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## Ecological Studies on Forest Soil Respiration

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<https://doi.org/10.11501/3166808>

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出版情報：九州大学, 1999, 博士（農学）, 課程博士  
バージョン：  
権利関係：

## Chapter 4 Effect of aboveground vegetation on soil respiration

### 4.1 Contribution of root respiration to total soil respiration in a *Quercus acutissima* and a *Cryptomeria japonica* planting pots

#### 4.1.1 Introduction

Most atmospheric carbon fixed by photosynthesis of green plants is provided to soil as litterfall. The organic carbon in soil is decomposed into CO<sub>2</sub> by soil microbial respiration and returned to the air again with CO<sub>2</sub> from root respiration. All CO<sub>2</sub> evolution from soil is commonly called soil respiration and regarded as an important factor in the carbon cycling of forest ecosystems. Since soil respiration mainly results from root and microbial respiration, it is important in order to separate the two respiration to examine soil respiration fluctuation (Katagiri, 1988; Nakane et al., 1996). Root contribution to total soil respiration has been estimated from the difference between soil respiration and fallen litter (Kawahara, 1976), from the linear relationship between soil respiration and root biomass (Katagiri, 1988; Behara et al., 1990), and by comparing soil respiration between an undisturbed area and a clear-felled area (Kawahara, 1976; Nakane et al., 1983; Nakane et al., 1996). Although a wide variety of techniques used to estimate root contribution has been developed, each technique is limited (Nakane et al., 1983; Katagiri, 1988; Ohashi and Saito, 1998). One reason may be the difficulty in separating root systems from soil because root system expand without any restriction in soil under field conditions.

Therefore, the objective of this study is to estimate the contribution of root respiration to total soil respiration using some

planting pots in which the expansion of root systems is restricted. In this study, it is assumed that differences in soil respiration rate before and after plant (shoot and root) removal was equal to root respiration. Effect of shoot removal only on soil respiration was also examined.

#### 4.1.2 Methods

Measurements were carried out from July to September 1996 in the nursery of Kyushu university, Fukuoka prefecture, south-west Japan. Two unglazed pots, 6 liter in volume, planted with an one-year-old *Quercus acutissima* (30 cm in height) and an one-year-old *Cryptomeria japonica* (50 cm in height), respectively, were used for measurements. The first measurement was conducted when each pot was intact (shoot+root+soil). The second measurement was conducted just after the shoot was cut at the base (root+soil). The last measurement was conducted 10 days after the root was removed (soil). Watering was carried out 12 hour before each measurement.

Soil respiration and soil temperature was measured hourly from 18:00 to 6:00 for two consecutive nights under field conditions in each of the 3 measurements. An 10 liter open-flow respiration chamber was used to measure soil respiration. The planting pot only was sealed in the chamber and buried in a large concrete pot, 1 m in diameter and 80 cm in height, in a field (Fig. 4-1-1). Wind speed in the chamber was maintained at  $1.0 \text{ ms}^{-1}$  using a fan in the chamber to maintain  $\text{CO}_2$  concentration equal in the chamber. Air flow rate through the chamber was maintained at  $1.5 \text{ L min}^{-1}$  and soil respiration rate was calculated from  $\text{CO}_2$  concentration in the air flowing in and out of the chamber measured by infrared gas analyzer (IRA-107, Shimadzu, Japan)(Ohashi et al, 1995). Soil temperature at a depth of 10 cm was measured using a thermistor thermometer (Kadec-us6, Kona system,



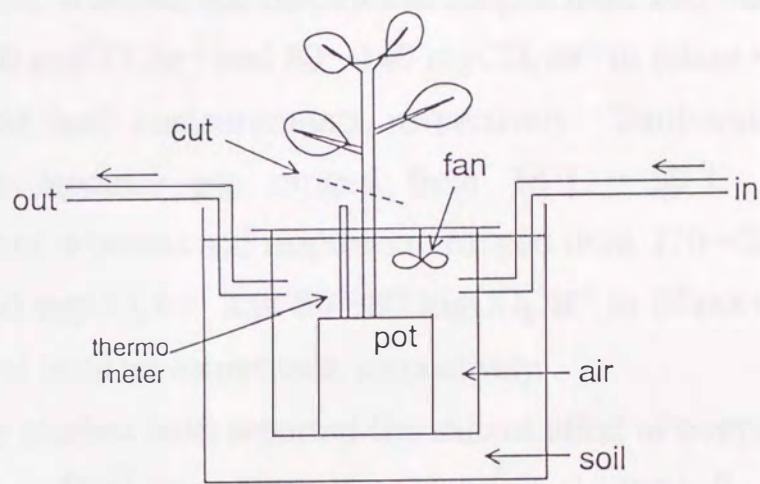


Fig. 4-1-1 Soil respiration measuring system.



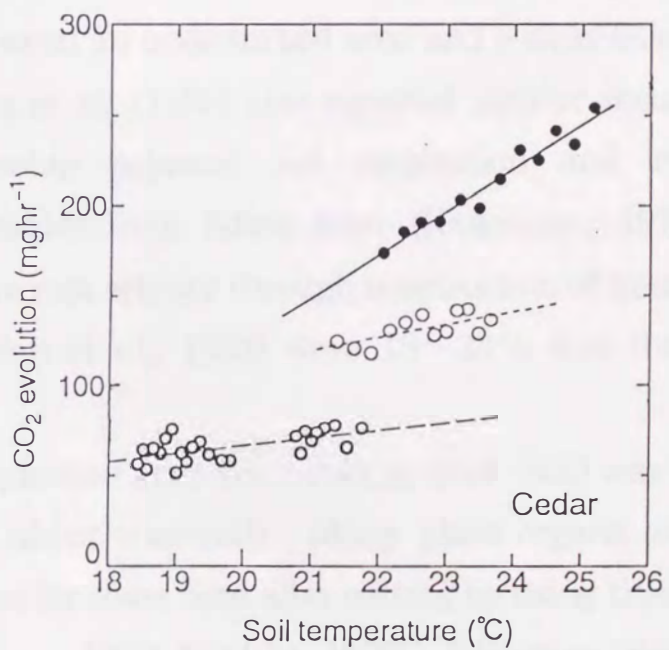
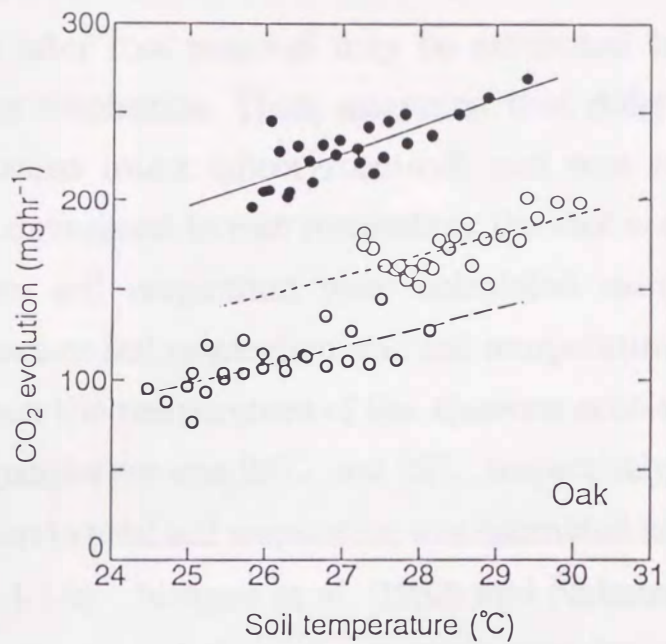
Japan) at the same time as soil respiration.

#### 4.1.3 Results and discussion

Soil respiration increased proportionally with increasing soil temperature in all 3 measurements (Fig. 4-1-2). However, the soil respiration range decreased after each treatment. Soil temperature in the *Quercus acutissima* pot ranged from 25 °C ~ 30 °C in all 3 measurements, whereas soil respiration ranged from 200~280 mgCO<sub>2</sub> hr<sup>-1</sup>, 150~200 mgCO<sub>2</sub> hr<sup>-1</sup> and 80~140 mgCO<sub>2</sub> hr<sup>-1</sup> in (shoot+root+soil), (root+soil) and (soil) measurements, respectively. Temperature in the *Cryptomeria japonica* pot ranged from 18 °C ~ 25 °C in all 3 measurements, whereas soil respiration ranged from 170~250 mgCO<sub>2</sub> hr<sup>-1</sup>, 120~140 mgCO<sub>2</sub> hr<sup>-1</sup> and 50~80 mgCO<sub>2</sub> hr<sup>-1</sup> in (shoot+root+soil), (root+soil) and (soil) measurement, respectively.

Many studies have reported the salient effect of temperature on soil respiration (Witkamp, 1969; Kanemasu et al., 1974; Parker et al., 1983; Grahammer et al., 1991; Osozawa and Hasegawa, 1995; Nakadai et al., 1996). Relationship between the two values often is expressed by an exponential equation (Kucera and Kirkham, 1971; Anderson, 1973; Hagihara et al., 1984; Sakai and Tsutsumi, 1987; Simono et al., 1989) or a linear equation (Gupta and Singh, 1981; Mathes and Schriefer, 1985; Rochette et al., 1991; Lassard et al., 1994). This results from the sensitive response of soil microbial activity and root respiration to temperature (Singh and Gupta, 1977). In this study, the linear relationship between soil respiration and soil temperature was confirmed.

Soil respiration decreased gradually through the two treatments, shoot cutting and root removal. In this study, pots were left for 10 days in the field before (soil) measurement in order to decrease the effect of



● Shoot+Root+Soil    -○- Root+Soil    -○- Soil

Fig. 4-1-2 Relationship between soil respiration and soil temperature.



soil disturbance from excavation of the root. Therefore, reduction in soil respiration after root removal may be attributed largely to the cessation of root respiration. Then, assuming that differences in soil respiration between intact (shoot+root+soil) and root removal (soil) measurements correspond to root respiration, the root respiration rate and its ratio to soil respiration were calculated using the linear relationship between soil respiration and soil temperature (Fig. 4-1-2). As a result, when the temperature of the *Quercus acutissima* pot and *Cryptomeria japonica* pot was 28°C and 22°C, respectively, contribution of root respiration to total soil respiration was estimated as 45~50% in both pots (Fig. 4-1-3). Nakane et al. (1983) and Nakane et al. (1996) estimated a similar contribution of root respiration by comparing soil respiration between an undisturbed area and a clear-felled area in the forest. Behara et al. (1990) also reported similar results using the linear relationship between soil respiration and root biomass. However, estimates from fallen litter (Kawahara, 1976) and from terminating live root activity through construction of trenches and root barriers (Bowden et al., 1993) were 18~33% less than the above result.

Soil respiration after shoot cutting (root +soil) was 70 % of intact measurement (shoot+root+soil). Many plant organs often maintain their respiration for some time after cutting by using their own organic matter (Karizumi, 1979; Negishi, 1970). Therefore, there may have been some remnant of root respiration just after shoot cutting in this study. There are two main functions in respiration, maintenance respiration and growth respiration. The former is associated with maintenance of old tissue and the latter with synthesis of new tissue (Marshall and Perry, 1987). In this study, most root respiration after shoot cutting may have been maintenance respiration. Growth



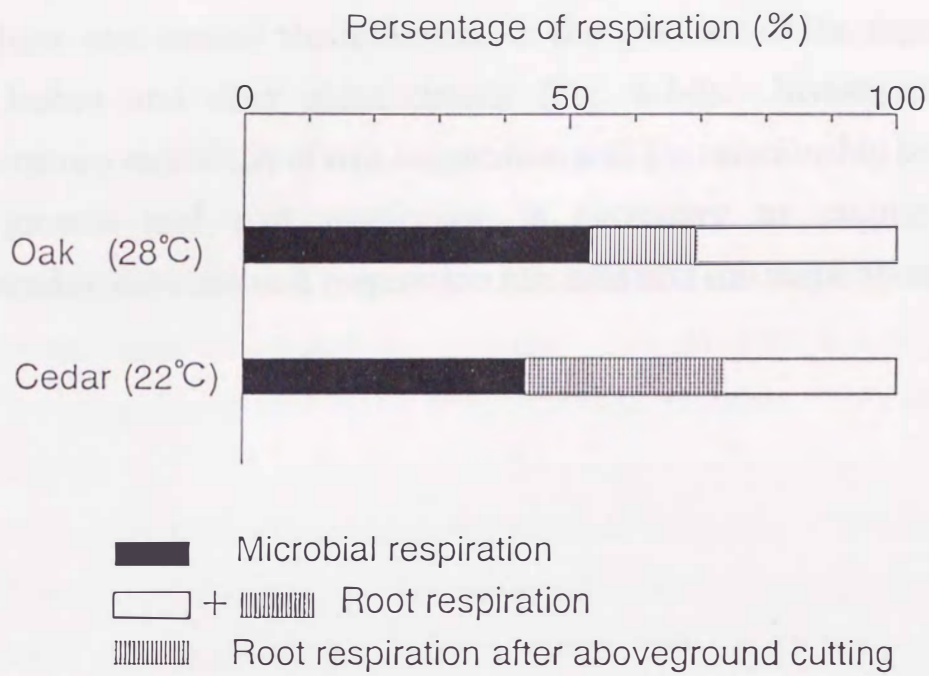


Fig. 4-1-3 Contribution of microbial and root respirations to soil respiration.

respiration may have decreased greatly because shoot cutting would have stopped the further supply of organic matter from shoot to root. If so, it is thought that growth respiration occupies two-thirds and half of root respiration in *Quercus acutissima* and *Cryptomeria japonica* pots, respectively (Fig. 4-1-3). The change in root respiration function may have also caused the difference in the gradient of the regression lines before and after shoot cutting (Fig. 4-1-2). Investigation of temperature sensitivity of root respiration and the relationship between tree growth and root respiration is necessary to examine the relationship between root respiration function and soil respiration.

