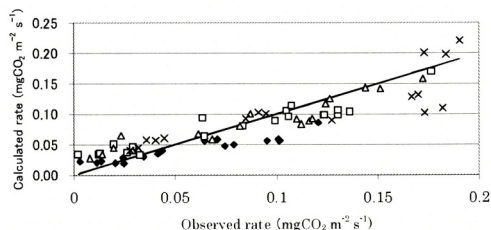

Figure 2. Comparison of observed (F_c) and calculated (F_{cal}) rate of soil respiration, Black diamond: Plot 1, White square: Plot 2, White triangle: Plot 3, Cross: Plot 4.

Estimation of annual soil respiration
The spatial variation in soil respiration rates was investigated by calculating and comparing rates at plots 1–5 from July 2002 to June 2003. The daily average soil temperature and soil moisture content ratio at 5 cm depth, as monitored at plots 1–5, were entered into Equation. (3), and the calculated value was taken to be the daily soil respiration rate. The average value for each month is shown in Figure. 3. The highest soil respiration rate for all months was in plot 4, the lowest in plot 1, and the second lowest in plot 5. This is because the soil temperature was low at ridge plots 1 and 5, soil moisture content was low at plot 1, and soil temperature was high at plot 4. The likely reason why soil temperature was high at plot 4 is that it is a south-facing slope with good sun exposure, and ridge plot 1 probably had a lower soil temperature because wind speed was comparatively high, causing major heat loss.
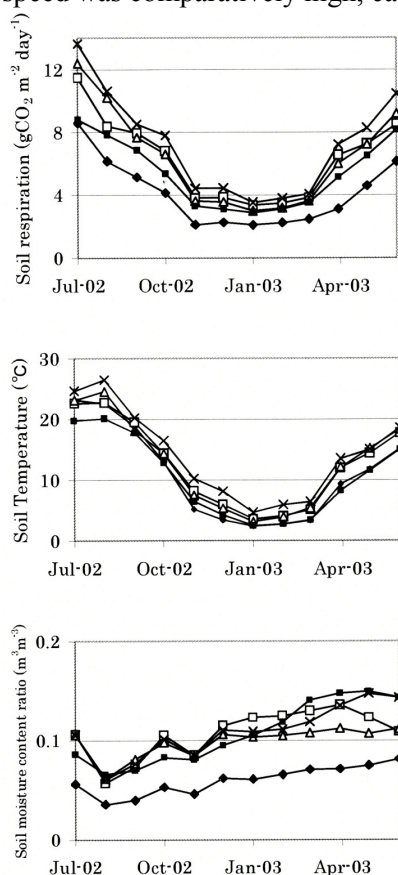

Figure 3. Estimated soil respiration rate in Plots 1-5, Upper: soil respiration, Middle: Soil temperature, Lower: Soil moisture content ratio, Black circle: Plot 1, White square: Plot2, White triangle: Plot 3, Cross: Plot 4, Black square: Plot 5.

Estimation of annual soil respiration rate and its validity
The validity of Eq. (9) was confirmed by comparing the annual soil respiration rate estimated using Eq. (9) against values given in previous reports. The cumulative value for 1 year, obtained from the average values for daily soil respiration rate, was 21.3 t CO_2/ha^2/y. The cumulative values obtained from maximum and minimum values were, respectively, 26.0 t CO_2/ha^2/y (122% of the cumulative value obtained from average values) and 15.6 t CO_2/ha^2/y (73% of the cumulative value obtained from average values).

Conclusion
This study has yielded an equation that estimates soil respiration rate using soil temperature and soil moisture content ratio with a precision of 25% (relative error). The equation was used to calculate time series data for daily soil respiration rate at four plots in a forest watershed. The four plots represented different topographical categories in the watershed (ridge, valley bottom, and south/north-facing slope), such that the time series and spatial variation results adequately reflect the overall characteristics and spatial variations within the Yamashiro Experimental Forest. For the purpose of evaluating spatial variation in time series data, it is best to have a high spatial density of measurements. Soil respiration, however, is difficult to measure at a large number of points. Fortuitously, we were able to estimate time series data on soil respiration rate based on soil temperature and soil moisture content, which are considerably easier to monitor. The time series data on soil respiration rate and its spatial variation from this study will be used in future work to evaluate the carbon-fixing capacity of forests on complex topographies by comparing them with time series data on CO_2 flux above the forest canopy.

References
Araki M, Torii A., Kaneko S, Yoshioka J (1997) Estimation of soil water holding capacity and soil water content in a granite small watershed. *Applied Forest Science* **6**, 49-52 (in Japanese).

Goto Y, Kominami Y, Miyama T, Tamai K, Kanazawa Y (2003) Aboveground biomass and net primary production of a broad-leaved secondary forest in the southern part of Kyoto prefecture, central Japan. *Bulletin of Forestry & Forest Products Research Institute* **2**, 115-147 (in Japanese with English abstract).

Irvine J, Law BE (2002) Contrasting soil respiration in young and old-growth ponderosa pine forest. *Global Change Biology* **8**, 1183-1194.

Kominami Y, Miyama T, Tamai K, Nobuhiro T, Goto Y (2003) Characteristics of CO_2 flux over a forest on complex topography. *Tellus* **55B**, 313-321.

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

Nobuhiro T, Tamai K, Kominami Y, Miyama T, Goto Y, Kanazawa Y (2003) Development of IRGA enclosed-chamber system for soil CO_2 efflux measurement and its application to a spatial variation measurement. *Journal of Forest Research* **8**, 297-301.