

Studies on carbon dioxide production and its transport in forest soil
森林土壌内における CO₂ ガスの発生と輸送に関する研究

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Contents

1	Introduction	4
1.1	General background/Climate change and soil carbon	4
1.1.1	Climate change and soil carbon	4
1.1.2	Forest carbon cycle and climate change	5
1.2	Soil respiration	6
1.2.1	What is soil respiration? What controls soil respiration?	6
1.2.2	History of soil respiration studies	6
1.2.3	Methods measuring soil respiration	6
1.2.4	Approaches to soil respiration	6
1.2.5	Modeling of soil respiration	8
1.3	The lack of considering the vertical processes	8
1.4	Gas diffusivity	11
1.4.1	Gas movement and gas diffusivity	11
1.4.2	Previous methods	11
1.4.3	A new system	11
1.5	Objectives of this study	11
2	A new apparatus for measuring the gas diffusion coefficient in sand soil	13
2.1	Introduction	13
2.2	Material and Method	14
2.2.1	Theory	14
2.2.2	Apparatus and Experimental Method	14
2.2.3	A simple technique to analyze a small volume of soil CO ₂ gas using an infrared gas analyzer	16
2.3	Results and Discussion	17
2.3.1	Measurements	17
2.3.2	The relationships between soil water suction and D_s/D_0	20
2.4	Conclusions	21
3	Vertical distributions of carbon dioxide diffusion coefficients and production rates in forest soil	22
3.1	Introduction	22
3.2	Materials and Methods	23
3.2.1	Theory	23
3.2.2	Apparatus	25
3.2.3	The dependence of soil CO ₂ production rate on soil temperature	27
3.2.4	Soil material and soil water retention curve	27
3.3	Results and Discussion	28
3.3.1	Measurements	28

3.3.2	Comparison with empirical model	29
3.3.3	The dependence of soil CO ₂ production rate on soil temperature	30
3.3.4	Simulation of unsteady CO ₂ profiles and surface flux	30
3.4	Conclusions	31
4	Experiment in Thailand/Soil respiration properties in tropical forest in Thailand	35
4.1	Introduction	35
4.2	Material and Method	36
4.2.1	Site description	36
4.2.2	Sampling	37
4.2.3	Incubation system	38
4.2.4	Incubation	38
4.2.5	Vertical distribution of the gas diffusion coefficient and the CO ₂ production rate	39
4.3	Results	39
4.3.1	Incubation	39
4.3.2	Temperature sensitivity	39
4.3.3	Vertical distribution of gas diffusion coefficient and CO ₂ production rate	42
4.3.4	Influence of incubation	45
4.3.5	The relationships between soil properties and CO ₂ production rate	45
4.4	Discussion	46
4.4.1	Temperature sensitivity	46
4.4.2	Unsteady temperature sensitivity	47
4.4.3	The vertical distributions of CO ₂ production rate and gas diffusivity	47
4.4.4	The relationships between soil properties and soil CO ₂ production	48
4.4.5	Q ₁₀ value	48
4.4.6	Environmental control limitation of this apparatus and its effect	48
4.5	Conclusions	49
5	Direct measurements of CO₂ production in each depth	50
5.1	Introduction	50
5.2	Material and Method	51
5.2.1	Sites	51
5.2.2	Field measurements	51
5.2.3	Theory of direct measurements	55
5.3	Results	57
5.3.1	Fukuroyamasawa watershed	57
5.3.2	Kog-Ma watershed	61
5.4	Discussion	61
5.4.1	Interpretation	61
5.4.2	Comparison between Fukuroyamasawa watershed and Kog-Ma watershed	65
5.4.3	Comparison with other studies	67
5.4.4	Evaluation the gas diffusion coefficient	67
5.5	Conclusions	67
6	Modeling of CO₂ production and transport in soil	68
6.1	Introduction	68
6.2	Material and Method	69
6.2.1	Model description	69
6.2.2	Gas movement and mass balance	71
6.2.3	Gas diffusivity	71

6.2.4	CO ₂ production	72
6.2.5	Data	72
6.2.6	Running conditions	72
6.3	Sensitivity analysis	73
6.3.1	Production rate	73
6.3.2	Maximum porosity	75
6.3.3	Soil temperature and water conditions	77
6.3.4	The gas diffusion coefficient at soil surface	79
6.4	Results and Discussion	81
6.4.1	Temperate forest	81
6.4.2	Tropical forest	83
6.4.3	Interannual changes	85
6.4.4	Future developments	86
6.5	Conclusions	87
6.6	List of symbols	87
7	Summary and Conclusions	91
8	Acknowledgements	93
9	References	94
A	The Crank-Nicholson implicit method	103
B	Homepages	104