## 4.2 Contribution of root respiration rate to total soil respiration rate in an Japanese cedar (*Cryptomeria japonica* D.Don) artificial forest

### 4.2.1 Introduction

Soil respiration or CO<sub>2</sub> evolution from the soil surface has been regarded as an excellent indicator of both root system activity and soil microorganisms activity (Lamade et al., 1996; Behara et al., 1990). Recently, understanding the amount and fluctuation of soil respiration has become more relevant due to the need to evaluate the capacity of forest ecosystems to fix carbon. This may be important to the global carbon budget (Houghton and Woodwell, 1989; Oikawa, 1991; Vose et al., 1997).

Many reports suggest that soil respiration is influenced strongly by environmental factors, such as soil moisture and temperature (Singh and Gupta, 1977; Schlentner and Van Cleve, 1985; Carlyle and Than, 1988; Lassard et al., 1994; Pajari, 1995). In forest ecosystems, soil respiration is also affected by forest management practices because root respiration may contribute a considerable proportion of soil respiration (Nakane et al., 1983). Some reports suggest that clear-felling or artificial gap formation causes a reduction of root respiration, thereby decreasing soil respiration (Brumme, 1995; Striegl and Wickland, 1998). Ohashi et al. (1999b) reported that thinning may have increased soil respiration temporarily because of increased development of the roots of remaining trees. Toland and Zak (1994) reported that the decomposition of dead roots after clear-felling offsets decreases in soil respiration. Therefore, in order to understand the complex fluctuations in soil respiration in forest ecosystems, it may be important to divide total soil respiration into microbial respiration and root



respiration.

Although many attempts have been made to estimate root contribution to total soil respiration, a precise estimate is difficult because of the complex nature of the soil sub-system (Behara et al., 1990). Some reports estimate the contribution of root respiration from measurement of CO<sub>2</sub> evolution in freshly cut roots (Edwards and Sollins, 1973) and from comparison of field measurement of total CO<sub>2</sub> flux and laboratory measurements of CO<sub>2</sub> flux from the same soil after removal of roots (Lamade et al., 1996; Thierron and Laudelout, 1996). However, these approaches result in a rate significantly different from the natural rate because of disturbance of ground through digging (Nakane et al., 1996; Ohashi and Saito, 1998). As a result, Kawahara (1976) considered that natural root respiration may be equal to the difference between soil respiration and fallen litter. Katagiri (1988) and Behara et al. (1990) calculated natural root respiration from the linear relationship between soil respiration and root biomass. However, the former method is only used for forest ecosystems in which soil organic matter is in dynamic equilibrium (Ohashi and Saito, 1998) and in the latter method it is difficult to measure root biomass accurately (Katagiri, 1988). Nakane et al. (1983) and Nakane et al. (1996) addressed these problems by comparing soil respiration between an undisturbed control area and a clear-felled area. They estimated natural root respiration more accurately by using a frame box covered with nets in clear-felled areas to maintain the same environmental conditions as those of the control, and by taking into consideration CO<sub>2</sub> evolution due to decomposition of roots which had died as a result of felling.

In the present study, I estimated the contribution of root respiration to total soil respiration in a Japanese cedar forest

(*Cryptomeria japonica* D. Don) using the technique that modified the methods of Nakane et al. (1983) and Nakane et al. (1996). Soil respiration rate was compared between an undisturbed area and the center of an artificial small gap that was expected to decrease the disturbance of environmental conditions, such as temperature and moisture. In this stand, factors have already been clarified that affect soil respiration, such as environmental factors, forest management, and thinning (Gyokusen and Saito, 1995; Ohashi et al., 1995). Therefore, in this study, the effect of an artificial gap formation on soil respiration was also examined by estimating the soil respiration gradient from the center of the gap into the stand.

#### 4.2.2 Study area

The study area was a 0.45 ha plantation of 10-year-old Japanese cedar in the Forest Research and Instruction Station of Kumamoto Prefecture, located in Kyushu, southwest Japan ( $32^{\circ} 49' N$ ,  $130^{\circ} 44' E$ ). Mean annual air temperature and precipitation in this area in 1996 were  $16.2^{\circ} C$  and 1970 mm, respectively (Kumamoto Local Meteorological Observatory, 1996). The soil type is a light color humid andosol (Kuroboku) derived from volcanic ash (Inoue, 1979) with a thin organic horizon. The forest is planted on a level topographic site and undergrowth is sparse. The study site had 16,000 trees  $ha^{-1}$ , 6 - 8 m in height. A description of this site may be found in reports by Gyokusen and Saito (1995) and Ohashi et al. (1999b).

In March 1996, four cedar trees were felled and set up G1 plot ( $0.8 m \times 0.8 m$ ) at the center of the gap ( $2.5 m \times 2.5 m$ ). G2, G3 and C (control) plots were also set up, at 0.8 m (edge of the gap), 1.6 m (edge of the surrounding stand), 6.0 m (in the forest, control) apart from G1, respectively (Fig. 4-2-1). Felled tree heights were not different from



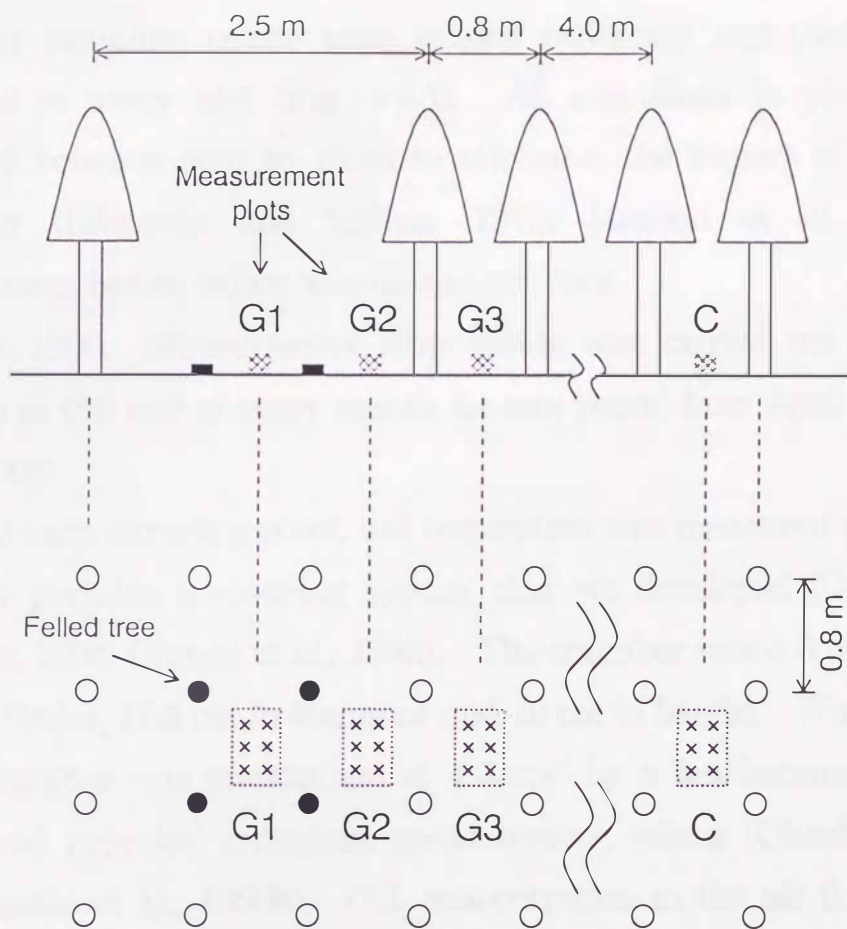


Fig. 4-2-1 Location of measurement plots. Each plots has 6 measurement points.



surrounding trees ( $P < 0.05$ ).

### 4.2.3 Methods

#### Soil respiration

Six sampling points were located randomly and their mean calculated in every plot (Fig. 4-2-1). All samplings in plots were conducted between 9:00 to 15:00 to minimize the impact of diurnal variability (Edwards and Sollins, 1973; Hanson et al., 1993). Measurement before felling was carried out once in March 1996. Measurement after felling was carried out once on fine days at the end of every month for two years, from April 1996 to March 1998.

At each sampling point, soil respiration was measured using an open-flow portable measuring system that we developed (Gyokusen and Saito, 1995; Ohashi et al., 1995). The chamber was a 3 mm thick acrylic cylinder, 12.5 cm in diameter and 10 cm in height. Wind speed in the chamber was maintained at  $4.0 \text{ ms}^{-1}$  by a fan because higher wind speed provided consistent measurement values (Ohashi et al., 1995; Ohashi et al., 1999b).  $\text{CO}_2$  concentration in the air flowing in and out of the chamber was measured by an infrared gas analyzer (SPB-H3, Shimadzu, Japan). Soil respiration rate was calculated when  $\text{CO}_2$  concentration in the chamber was exactly 400 ppm using  $\text{CO}_2$  concentration regulation (Ohashi et al., 1995; Ohashi et al., 1999b)

#### Soil surface temperature and soil moisture

Soil surface temperature was simultaneously measured using a thermistor thermometer (SL5-FF, Chino, Japan) at each point when soil respiration was measured. Three soil cores ( $20 \text{ cm}^2 \times 5 \text{ cm}$ ) were taken at 10 cm depth inside and outside the gap, respectively, at the

end of each measurement. Cores were oven-dried at 105 °C for 48 h and soil moisture content was determined gravimetrically.

### **Statistical analysis**

In order to compare tree heights between felled and surrounding trees, a non-parametric test was used. Soil respiration, soil surface temperature and soil moisture were compared over years and between the four plots using ANOVA. Monthly difference in soil respiration, soil temperature and soil moisture between the each G plot (G1, G2, G3) and C plot were compared by *t*-test. In order to examine the correlation of soil respiration rates with temperature and soil moisture in each plot, non-linear regression analyses was used. Comparison of regression lines between soil respiration rate and soil temperature was carried out by ANCOVA.

## **4.2.4 Results**

### **Soil surface temperature and soil moisture**

Soil surface temperature, ranging from 4.5 to 30.7°C and 6.0 to 26.8°C in the first and second years, respectively, increased in summer and decreased in winter (Fig. 4-2-2). Maximum and minimum values were recorded in July and February, respectively, in each year.

There was hardly any seasonal fluctuation over the two years in soil moisture content which ranged from 29 to 51% and 36 to 51% in the first and second years, respectively. Maximum and minimum values were recorded in July and March, respectively, in the first year, and in June and October, respectively, in the second year. Soil surface temperature and soil moisture content did not vary between plots or over years ( $P < 0.05$ ).



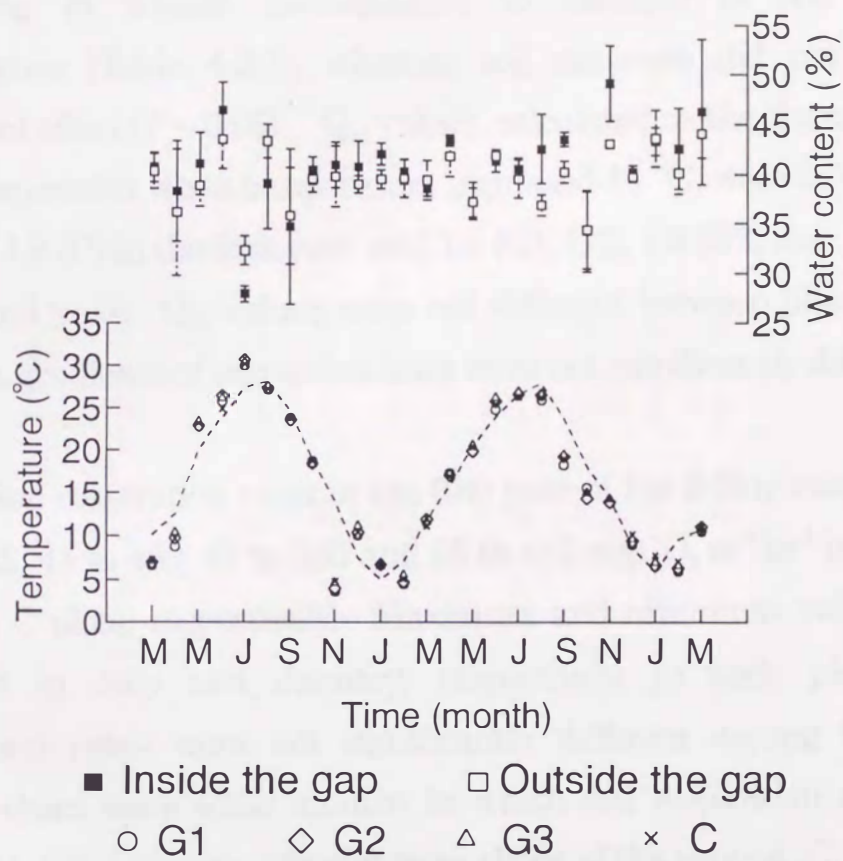


Fig. 4-2-2 Seasonal changes in soil surface temperature and water content of the sampling time. Vertical bars indicate  $\pm$ S.D. G1, G2, G3 and C are the same as in fig.1. ---- indicate monthly mean temperature of the study area.



### Soil respiration

Soil respiration rates before tree felling, ranging from 120 to 136  $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ , did not vary between plots ( $P < 0.05$ ) (Fig. 4-2-3). Seasonal fluctuation in soil respiration, increasing in summer and decreasing in winter, corresponded to changes in soil surface temperature (Table 4-2-1), whereas soil moisture did not have a significant effect ( $P < 0.05$ ).  $Q_{10}$  values, calculated as the changing rate of soil respiration when temperature increased 10 °C, were 2.0 (G1, G2, G3) and 1.8 (C) in the first year, and 1.6 (G1, G2), 1.9 (G3) and 1.8 (C) in the second year.  $Q_{10}$  values were not different between plots or over years, as gradients of regression lines were not significantly different ( $P < 0.05$ ).

Soil respiration rates in the first year of the felling ranged from 31 to 442, 41 to 489, 37 to 520 and 55 to 482  $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  in G1, G2, G3 and C plots, respectively. Maximum and minimum values were recorded in July and January, respectively, in each plot. Soil respiration rates were not significantly different among the plots though there were some months in which soil respiration rate in G plots (G1, G2, G3) was different from those of the control (C) plot ( $P < 0.05$ ) (Fig. 4-2-3).

In the second year, soil respiration rates in the G1 plot, ranging from 38 to 221  $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  were significantly lower than those of the C plot, ranging from 92 to 540  $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  ( $P < 0.05$ ). All months except April and October were significantly different for the two plots ( $P < 0.05$ ). Soil respiration rates in the G2 plot, ranging from 73 to 444  $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ , were also significantly lower than those of the C plot ( $P < 0.05$ ). There were monthly differences between the two plots in June, December and February ( $P < 0.05$ ). Soil respiration rates in the G3 plot, ranging from 117 to 720  $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ , were not significantly

3/1996 - 3/1997 4/1997 - 3/1998

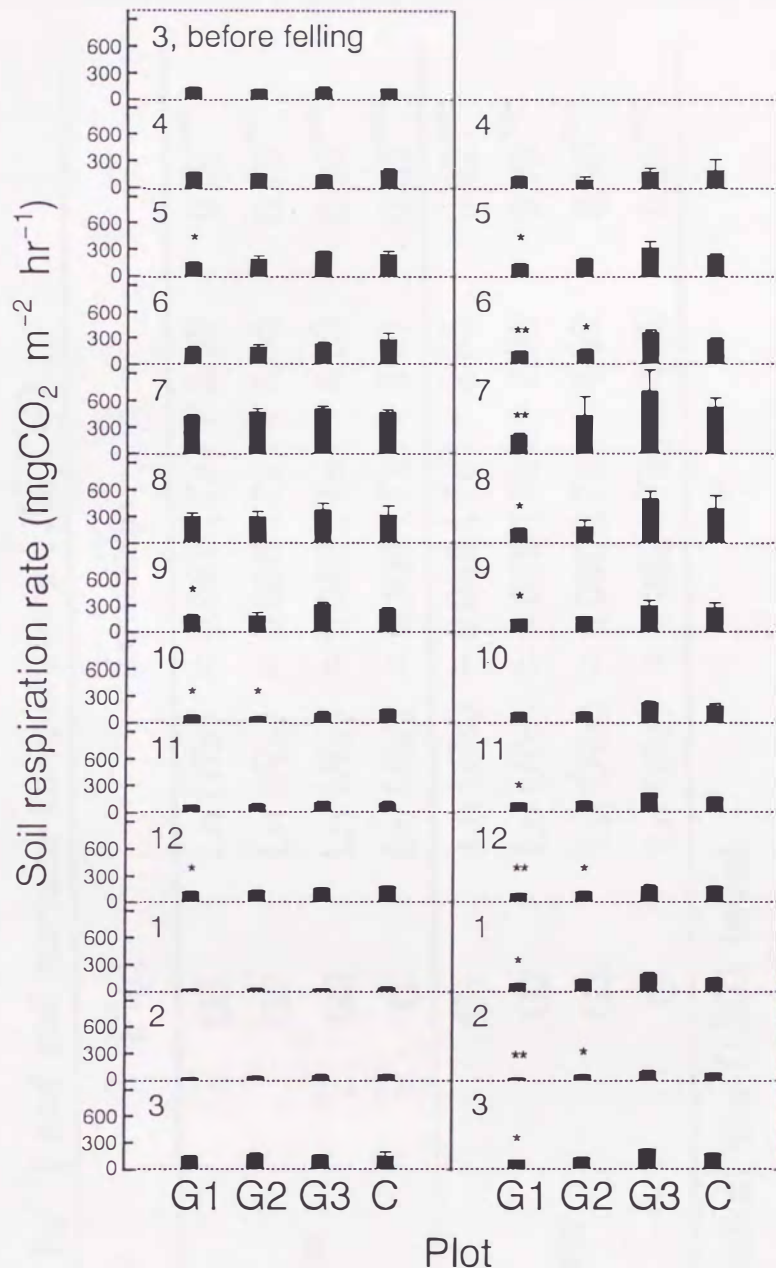


Fig. 4-2-3 Seasonal changes in soil respiration. Vertical bars indicate  $\pm$ S.D. \* and \*\* are significantly different from C at 0.05 and 0.001 levels, respectively.



Table 4-2-1 Correlation equations between soil respiration rate ( $R_s$ ) ( $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ ) and soil surface temperature ( $T_s$ ) ( $^{\circ}\text{C}$ ).

Year	Plot	Equation	$r$
1st year	G1	$\text{Ln}(R_s) = 0.061(T_s) + 3.90$	$0.78^{***}$
	G2	$\text{Ln}(R_s) = 0.056(T_s) + 4.06$	$0.75^{***}$
	G3	$\text{Ln}(R_s) = 0.068(T_s) + 4.03$	$0.86^{***}$
	C	$\text{Ln}(R_s) = 0.106(T_s) + 3.61$	$0.87^{***}$
2nd year	G1	$\text{Ln}(R_s) = 0.088(T_s) + 2.95$	$0.82^{***}$
	G2	$\text{Ln}(R_s) = 0.079(T_s) + 2.98$	$0.75^{***}$
	G3	$\text{Ln}(R_s) = 0.060(T_s) + 4.59$	$0.90^{***}$
	C	$\text{Ln}(R_s) = 0.062(T_s) + 4.38$	$0.92^{***}$

\*\*\* Significant at the 0.001 level.

different from those of the C plot. Nevertheless a higher tendency was observed. Maximum and minimum values of soil respiration were recorded in July and January, respectively, in each plot.

In each G plot (G1, G2, G3), difference in soil respiration rates from C plot increased rapidly in the second summer (Fig. 4-2-4). In G1 and G2 plots, soil respiration was lower than in the C plot and the reduction in the G2 plot was not as great as in G1. This variation reached a maximum of  $319 \text{ mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  (July) and  $210 \text{ mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  (August) in G1 and G2 plots, respectively. Soil respiration rates in the G3 plot was higher than in the C plot. Variations reached a maximum of  $180 \text{ mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  in the second July of gap formation.

#### 4.2.5 Discussion

##### Temporal change in soil respiration

It is supposed that seasonal changes in soil respiration are mainly influenced by soil temperature in temperate environments such as Japan since many similar findings have been reported in other Japanese forests (Kirita, 1971d; Seto et al., 1978; Sakai and Tsutsumi, 1987; Simono et al., 1989). In this study, soil respiration rates increased exponentially with soil temperature (Table 4-2-1).  $Q_{10}$  values, a convenient index in comparing sensitivity of soil respiration with soil temperature, were  $1.6 \sim 2.0$  which were a little lower than the range of  $1.8 - 4.1$ , as reported for a variety of temperate forests (Fung et al., 1987; Sakai and Tsutsumi, 1987; Hanson et al., 1993).  $Q_{10}$  values obtained by field measurements are affected by many other factors, such as soil moisture and soil nutrient status (Chiba, 1975; Singh and Gupta, 1977; Townsend et al., 1992; Kirschbaum, 1995). Kirschbaum (1995) reported that even at the same sites, there might be different



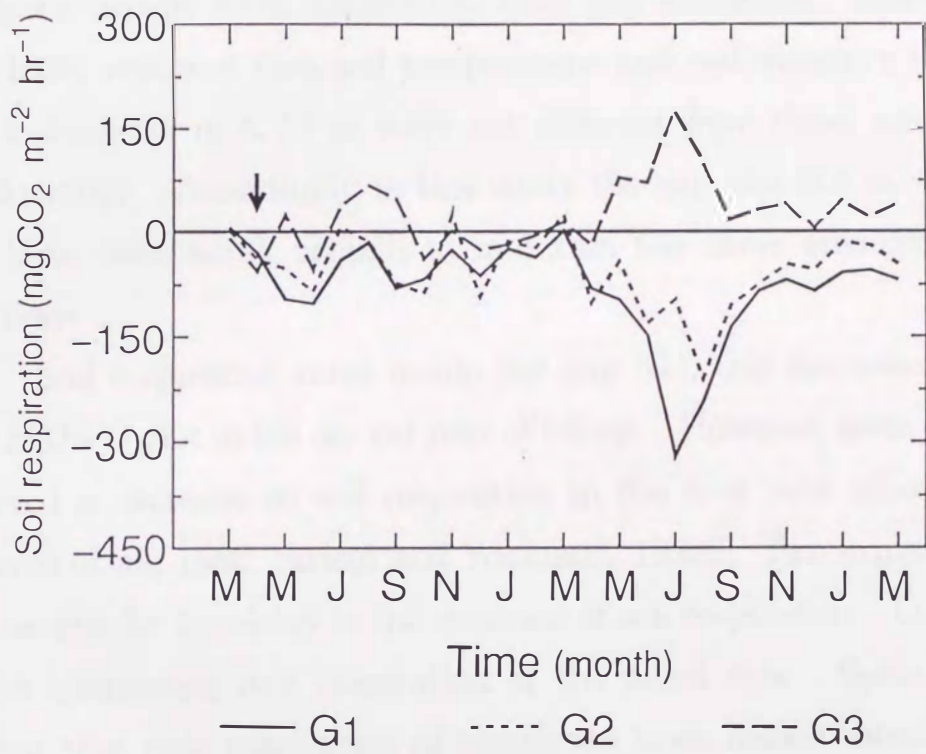


Fig. 4-2-4 Seasonal changes in difference in soil respiration from the C plot. The arrow indicates tree felling time. G1, G2, G3 and C are the same as in fig.1.

recordings in different years. In this study, however,  $Q_{10}$  values were not significantly different either between the four plots or over years ( $P < 0.05$ ). Since soil surface temperature and soil moisture content were also not different between plots or over years ( $P < 0.05$ ), it is thought that the same environmental conditions in the gap site as those under the closed canopy were maintained after gap formation. Zhang and Zak (1995) reported that soil temperature and soil moisture in gaps with a diameter of  $< 15$  m were not different from those under the closed canopy. Accordingly, in this study, the gap size ( $2.5 \text{ m} \times 2.5 \text{ m}$ ) may have been small enough to maintain the same environmental conditions.

Soil respiration rates inside the gap (G1, G2) decreased more than in the C plot in the second year of felling. However, some reports observed a decrease in soil respiration in the first year after felling (Nakane et al., 1983; Striegl and Wickland, 1998). Two explanations are possible for the delay in the decrease of soil respiration. One may be the continuing root respiration of the felled tree. Some report suggest that root respiration of coniferous trees ceases immediately after felling (Kawahara, 1976; Nakane et al., 1983). However, in forest ecosystems, there are many rhizosperic microbes around root systems and root respiration often is at a high rate due to a symbiotic relationship with mycorrhiza fungi (Tsutsumi, 1987; Hatano and Sasaki, 1987). Therefore, in this study, it may have taken some time for root respiration to cease after the felling. The other explanation may be the acceleration of microbial respiration following decomposition of dead roots due to felling. Toland and Zak (1994) reported that acceleration of microbial respiration offset a decline in soil respiration in the first year of clear-felling in northern hardwood forests. Arunnachalam et al. (1996) reported that a rapid decomposition of fine



roots occurred from 60 days after root cutting in a subtropical humid forest. Therefore, in this study, the remnant of root respiration may offset the decrease in soil respiration in the early period of the first year and thereafter the decomposition of dead roots may offset the decrease. Since almost all dead roots have been decomposed, soil respiration within the gap may be reduced in the second year.

### **Spatial change in soil respiration**

Nakane et al. (1996) and Striegl and Wickland (1998) observed lower soil respiration rates in clear-felling areas than in the control area. Brumme (1995) reported that soil respiration rates were lowest in the center of the 30 m diameter gap. They explained the reduction in soil respiration was mainly attributed to the cessation of root respiration. Thus, in this study, the reduction of soil respiration inside the gap (G1, G2) may have been caused by the diminution of root respiration. Since some live roots are intermingled with dead roots, the reduction in the G2 plot (edge of the gap) may not be as great as in G1 (center of the gap).

In this study, soil respiration in the G3 plot (edge of the surrounding forest) tended to be higher than in the C plot. Brumme (1995) also observed that the highest soil respiration occurred at the edge of the surrounding forest of the gap rather than in the stand. Ohashi et al. (1999b) reported that thinning increased soil respiration because of increased development of the roots of remaining trees in the stand. These reports suggest that an improvement in light conditions may accelerate root respiration. Therefore, in this study, the improvement in light conditions due to gap formation accelerated the root respiration rate in the G3 plot.

This study suggests that the small gap (2.5 m × 2.5 m) has the

potential to change the soil respiration rate in the gap site. Small gaps like this are often made by forest management activities, such as thinning, cleaning and cutting, and by natural disasters, such as typhoons. However most investigations have concentrated on larger disturbances, such as clear-felling (Toland and Zak., 1994; Zhang and Zak., 1995; Striegl and Wickland, 1998). Ohashi et al. (1999b) reported that forest management activities, such as thinning, may have the potential to change the carbon balance of the ecosystems and may even cause a small change in soil respiration, thereby substantially altering the global carbon budget. Thus, further studies, using gaps of different size and frequency, are necessary to fully determine the effect of small gap formation on soil respiration.