List of Figures

1.1	The history of studies on soil respiration. The background, methods, observation purpose, and models.	7
1.2	A conceptual diagram of soil respiration, which ignores its complex processes.	9
1.3	A conceptual diagram of soil respiration, which considers real processes.	9
1.4	A simple model which explains the relationship between a seasonality of soil temperature and soil respiration.	10
2.1	Diagram of the diffusion system.	15
2.2	Procedure of analyzing the gas in small volumes.	16
2.3	Comparison between standards and measured CO ₂ concentration.	18
2.4	Measured CO ₂ profiles at various temperature. Open circle: first measurement, open diamond: second measurement, open squares: third measurement	18
2.5	Soil water suction, CO ₂ gas distribution under a steady state, and calculated D_s/D_0 under two different soil water conditions (condition A, condition B). Open triangle: measured at time 1 in Fig. 2.6. Open triangle: measured at time 2. Open square: measured at time3.	19
2.6	Results of measurements made under conditions A and B. The change in the CO ₂ flux with time is measured above the soil surface.	20
2.7	Relationship between suction and relative gas diffusion coefficient (D_s/D_0 . Open square, layer 1 (9.5- 19.5 cm depth): open circle, layer 2 (19.5-29.5 cm depth); open diamond, layer 3 (29.5-39.5 cm); open triangle, layer 4 (39.5-49.5 cm).	21
3.1	Model for the measuring system.	24
3.2	Schematic diagram of (A) the measuring system, (B) the system for controlling soil water, and (C) the system for controlling soil temperature.	25
3.3	Schematic diagram of the boundary control.	26
3.4	Average suction profiles for wetter conditions (condition WT) and drier conditions (condition DR) (A1, B1) and the measured CO ₂ profiles used to determine the gas diffusion coefficients (A2, B2) and the obtained gas diffusion coefficients (A3, B3). The CO ₂ fluxes were calculated at each depth from the CO ₂ profile and the gas diffusion coefficient (A4, B4). The CO ₂ production rate in a certain layer is the difference between the flux of inflow and outflow (A5, B5). The CO ₂ profiles were measured at 0-, 10-, 20-, 30-, and 40-cm depths. I used the average values between these depths.	28
3.5	Comparison of the gas diffusion coefficient values measured in this study and values calculated from the Millington-Quirk model and new Moldrup models. Open and solid circles: 10 cm; diamonds: 20 cm, triangles: 30 cm. Open symbols are values under wetter conditions (condition WT), and solid symbols are values under drier conditions (condition DR).	30
3.6	Soil surface flux (total CO ₂ production) versus average soil temperature. The dependence of soil CO ₂ production on soil temperature. Soil temperature is the average temperature of 10, 20, 30 cm depth.	31