#### Estimation of root respiration

Assuming that differences in soil respiration rates between the center of the gap (G1) and in the forest (C) corresponds to root respiration rates, the root respiration rate of this stand was calculated. The relationship between root respiration ( $R_r$ ;  $\text{mgCO}_2 \text{m}^{-2} \text{hr}^{-1}$ ) and soil surface temperature ( $T_s$ ;  $^{\circ}\text{C}$ ) in the second year is expressed by the following equation (Fig. 4-2-5) ( $r^2 = 0.90$ ,  $P < 0.001$ );

$$\text{Ln}(R_r) = 0.07 T_s + 3.48 \quad \cdot \cdot \cdot (1)$$

Being a biochemical process, the relationship between root respiration rate and temperature usually has a  $Q_{10}$  of 2 (Singh and Gupta, 1977). Since the  $Q_{10}$  value calculated from equation (1) was also 2.0, it is thought that  $T_s$  is equal to root respiration rate. Thus, root respiration rate was estimated from soil surface temperature in the C plot using equation (1). Its ratio to soil respiration in the C plot was also calculated as root contribution to total soil respiration of this stand. Root respiration rate from April, 1996 to March, 1997, ranging from 54



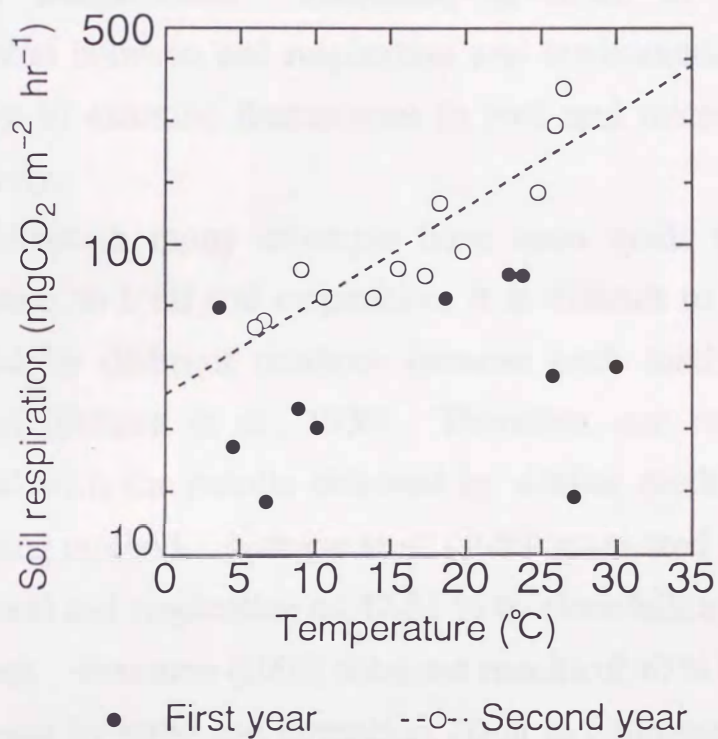


Fig. 4-2-5 Relationship between differences in soil respiration between G1 and C, and soil surface temperature.

to  $217 \text{ mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$  increased in summer and decreased in winter (Fig. 4-2-6). Contribution of root respiration was 49% on average, varying from 40 to 70 %. This variation suggests that root and microbial respiration have different sensitivities to environmental conditions, such as temperature. Therefore, in order to understand the relationship between soil respiration and environmental factors, it is necessary to examine fluctuations in root and microbial respiration, respectively.

Although many attempts have been made to estimate root contribution to total soil respiration, it is difficult to compare results estimated by different methods because each method has its own limitation (Behara et al., 1990). Therefore, our results have been compared with the results obtained by similar methods, such as the clear-felling method. Nakane et al. (1983) estimated the proportion of root to total soil respiration as 47-51 % by clear-felling of a mature red pine forest. Brumme (1995) obtained results of 40 % in a 146-year old beech forest by large gap formation, 30 m in diameter. Nakane et al. (1996) recorded 51 % in a mature, deciduous, broad-leaved forest. In this study, root contribution to total soil respiration, 49 % on average, was within the range of these previous studies. Nakane et al. (1983) concluded that the proportion of root respiration to soil respiration may converge to around 50 %, irrespective of the type of forest concerned, when soil organic carbon is in dynamic equilibrium in the forest ecosystem. However, it cannot be concluded that soil organic carbon is in dynamic equilibrium in this forest because it was still young, at 10-years-old. Further study is needed to determine the state of soil organic carbon in this stand over a longer period of time.

Comparison of soil respiration rates between an undisturbed control area and a tree felling area can allow estimation of natural root



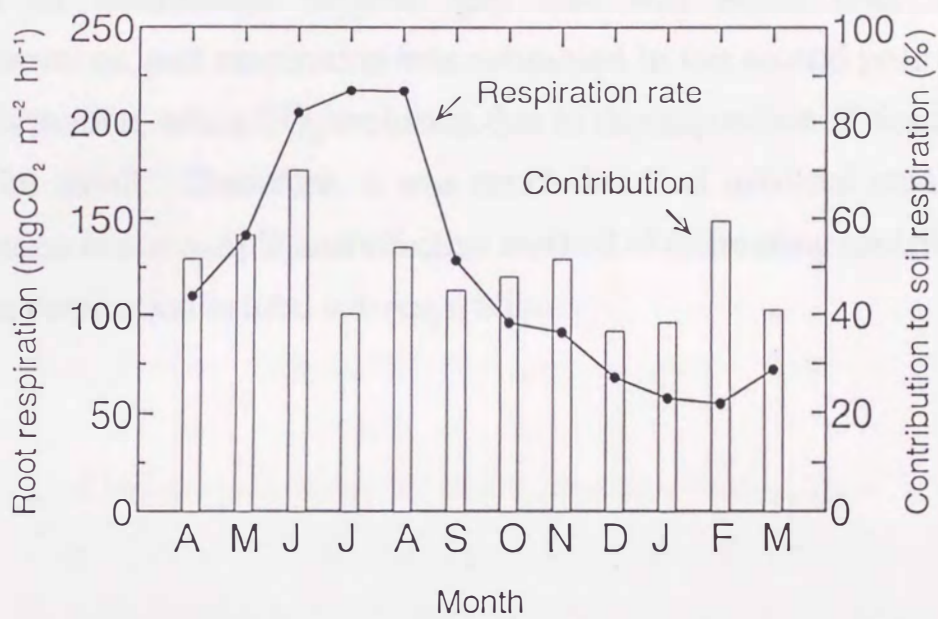


Fig. 4-2-6 Seasonal changes in root respiration rate and contribution to soil respiration from April 1997 to March 1998.

respiration without any soil disturbance. However, large area felling is difficult because it requires a large labor force and permission from various authorities. Furthermore, this method needs to consider the effects of changes in environmental conditions after felling and  $\text{CO}_2$  evolution due to decomposition of roots killed by cutting. In this study, however, the same environmental conditions in the gap as in the forest could be maintained because gap size was small (Fig. 4-2-2). Furthermore, root respiration was estimated in the second year of the gap formation, when  $\text{CO}_2$  evolution due to decomposition of dead roots may be small. Therefore, it was concluded that artificial small gap formation is one simple and effective method of estimating contribution of root respiration to total soil respiration.



### 4.3 Changes in soil respiration following aboveground growth in red oak and Japanese cedar forest stands

#### 4.3.1 Introduction

Carbon fixation by photosynthesis and the storage of the carbon above- and below-ground in forests are expected to contribute to decreased carbon dioxide in the air. Therefore, recently, reforestation has been carried out all over the world. However, carbon storage capacity in forest ecosystems is regulated by a balance between carbon fixation by photosynthesis and carbon emission by respiration. Therefore, since soil respiration is a major flux of carbon in ecosystems, the determination of soil respiration requires a clear understanding of the carbon storage capacity of the ecosystems (Freijer and Bouten, 1991).

Soil respiration in forest ecosystems has been studied in terms of seasonal (Kirita, 1971d; Anderson, 1973; Carlyle and Than, 1988; Holt et al., 1990; Pajari, 1995), diurnal change (Witkamp, 1969; Gyokusen and Saito, 1995; Nakadai et al., 1996; Eguchi et al., 1997), and relation to environmental factors, such as temperature and moisture (Chiba, 1975; Schlentner and Van Cleve, 1985; Sakai and Tsutsumi, 1987). However, most studies were carried out in mature forest ecosystems in which soil carbon cycles are already in dynamic equilibrium. Therefore, fluctuation of soil respiration in young forests during growth, when carbon dynamics are unstable, has been scarcely investigated. This is because soil respiration has been measured generally in order to clarify carbon cycling in forest ecosystems (Witkamp, 1969; Kucera and Kirkham, 1971; Edwards and Sollins, 1973; Anderson, 1973; Simono et al., 1989). However, the significance of the study of soil respiration has changed recently. Understanding

the extent and fluctuation of soil respiration has become more relevant due to the need to evaluate the capacity of forest ecosystems to fix carbon (Houghton and Woodwell, 1989; Oikawa, 1991; Vose et al., 1997). Therefore, it is important to study soil respiration dynamics in young forests which have a potential to fix more carbon than mature forests.

In forest ecosystems, not only microbial respiration but also root respiration may contribute a considerable proportion of soil respiration (Singh and Gupta, 1977; Behara, 1990). Therefore, changes in root biomass and root activity, depending on aboveground vegetation conditions, change root respiration rate, thereby affecting soil respiration. Changes in aboveground vegetation may also influence microclimate in forests and indirectly affect soil respiration. Some reports suggest that clear-felling or artificial gap formation causes a reduction of root respiration, thereby decreasing soil respiration (Brumme, 1995; Striegl and Wickland, 1998). Ohashi et al. (1999b) reported that thinning may have increased soil respiration temporarily due to increased development of the roots of remaining trees. Differences in the root and microbial ratio to soil respiration would cause variations in temperature sensitivity of soil respiration rates (Kirschbaum, 1995). These reports suggest that, changes in aboveground vegetation, such as planting and felling, may have significant effects on soil respiration.

The objective of this study is to examine the effects of aboveground growth on soil respiration. Red oak (*Quercus acutissima*) and Japanese cedar (*Cryptomeria japonica*) stands were grown from seed for 3 years and cuttage, respectively. One-and-a-half years after planting, 50% of each stand was clear-felled and the effect of clear-felling on soil respiration was also examined.



### 4.3.2 Study Site

Measurement was conducted in young red oak (*Quercus acutissima*) and young Japanese cedar (*Cryptomeria japonica*) stands grown in large concrete pots in the nursery of Kyushu university, Fukuoka prefecture, south-west Japan. In March 1995, 5 large concrete pots, 4 m<sup>2</sup> in area and 1 m in depth, were filled with Masa soil and left for a year. Rainwater was drained through many small holes, 5 cm in diameter, made in the bottom of the pot. In April 1996, seeds of red oak were sown in two of the pots in 16 seed m<sup>-2</sup> and cuttings of Japanese cedar was planted in the other two pots in 16 cutting m<sup>-2</sup>. The remaining pot was used as control. In December 1997, all trees in one pots from the oak and cedar stands, respectively, were clear-felled (Fig. 4-3-1). Each pot was designated as oak intact plot, oak felled plot, cedar intact plot, cedar felled plot and control plot, respectively. Watering was carried out in all plots as required.

### 4.3.3 Methods

#### Soil respiration, tree height and tree diameter

6 sampling points were located randomly in each plot. Measurement was carried out once on a fine day at the end of every month for three years, from April 1996, as near to just after planting, to May 1999.

Soil respiration was measured using an open-flow portable measuring system that developed by the authors (Gyokusen and Saito, 1995; Ohashi et al., 1995). The chamber was a 3 mm thick acrylic cylinder, 12.5 cm in diameter and 10 cm in height. Wind speed in the chamber was maintained 4.0 ms<sup>-1</sup> by a fan in the chamber (Hanson et al., 1993). CO<sub>2</sub> concentration in the air flowing in and out of the chamber was measured by infrared gas analyzer (SPB-H3, Shimadzu,

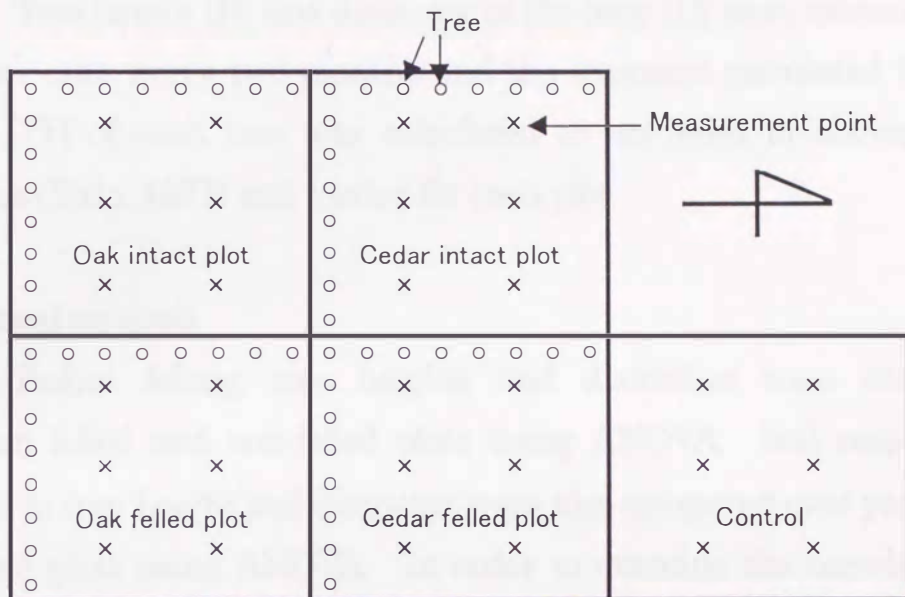


Fig. 4-3-1 Design of measurement plots. Each plot has 6 measurement points of soil respiration.



Japan). Soil respiration rate was calculated when CO<sub>2</sub> concentration in the chamber was exactly 400 ppm using CO<sub>2</sub> concentration regulation (Gyokusen and Saito, 1995; Ohashi et al, 1995) Soil surface temperature was measured using a thermistor thermometer (SL5-FF, Chino, Japan) as the same time as soil respiration.

Tree height (H) and diameter at the base (D) were measured for all trees once every two months and the averages calculated in each plot. D<sup>2</sup>H of each tree was calculated as an index of aboveground biomass (Yoda, 1971) and totaled for each plot.

### Statistical analysis

Before felling, tree heights and diameters were compared between felled and non-felled plots using ANOVA. Soil respiration, growth in tree height and diameter were also compared over years and between plots using ANOVA. In order to examine the correlation of soil respiration rate with temperature in each plot, non-linear regression analysis was used. Comparison of regression lines between soil respiration rate and soil temperature was carried out using ANCOVA. Significance for all statistical analyses was accepted at  $\alpha = 0.05$ .

#### 4.3.4 Results

##### Tree height, tree diameter and D<sup>2</sup>H

Growth in tree height and diameter were concentrated from May till September in both oak and cedar intact plots (Fig. 4-3-2, Fig. 4-3-3). Heights in May, the final month of each measurement year, in oak and cedar intact plots were 41 cm and 75 cm, 82 cm and 113 cm, and 95 cm and 126 cm in 1st, 2nd and 3rd years, respectively. Annual height increase was 32~41 cm in the 1st and 2nd years, decreasing to

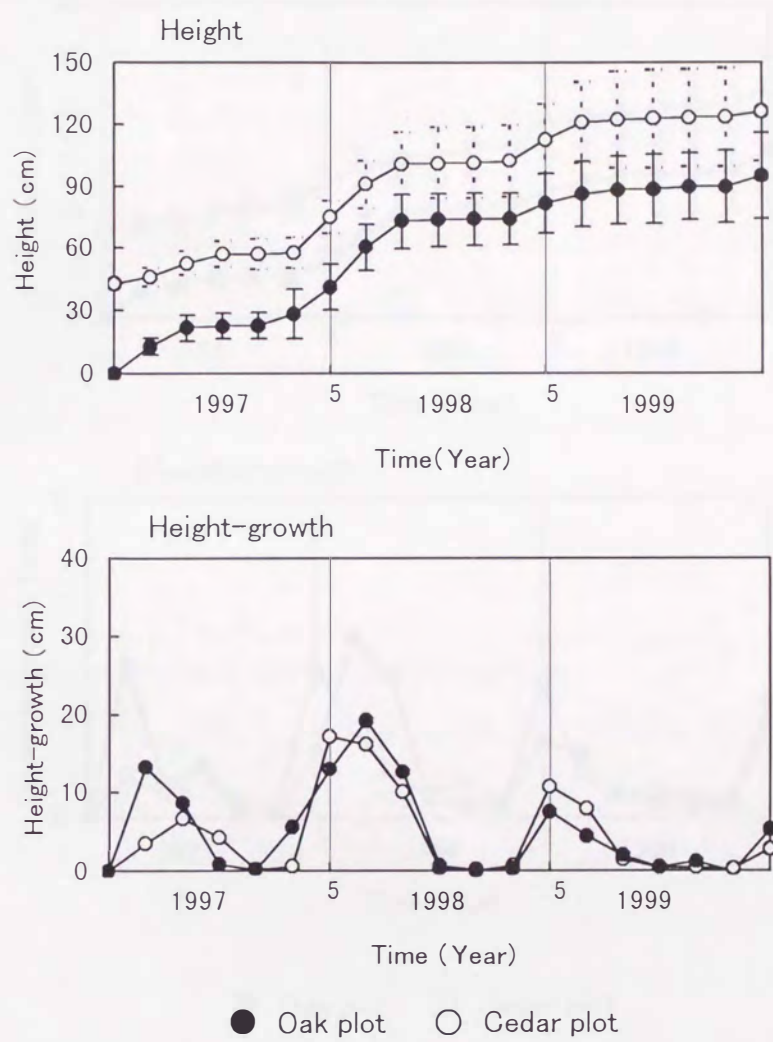


Fig. 4-3-2 Temporal change in tree height.



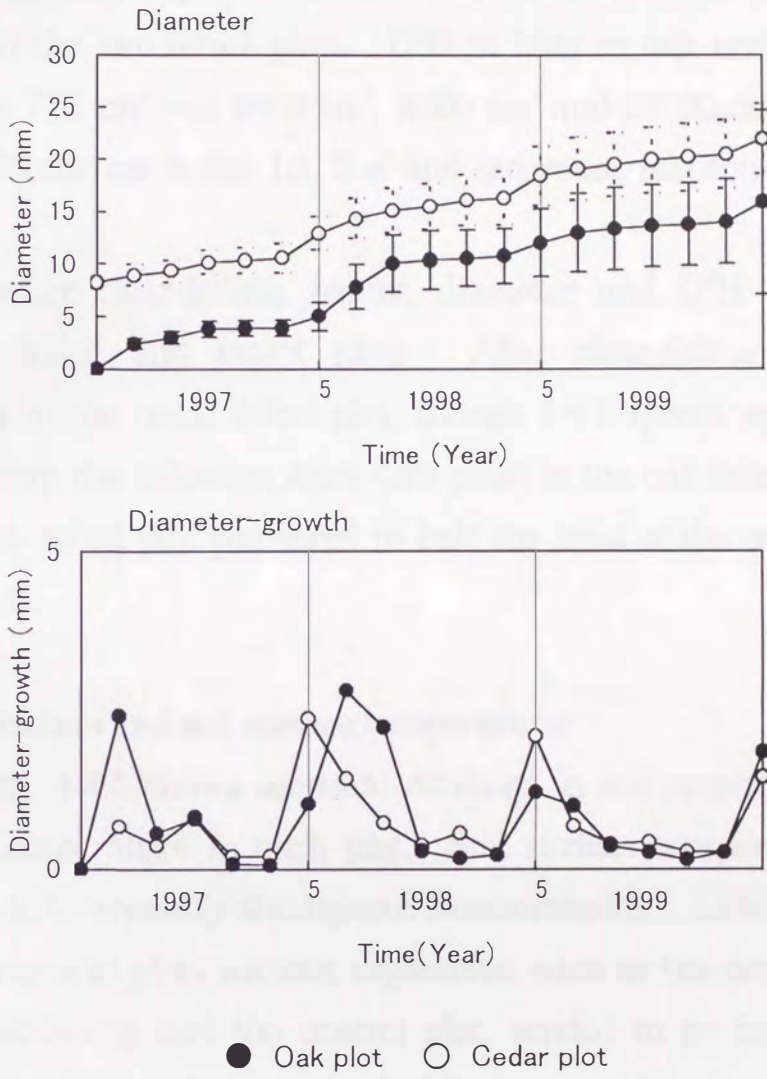


Fig. 4-3-3 Temporal change in tree diameter.

13 cm in the 3rd year. Diameters in May in oak and cedar intact plots were 5 mm and 13 mm, 12 mm and 18 mm, 16 mm and 22 mm in 1st, 2nd and 3rd years, respectively. Annual diameter growth was 4~7 mm throughout the year. Increase in  $D^2H$  was concentrated from May to July in the two intact plots.  $D^2H$  in May in oak and cedar intact plots was 770 cm<sup>3</sup> and 8400 cm<sup>3</sup>, 8600 cm<sup>3</sup> and 26000 cm<sup>3</sup>, 22000 cm<sup>3</sup> and 41000 cm<sup>3</sup> in the 1st, 2nd and 3rd years, respectively (Fig. 4-3-4).

Before clear-felling, height, diameter and  $D^2H$  did not vary between felled and intact plots. After clear-felling, no sprouts appeared in the cedar felled plot, though 2~6 sprout appeared from every stump the following April (3rd year) in the oak felled plot.  $D^2H$  in the oak felled plot recovered to half the level of the oak intact plot (Fig. 4-3-4).

#### Soil respiration and soil surface temperature

Fig. 4-3-5 shows seasonal readings in soil respiration and soil surface temperature in each plot. Soil surface temperature ranged from 8~40°C annually throughout measurement. Although summer temperatures in plots without vegetation, such as the cedar felled plot after clear-felling and the control plot, tended to be higher than in vegetation plots (oak intact, oak felled and cedar intact plots), the differences were not significant.

Seasonal fluctuation in soil respiration, increasing in summer and decreasing in winter, corresponded to changes in soil surface temperature. Soil respiration rates in the control plot, ranging from 21~270 mgCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>, were not significantly differed over years of measurement. Soil respiration in the oak stand (intact plot and felled plot) ranged from 54~304 mgCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>, 51~511 mgCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup> and



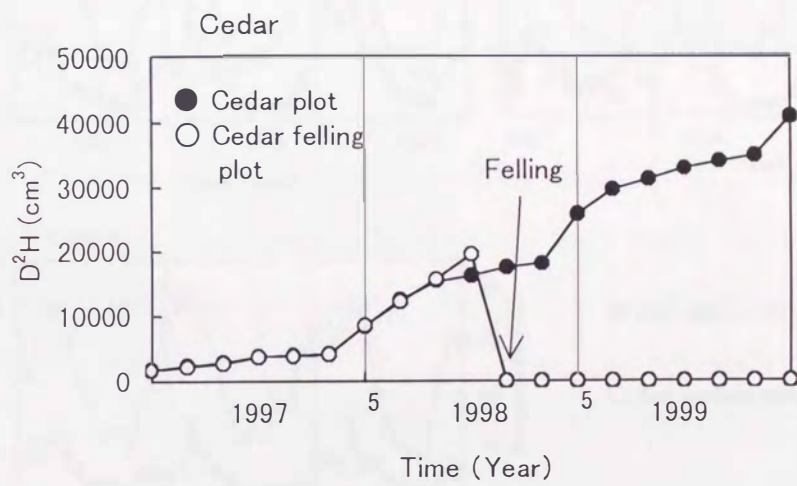
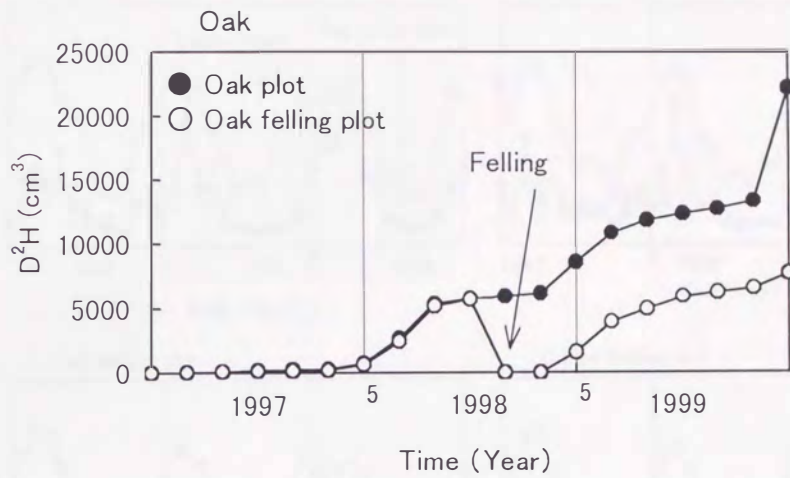


Fig. 4-3-4 Temporal change in D<sup>2</sup>H .

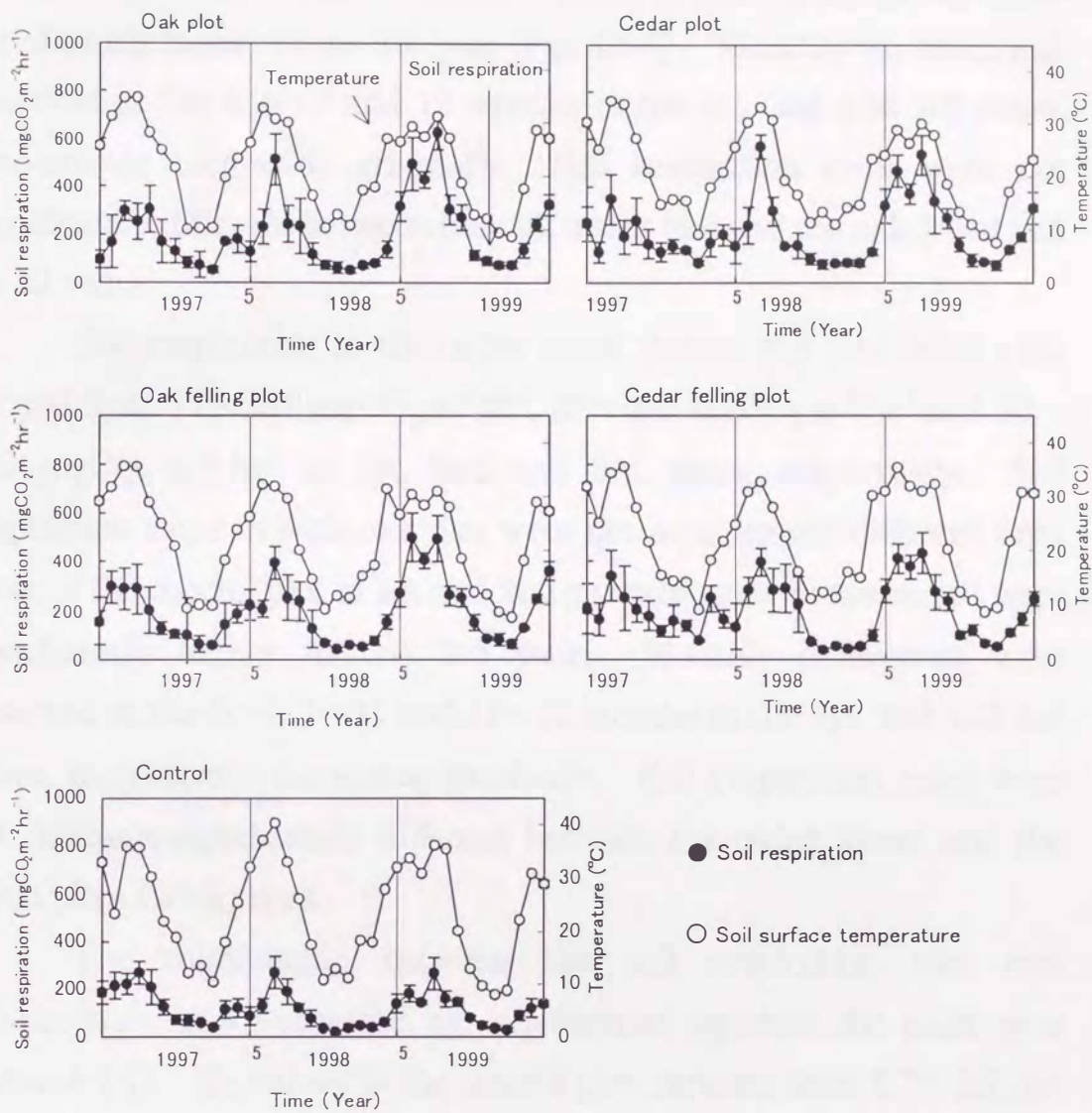


Fig. 4-3-5 Temporal changes in soil respiration and soil surface temperature.



63~625 mgCO<sub>2</sub>m<sup>-2</sup>hr<sup>-1</sup> in the 1st, 2nd and 3rd years, respectively. Soil respiration rates in each oak plot did not vary significantly from those of the control plot in the 1st and 2nd years of measurement, but were significantly higher in the 3rd year (Fig. 4-3-6). Monthly variation was observed in the 4, 8~9 and 12 months in the 1st, 2nd and 3rd years, respectively, increasing gradually. Soil respiration rates were not significantly different between the oak intact plot and the oak felled plot for all years.

Soil respiration in the cedar stand (intact plot and felled plot) ranged from 77~257 mgCO<sub>2</sub>m<sup>-2</sup>hr<sup>-1</sup>, 37~569 mgCO<sub>2</sub>m<sup>-2</sup>hr<sup>-1</sup> and 50~533 mgCO<sub>2</sub>m<sup>-2</sup>hr<sup>-1</sup> in 1st, 2nd and 3rd years, respectively. Soil respiration rates in each oak plot were not significantly different from those of the control plot in 1st and 2nd years of measurement, but were significantly higher in the 3rd year. Monthly differences were observed in the 6~7, 7~11 and 11~12 months in the 1st, 2nd and 3rd years, respectively, increasing gradually. Soil respiration rates were not different significantly different between the cedar intact and the felled plots for all years.

The relationship between the soil respiration rate and temperature was expressed by exponential equation for each year (Table 4-3-1). Q<sub>10</sub> values in the control plot, ranging from 1.7~1.9, did not vary among years of measurement. Q<sub>10</sub> values in the oak and cedar intact stands did not vary significantly from the control plot in the 1st year, ranging from 1.4~1.7, but significantly higher in the 2nd and 3rd year, ranging from 2.0~2.2, 1.9~2.3, respectively (Fig. 4-3-7). There were no significant differences in Q<sub>10</sub> value between the oak and cedar stands in any year. Correlation equations between soil respiration and soil surface temperature were used to estimate annual soil respiration at each plot. Daily mean soil respiration was

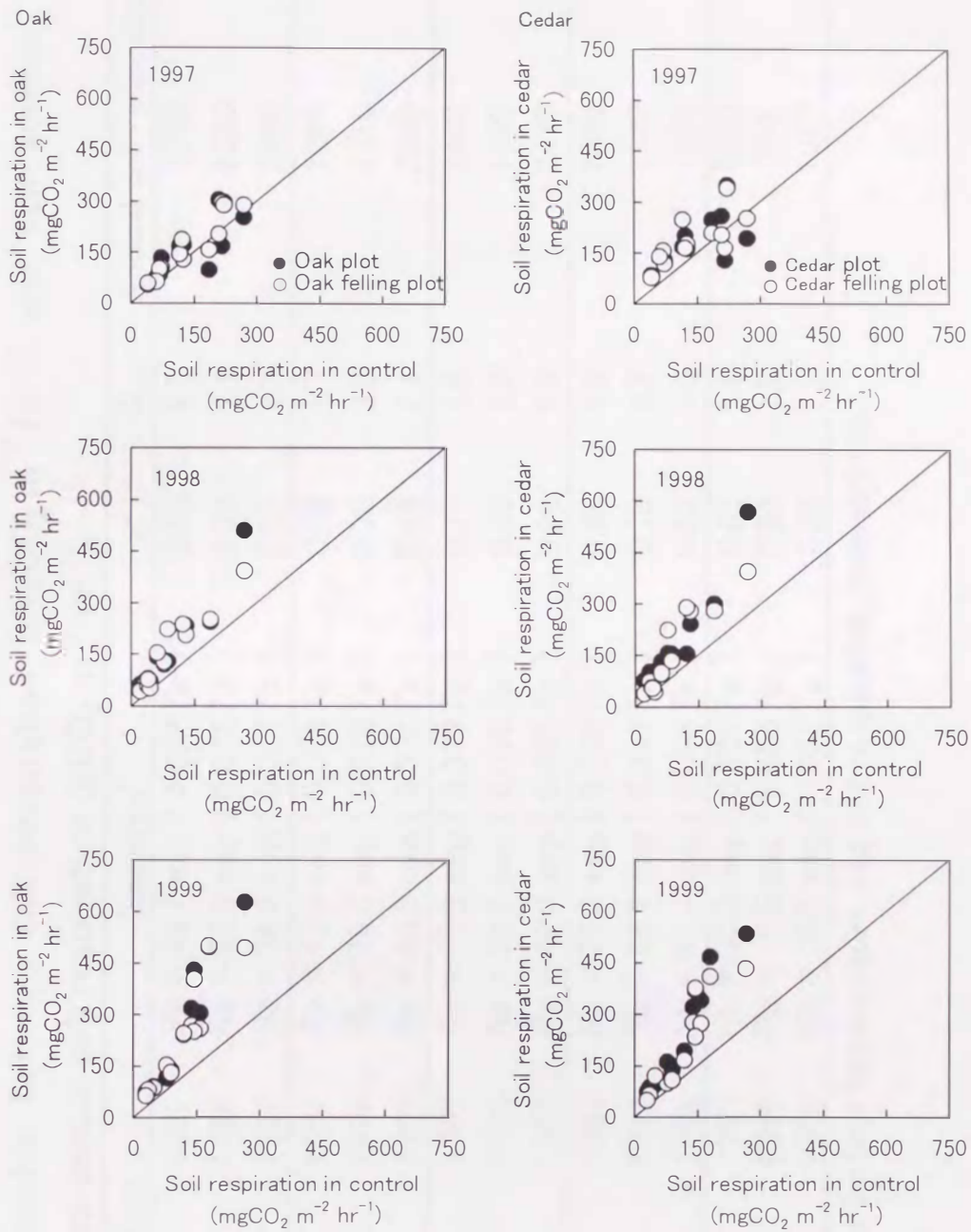


Fig. 4-3-6 Relationship between soil respiration in oak and control stands, and between soil respiration in cedar and control stands.



Table 4-3-1 Relationship between soil respiration ( $\text{mgCO}_2 \text{ m}^{-2} \text{ hr}^{-1}$ ) and soil surface temperature ( $^{\circ}\text{C}$ ), and annual soil respiration ( $\text{gCO}_2 \text{ m}^{-2} \text{ yr}^{-1}$ ).

Plot	Year	Equation*	$r^2$	$Q_{10}$	Annual soil respiration
Oak plot	1997	$Rs = 43.7 \exp ( 0.052 Ts )$	0.73	1.7	1240
	1998	$Rs = 27.8 \exp ( 0.073 Ts )$	0.73	2.1	1330
	1999	$Rs = 36.8 \exp ( 0.084 Ts )$	0.90	2.3	2460
Oak felling plot	1997	$Rs = 43.6 \exp ( 0.053 Ts )$	0.85	1.7	1280
	1998	$Rs = 29.0 \exp ( 0.070 Ts )$	0.70	2.0	1310
	1999	$Rs = 43.0 \exp ( 0.073 Ts )$	0.86	2.1	2210
Cedar plot	1997	$Rs = 73.3 \exp ( 0.039 Ts )$	0.71	1.5	1480
	1998	$Rs = 35.8 \exp ( 0.070 Ts )$	0.83	2.0	1490
	1999	$Rs = 42.3 \exp ( 0.082 Ts )$	0.93	2.3	2470
Cedar felling plot	1997	$Rs = 77.3 \exp ( 0.036 Ts )$	0.66	1.4	1530
	1998	$Rs = 24.1 \exp ( 0.077 Ts )$	0.79	2.2	1320
	1999	$Rs = 41.7 \exp ( 0.063 Ts )$	0.57	1.9	1680
Control	1997	$Rs = 30.0 \exp ( 0.061 Ts )$	0.83	1.8	1230
	1998	$Rs = 15.5 \exp ( 0.065 Ts )$	0.83	1.9	710
	1999	$Rs = 28.1 \exp ( 0.055 Ts )$	0.79	1.7	1030

\* T and SR indicate soil surface temperature and soil respiration, respectively.

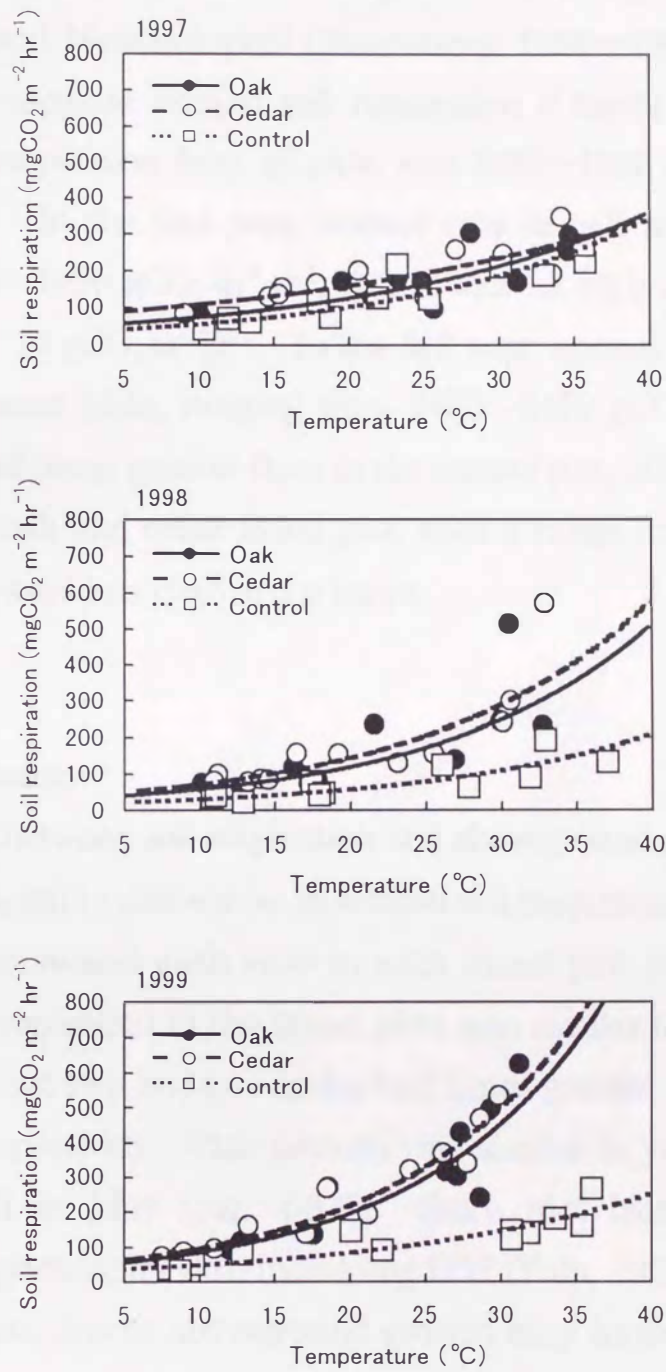


Fig. 4-3-7 Relationship between soil respiration and soil surface temperature.



calculated from daily mean temperatures using the equations (Fukuoka Local Meteorological Observatory, 1996~1999) and totaled in order to calculate annual soil respiration (Ohashi et al., 1999b). Annual soil respiration from all plots was 1230~1250 gCO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>, in the 1st year. In the 2nd year, annual rate in oak and cedar intact stands, 1310~1490 gCO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>, were twice as high as those in the control plot, 710 gCO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>. In the 3rd year, annual rate in the oak and cedar intact plots, ranging from 2460~2470 gCO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>, were two-and-a-half times greater than in the control plot, 1030 gCO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>, while in the oak and cedar felled plot, with a range from 1680~2210 gCO<sub>2</sub> m<sup>-2</sup> yr<sup>-1</sup>, were less than in the intact plots.

#### 4.3.5 Discussion

##### Relationship between soil respiration and aboveground growth

In this study, differences in annual soil respiration rate from the control plot increased each year in each intact plot (oak and cedar). Annual soil respiration in the intact plots was similar to the control in the 1st year, but two and two-and-a-half times greater in the 2nd and 3rd years, respectively. This pattern was similar to yearly growth of D<sup>2</sup>H, or D<sup>2</sup>H in May (Fig. 4-3-8). Since root biomass generally increases proportionally with increasing D<sup>2</sup>H (Yoda, 1971), the increase in root biomass due to aboveground growth may have increased root respiration, thereby increasing soil respiration. Katagiri (1988) and Behara et al. (1990) also reported a linear relationship between soil respiration and root biomass. This suggests that annual soil respiration in young forests may increase annually due to increasing root biomass.

However, changes in D<sup>2</sup>H did not seasonally affect soil

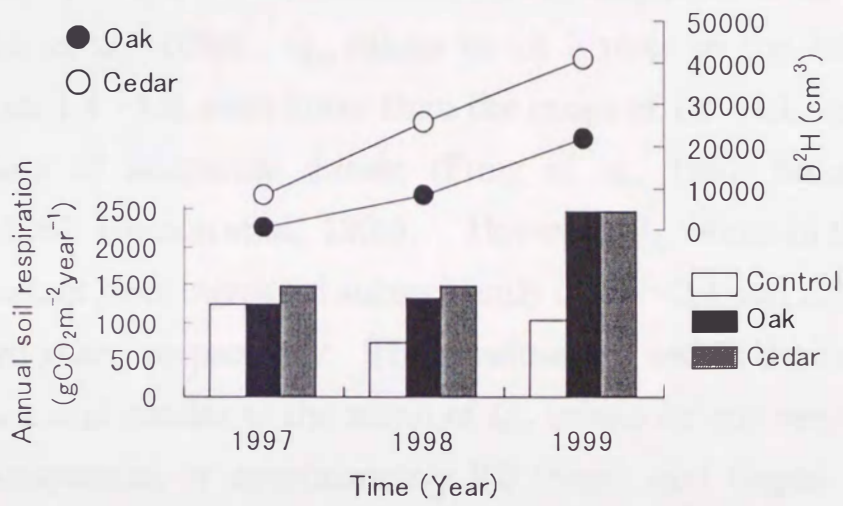


Fig. 4-3-8 Annual change in soil respiration and D<sup>2</sup>H.



respiration in this study. Seasonal changes in soil respiration corresponded to soil temperature. Increases in  $D^2H$  were concentrated from May to July, while soil respiration increased mainly from June to September (Fig. 4-3-4). This indicates that the sensitive response of soil microbial and root respiration to temperature more seriously affects seasonal change in soil respiration than growth of root respiration. In this study, the relationship between soil respiration rate and temperature is expressed by an exponential equation (Table 4-3-1), like many other studies, such as Anderson (1973), Hagihara et al. (1984) and Simono et al. (1989).  $Q_{10}$  values in all 5 plots in the 1st year, ranging from 1.4~1.9, were lower than the range of 1.8 - 4.1, reported for a variety of temperate forests (Fung et al., 1987; Sakai and Tsutsumi, 1987; Hanson et al., 1993). However,  $Q_{10}$  values in the oak and cedar intact plots increased subsequently to 2.0~2.1 and 2.3 in the 2nd and 3rd years, respectively. These values are within the range of other studies and similar to the mean of  $Q_{10}$  values for soil respiration in forest ecosystems, or approximately 2.0 (Singh and Gupta, 1977). Therefore, in this study, not only annual soil respiration but also temperature sensitivity of soil respiration increased due to aboveground growth. Kirschbaum (1995) reported that since root and microbial respiration have different temperature sensitivities, differences in root and microbial ratio to soil respiration would cause variations in the temperature sensitivities of soil respiration rates. In this study, increases in root respiration ratio to soil respiration may have caused an increase in  $Q_{10}$  values. If so, temperature sensitivities of soil respiration from other young forests may change annually. Recently, understanding changes in  $Q_{10}$  values is important in order to predict and adapt to the response of ecosystems to global warming (Townsend et al., 1992; Kirschbaum, 1995). Therefore, further studies in other

young forests of different ages, density and other parameters are necessary in order to understand changes in temperature sensitivity of soil respiration. It is also important to examine temperature sensitivity in root and microbial respiration, respectively, in order to determine the factors affecting  $Q_{10}$  values.

Assuming that differences in soil respiration rates between each intact plot and the control plot correspond to root respiration rate, the root respiration rate of this stand was calculated approximately. As a result, mean ratio of root respiration to soil respiration in the oak intact plot was 15%, 50% and 55% in the 1st, 2nd and 3rd years, respectively (Fig. 4-3-9). Mean ratio in the cedar intact plot, was 33%, 59% and 60% in the 1st, 2nd and 3rd years, respectively. Nakane et al. (1983) estimated the proportion of root to total soil respiration as 47~51 % by clear-felling of a mature red pine forest. Brumme (1995) obtained results of 40 % in a 146-year old beech forest by large gap formation, 30 m in diameter. Nakane et al. (1996) recorded 51 % in a mature, deciduous, broad-leaved forest. In this study, root contribution to total soil respiration was within the range of these previous studies, though the forest was still immature. This may have been caused by the high density of root systems due to the high density of trees ( $16 \text{ trees m}^{-1}$ ) or shallower spread of roots than those of mature trees.

### **Effect of clear-felling**

Soil respiration rates were not significantly differed between intact and felled plots after clear-felling. However, although no sprouts appeared in the cedar felled plot, 2~6 sprouts appeared from every stump the following April (3rd year) in the oak felled plot after clear-felling. Therefore other factors may have been involved in the two felled plots resulting in unchanged soil respiration after clear-



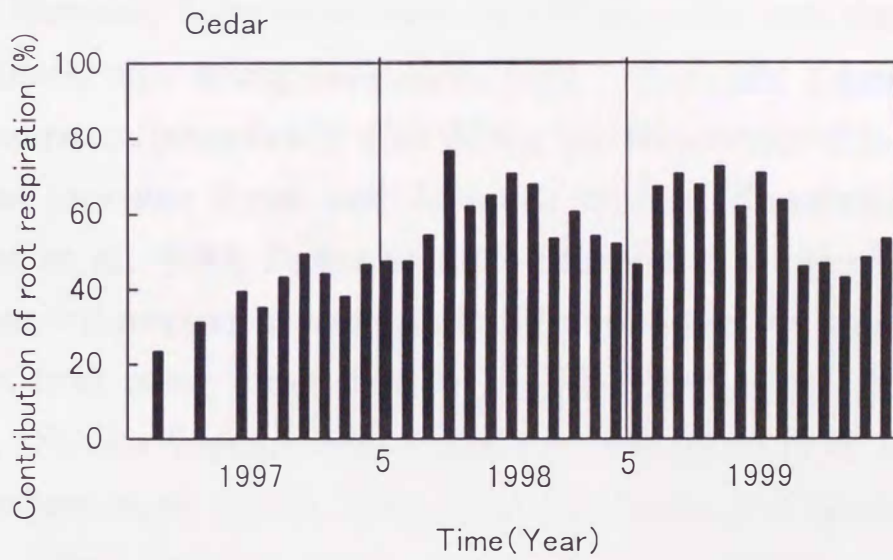
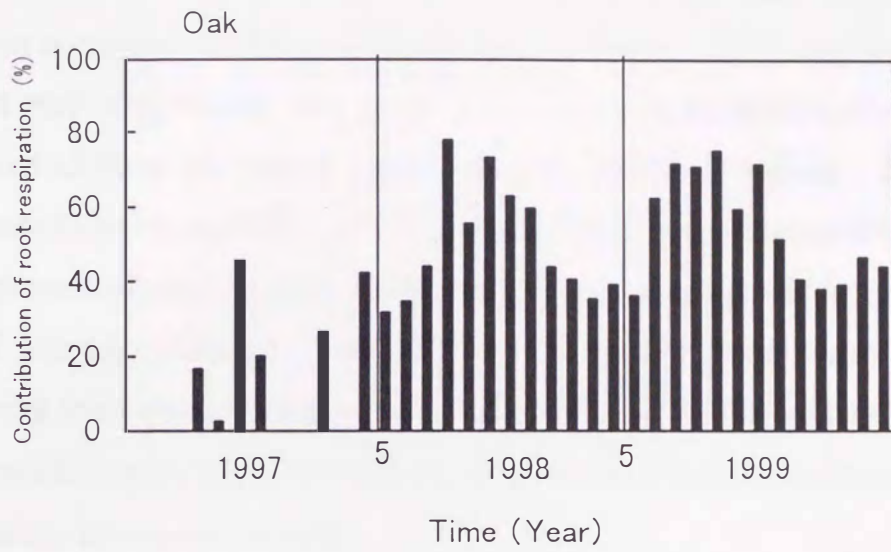


Fig. 4-3-9 Contribution of root respiration to soil respiration.

cutting.

Nakane et al. (1996) compared soil respiration between two clear-felled areas (one with dead roots and the other with undisturbed roots) in a mature deciduous broad-leaved forest. They reported that 70% of root respiration remained in the area with undisturbed roots and most of the root system might live just after clear-felling. It is also considered that generally root systems of broad-leaved trees live even if aboveground shoots are cut and some sprouts often appear from the cut end of stumps (Karizumi, 1979). In this study, since some sprouts appeared from every stump in the oak felled plot, the continuation of root respiration in each oak tree may have resulted in unchanged soil respiration after clear-felling.

However, some trees, such as conifers, cease root respiration immediately after felling (Kawahara, 1976). Therefore, a decrease in soil respiration immediately after felling has been reported in forests, such as jack-pine forest and Japanese cypress (Kawahara, 1976; Nakane et al., 1983; Brumme, 1995; Striegl and Wickland, 1998). However, soil respiration rate in cedar felled plot were not significantly differed from cedar intact plots for one-and-a-half years after clear felling. Similar findings were reported by Thlaphitak et al. (1985), Hendrickson et al. (1989), Toland and Zak (1994) and Londo et al. (1999). Toland and Zak (1994) and Londo et al. (1999) considered acceleration of microbial respiration following decomposition of dead roots due to felling may offset the decline in soil respiration. Therefore, in this study, the decomposition of dead roots may offset the decrease in soil respiration resulting from a reduction in root respiration. Further, soil respiration in the cedar felled plot may decrease in future after almost all dead roots have decomposed.

In this study, two different explanations are possible for



unchanged soil respiration in the oak felled plot and cedar felled plot, respectively. In the oak felled plot, root respiration may have continued, while root respiration may have ceased and the decomposition of dead roots may have offset the decrease in soil respiration in the cedar felled plot. Annual soil respiration rate in the cedar felled plot, which did not vary from the intact plot in the 1st and 2nd year, felled to two-thirds of those of the intact plot in the 3rd year (Table 4-3-1). This suggests a decrease in dead roots following decomposition in the 3rd year. In this study, root contribution to total soil respiration was estimated to be about 60% in the cedar stand (Fig. 4-3-8). Subsequently, soil respiration may decline further to less than half that of the intact plot. However, it has been reported that decrease in soil respiration was not observed three years after clear-felling in a coniferous forest (Hendrickson et al., 1989) and in white spruce forests (Gordon et al., 1987). Toland and Zak (1994) presumed that more than five years may be needed until all dead roots decompose in clear-felling forests. Therefore, further observation is needed to determine the extent to which soil respiration changes over longer periods, in excess of five years. It is also necessary to investigate changes in soil microbial respiration and root biomass in order to completely understand changes in CO<sub>2</sub> fluctuation in soil after felling.

## Chapter 5 Conclusion

Many factors affecting soil respiration in forest ecosystems were clarified through this study. First, it was found that wind speed and CO<sub>2</sub> concentration greatly affect soil respiration (2.1, 2.2). Soil respiration rate decreased with increasing CO<sub>2</sub> concentration, and increased with increasing wind speed. The chamber method is used widely to measure soil respiration. However wind speed and CO<sub>2</sub> concentration in the chamber had not been considered as important factors. It can be seen that wind speed and CO<sub>2</sub> concentration must be clarified when soil respiration is measured by the chamber method.

Soil respiration fluctuation in natural conditions estimated from diurnal changes in temperature, CO<sub>2</sub> concentration and wind speed on the forest floor, increased in the daytime and decreased at night (2.2). Soil respiration has been estimated using various models. However, most models estimated seasonal change in soil respiration and used temperature, moisture and precipitation as explanatory variables in the models. In this study, however, the effects of natural fluctuation of CO<sub>2</sub> concentration, wind speed and temperature on diurnal fluctuation of soil respiration were pointed out. Therefore, it is important to regulate environmental factors in the chamber similarly to external conditions in order to estimate soil respiration accurately.

The spatial and temporal variability in soil respiration on forest floor was verified (3.1, 3.2). Temporal fluctuation in soil respiration mainly corresponds to changes in two environmental factors, soil moisture and temperature, because of the sensitive response of soil microbial activities and root respiration to these factors (Singh and Gupta, 1977). The effect of these two factors, however, varies



depending on geographical location and season. In this study, seasonally soil respiration increased in summer and decreased in winter. These changes corresponded to temperature (2.2, 3.1, 3.2, 4.2, 4.3), whereas soil moisture did not have a significant effect (3.1, 3.2). Diurnal change in soil respiration also corresponded to temperature (2.2, 2.3). Therefore, it is supposed that temporal changes in soil respiration from a forest floor is mainly influenced by soil temperature in temperate environments like Japan.

There are few studies that determine the spatial variability of soil respiration on a slope in a forest due to limitations relating to the portability of the measurement system. Therefore, in this study, soil respiration was measured using the portable open-flow soil respiration measuring system on points located in a grid-like pattern on a slope of a Japanese cedar forest in order to examine the spatial variability of soil respiration (3.2). As a result, the number of measurements required to estimate mean soil respiration on the Japanese cedar slope was estimated to be 50 from the coefficient of variations of soil respiration. This number suggests soil respiration may have high spatial variability in Japanese forests and a large number of measurement points may be needed to estimate average values. Spatial variability in soil respiration is caused by many factors which have both direct and indirect effects on soil respiration. Further, the relative importance of these factors varies greatly depending on local geographical and environmental conditions at the site. At study site, soil properties, such as soil pH, carbon and nitrogen concentration did not explain the spatial distribution of soil respiration. Therefore, it is important not only to carefully examine factors controlling spatial change in soil respiration in a forest closely, but also to accumulate the information on distribution patterns of soil respiration in other forests different in

topographical location, geographical features and other parameters.

Contribution of root respiration to total respiration was estimated to be 40~70% in this study (4.1, 4.2). This suggests that root respiration contributes a fair proportion of soil respiration and that changes in root respiration depending on changes in aboveground vegetation may affect soil respiration. In this study, soil respiration increased following growth of aboveground vegetation (4.2). It was suggested that thinning may have increased soil respiration temporarily because of increased development of the roots of remaining trees (3.1). It was also suggested that clear-felling may have effects on root respiration in oak stands and cedar stands, respectively. However, in natural ecosystems, effects of root respiration changes on soil respiration are not always observed. In this study, soil respiration rates in the first year after gap formation did not vary significantly inside and outside of the gap in the Japanese cedar forest. Soil respiration rates in oak and cedar clear-felled stands did not differ significantly from the intact oak and cedar stands, though changes in root respiration by clear-felling may vary between the two clear-felled stands. One reason for the lack of variation in soil respiration may be the decomposition of dead roots which increases microbial respiration (4.2, 4.3). Therefore, since changes in aboveground vegetation may affect not only root respiration, but also microbial respiration and microclimate in the soil, effects of aboveground change on soil respiration may be offset in natural forest ecosystems. Therefore, further observation is necessary to determine the extent to which soil respiration changes over longer periods and to investigate changes in soil microbial respiration and root biomass in order to completely understand the relationship between soil respiration and aboveground



vegetation.

Increased atmospheric CO<sub>2</sub> concentrations will have a direct effect on vegetation through the greenhouse effect, which will lead to a warming of the atmosphere and a rise in the temperature of the ground. This will lead to a change in the distribution of the world's climate zones, which will affect the growth of various plants and animals and hence the structure of the vegetation.

The most important problem in soil research is that the physical properties of the soil, such as its water and CO<sub>2</sub> content, will change from the present conditions. Therefore, a possible soil research program will be to study the effects of CO<sub>2</sub> concentration on soil water and CO<sub>2</sub> content, and to study the effects of CO<sub>2</sub> concentration on soil water and CO<sub>2</sub> content.

Soil research is a very important part of the study of the environment. It is important to study the effects of CO<sub>2</sub> concentration on soil water and CO<sub>2</sub> content, and to study the effects of CO<sub>2</sub> concentration on soil water and CO<sub>2</sub> content.

## Summary

Increased information on the fluctuation of soil respiration and factors regulating this fluctuation is critical for understanding ecosystem C budget and potential response to factors such as global warming. However, in forest ecosystems, data on amount, fluctuation and affecting factors of soil respiration is still inadequate because of the difficulty of field measurement and the limitations of measuring systems. Thus, in this study, a portable soil respiration measuring system, which improved the precision of current models was constructed, and factors affecting soil respiration in forest ecosystems were examined.

1) The most important problem in soil respiration measuring systems is that the internal environments of the chambers, such as wind speed and CO<sub>2</sub> concentration, differ greatly from the external environment. Therefore, a portable soil respiration measuring system which capable of regulating temperature, CO<sub>2</sub> concentration, and wind speed in a chamber was developed. The effects of CO<sub>2</sub> concentration and wind speed on soil respiration were investigated. From the results, soil respiration rate decreased with increasing CO<sub>2</sub> concentration, and increased with increasing wind speed.

2) Relationships between soil respiration and 3 environmental factors, wind speed, CO<sub>2</sub> concentration and temperature were examined. The relationship between soil respiration and CO<sub>2</sub> concentration was expressed by a linear equation using slope and intercept including wind speed as a explanatory variable. The relationship between soil respiration and soil surface temperature in



each season was expressed by an exponential equation. Therefore, equations that included temperature, CO<sub>2</sub> concentration and wind speed as explanatory variables were formulated in order to estimate soil respiration.

Diurnal changes in the 3 environmental factors were observed on a *Quercus glauca* forest floor. CO<sub>2</sub> concentration on the forest floor tended to be low in the daytime and high at night and the value was higher than atmospheric concentration. Soil temperature and wind speed tended to be high in the daytime and low at night.

Substituting the natural values of the 3 environmental factors in the equations, the natural fluctuation in soil respiration was estimated. Diurnal changes in soil respiration, ranging from 0~300 mgCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>, were high in the daytime and low at night. Taking chamber methods into consideration, temperature only was substituted in the equations and the other two factors, wind speed and CO<sub>2</sub> concentration, were fixed similar to those of chamber conditions, respectively. As a result, although the fluctuation pattern was similar to natural conditions, estimated values, 40~510 mgCO<sub>2</sub> m<sup>-2</sup> hr<sup>-1</sup>, were about twice as high as those of natural.

3) Seasonal change in soil respiration over three years in thinned and intact sections of a Japanese cedar forest was measured in order to clarify the relationship between soil respiration and environmental factors and to examine the effects of a common silvicultural practice, forest thinning.

Soil respiration ( $R_s$ ) increased in summer and decreased in winter and was significantly correlated with soil surface temperature ( $T_s$ ). The relationship was approximately  $\ln(R_s) = a(T_s) + b$ , where  $a$  and  $b$  are constant values. The  $Q_1$  values were 2.0 and 2.5 in the

thinned and intact sections, respectively. Soil surface  $\text{CO}_2$  concentrations calculated from the soil respiration rates, were higher than ambient atmospheric  $\text{CO}_2$  concentrations, and tended to increase in summer and decrease in winter. Soil respiration rates in the thinned section were significantly higher than those of the intact section in the first and second years of measurement, but, not in the third year, the fifth years after thinning; an indication that thinning may have temporarily increased soil respiration from the forest floor.

4) Seasonal and diurnal change in soil respiration was measured using the portable open-flow soil respiration measuring system on points located in a grid-like pattern on a slope of a Japanese cedar forest in order to examine the spatial and temporal variability of soil respiration.

Distribution of soil respiration changed seasonally at the study site. Maximum part of soil respiration were observed in the center of the study area in spring and spread in a southern direction in summer. In autumn and winter, high and low soil respiration appeared randomly. Coefficient of variation among the measurement spots was 32%~58% and the number of measurements required to estimate soil respiration at this study site was estimated as 50 on average.

Diurnal changes in soil respiration and soil temperature were not clearly observed, while seasonal changes in soil respiration and soil temperature increased in summer and decreased in winter. Soil respiration rates increased exponentially with soil temperature, whereas soil moisture did not have a significant effect.  $Q_{10}$  values, calculated as the changing rate of soil respiration when the temperature increased by 10 °C, were an average of 2.3 in a range from 1.3 to 3.0.



5) Soil respiration from a *Quercus acutissima* and a *Cryptomeria japonica* planting pots were measured in order to estimate contribution of root respiration to total soil respiration and to examine the effect of shoot removal on soil respiration. Soil respiration was measured when the pots were in shoot+root+soil (intact), root+soil (shoot cut) and soil (root removal) condition.

Soil respiration increased proportionally with increasing soil temperature throughout measurement. However, soil respiration decreased gradually throughout the two treatments, shoot cutting and root removal. Soil respiration after shoot cutting (root +soil) was 70 % of intact condition (shoot+root+soil). Assuming that the differences in soil respiration between intact (shoot+root+soil) and root removal (soil) measurement correspond to root respiration, root respiration rate was calculated using the linear relationship between soil respiration and soil temperature. When the temperature of the *Quercus acutissima* pot and the *Cryptomeria japonica* pot was 28°C and 22°C, respectively, contribution of root respiration to total soil respiration was estimated as 45~50%.

6) Soil respiration rates were measured over two years in an artificial gap and in an undisturbed area in a Japanese cedar forest in order to estimate the contribution of root respiration rate to total soil respiration rate.

Seasonal fluctuations in soil respiration, increasing in summer and decreasing in winter, corresponded to changes in soil surface temperature. Soil respiration rates in the gap site were not significantly different from those in the forest in the first year of gap formation. However in the second year, minimum and maximum CO<sub>2</sub> flux were observed at the center of the gap and at the edge of the

surrounding stand, respectively. Assuming that differences in soil respiration rates between the center of the gap and in the forest are equal to root respiration rate, root respiration rate was calculated. Contribution of root respiration rate to total soil respiration rate, estimated from soil surface temperatures in the forest using the equation, was an average of 49% in a range from 40 to 70 %.

7) Soil respiration was measured for 3 years in young red oak and Japanese cedar stands grown from seed and cuttage, respectively, in order to examine the effects of aboveground planting, growing and clear-felling on soil respiration.

Annual soil respiration in the intact plots were not differed from those of control in the first year, but twice and two-and-a-half times higher in the second and third years, respectively. This pattern was similar to yearly growth of  $D^3H$ . Assuming that differences in soil respiration rates from the control plot are equal to root respiration rate in each vegetation plot, root respiration rate was calculated. Mean ratio of root respiration from the oak and cedar intact plot, was 15% and 33%, 50% and 59%, and 55% and 60% in the first, second and third years, respectively.

Soil respiration rates did not differ between intact and clear-felled plots both before and after clear-felling. However, after clear-felling, no sprouts appeared in the cedar felled plot, while 2~6 sprout appeared from every stump in the oak felled plot. Therefore, it was presumed that root respiration still remained in the oak felled plot, while root respiration had ceased and the dead roots decomposed into  $CO_2$  in the cedar felled plot after clear-felling.



## Acknowledgements

I wish to express my profound appreciation to Professor Akira Saito, Professor Morio Imada and Associate Professor Koichiro Gyokusen for their helpful support and constructive comments on this study. I wish to thank the staff of the Forest Research and Instruction Station of Kumamoto Prefecture for their support. I am also thankful to Dr. Shigeyuki Sasaki and the others from the Fukuoka Prefecture Forest Research and Extension Center, the technical officer T. Hosaka and students of the Silvicultural Laboratory of Kyushu University for their assistance and support.

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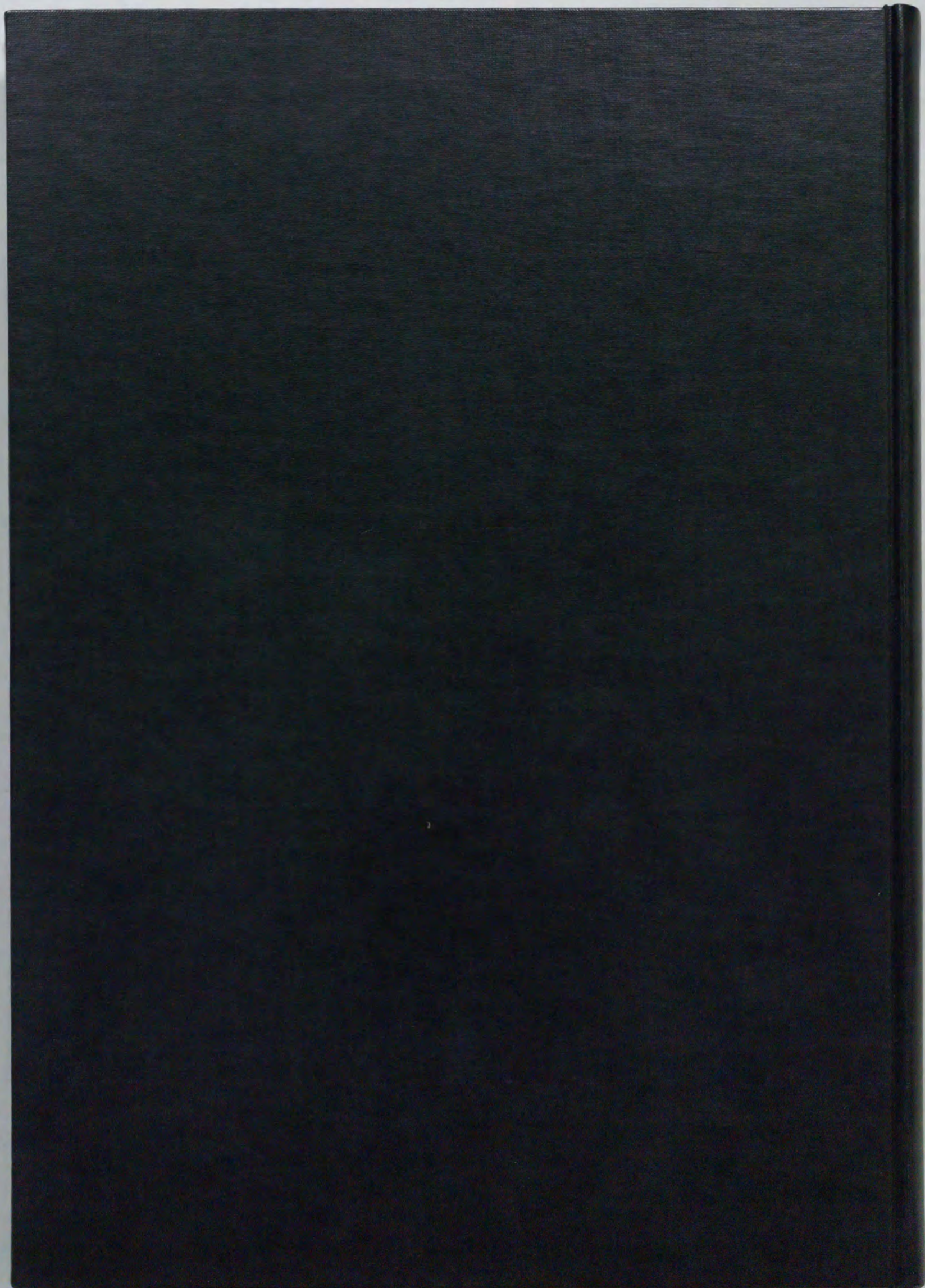


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\* The titles are tentative translation from Japanese titles by the author of this thesis.







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