3.7	The relationships between soil depth and air porosity, the relative gas diffusion coefficient, and CO ₂ production rate.	32
3.8	The relationship between soil temperature and the CO ₂ production rate. These relationships were approximated as linear equations.	32
3.9	The change in soil temperature (A), and a comparison between simulated and measured CO ₂ flux from the soil surface (B) and comparison of soil CO ₂ profiles (C). The lines are the simulated values.	33
4.1	Location of Kog-Ma watershed.	36
4.2	Soil, air, and CTP's temperature; soil water content; matric potential during the incubation period. Also, CO ₂ flux measured at soil surface, which was the total CO ₂ production from the soil sample, and CO ₂ concentration at each depth in soil sample.	40
4.3	The temperature dependence of soil surface flux (total CO ₂ production from the soil sample). Soil temperature near the surface was affected by the air temperature, although soil temperatures below the depth were almost the same. Then, I used average soil temperatures.	41
4.4	Unsteady change of soil temperature, and unsteady response of soil surface flux and CO ₂ concentration in soil sample which were induced by the change of soil temperature. Temperature was changed suddenly when it was in steady state. See the Fig. 4.2caption for explanation of symbols.	43
4.5	Vertical distributions of soil CO ₂ concentration used for calculating vertical profiles of soil gas diffusion coefficients and CO ₂ production rates, and obtained profiles. Measurements were conducted at 20 °C	44
4.6	The relationship between air porosity and relative gas diffusion coefficient. Circle: 0.1 m depth; diamond: 0.2 m depth; square: 0.3 m depth. Solid lines are empirical models.	44
4.7	Soil surface flux (total CO ₂ production of soil sample) during the experimental period, and flux normalized by the exponential relationships between soil temperature and soil surface flux in Fig. 4.3.	45
4.8	The relationships between soil CO ₂ production rate on volumetric basis and soil properties (the ratio of organic matter in small particle, the amount of organic matter in small particle, and C/N ratio). Both are the results at about 20 °C	46
4.9	The relationships between soil CO ₂ production rate on gravimetric basis and soil properties.	47
5.1	Locations of two watersheds.	52
5.2	Seasonality of air temperature and rainfall in Fukuroyamasawa watershed.	53
5.3	Seasonality of air temperature and rainfall in Kog-Ma watershed (Chunkao et al. 1981).	53
5.4	Diagram of model used for evaluating CO ₂ production rate at each depth in Fukuroyamasawa watershed. F_i is the soil CO ₂ flux, D_i is the gas diffusion coefficient, dC_i/dz_i is the gradient of soil CO ₂ gas concentration, and $Y_i\Delta z_i$ is the CO ₂ production rate.	56
5.5	Diagram of model used for evaluating CO ₂ production rate at each depth in Kog-Ma watershed. See the Fig. 5.4caption for explanation of symbols.	56
5.6	Seasonal variation of soil respiration, soil temperature, soil water content, gas diffusion coefficient, CO ₂ concentration, CO ₂ flux at each depth, and CO ₂ production rate at each depth in Fukuroyamasawa watershed.	58
5.7	The relationships between soil respiration (soil surface CO ₂ flux) and soil temperature.	59
5.8	Seasonal variations in contributions of each depth to CO ₂ production.	60
5.9	Seasonal temperature dependence of soil CO ₂ production at each depth.	60
5.10	Seasonal variation of soil respiration, soil temperature, soil water content, gas diffusion coefficient, CO ₂ concentration, CO ₂ flux at each depth, and CO ₂ production rate at each depth in Kog-Ma watershed.	62
5.11	The relationships between soil respiration and soil water content.	63
5.12	Seasonal variations in contributions of each depth to CO ₂ production.	63

5.13	The relationships between CO ₂ production rate and degree of saturation. Degree of saturation was the ratio of soil water content to saturated soil water content. I separate into two (1998-1999 and 2000-2001) because the CO ₂ production at shallowest layer was different between the two intervals. Vertical scales are different between shallowest depth and other depths.	64
5.14	An explanatory diagram showing the different performances among layers in rainy and dry season. To clarity, plotted values are not observed data.	66
6.1	Diagram of CO ₂ production and transport model.	70
6.2	Sensitivity analysis: assumed various vertical profiles of CO ₂ production rate, and simulated CO ₂ gas concentration profile and CO ₂ flux.	74
6.3	Sensitivity analysis: given vertical profiles of soil air, water, solid content, and simulated CO ₂ gas concentration profile and CO ₂ flux.	76
6.4	Sensitivity analysis: given vertical profiles of soil water or soil temperature, and simulated CO ₂ gas concentration profile and CO ₂ flux.	78
6.5	Sensitivity analysis: simulated CO ₂ gas concentration profile and CO ₂ flux with different soil surface gas diffusivities.	80
6.6	Simulated soil surface CO ₂ flux, CO ₂ concentration at each depth in Fukuroyamasawa watershed.	82
6.7	Vertical distributions of CO ₂ gas concentration, measured (marks) and simulated (lines) in Fukuroyamasawa watershed.	83
6.8	Simulated soil surface CO ₂ flux, CO ₂ concentration at each depth in Kog-Ma watershed.	84
6.9	Vertical distributions of CO ₂ gas concentration, measured (marks) and simulated (lines) in Kog-Ma watershed.	85

List of Tables

3.1	Site location, climate, and soil properties. The layer 0-10cm contained the A ₀ layer.	27
3.2	Measured CO ₂ flux from the upper and lower surface, and the sum of them.(kg m ⁻² s ⁻¹ , the number of measurements and standard error in parenthesis)	29
4.1	Site location, climate, and soil properties in Kog-Ma watershed.	37
5.1	Comparison in location, climate, vegetation, and observations. See the locations in Fig. 5.1. . . .	54
5.2	The fitted parameters of the relationships between soil respiration, and soil temperature and soil water content. In Fukuroyamasawa watershed, the function is $y = Ae^{kT}$, where y is the soil respiration and T is the soil temperature at 0.1 m depth. In Kog-Ma watershed, the relationship is the $y = A(l\theta + m)(\phi T^p)$, where θ is the soil water content at 0.1 m depth and T is the soil temperature at 0.1 m depth.	57
6.1	Sensitivity analyses conducted in this study. Production rate, maximum air porosity, soil temperature and soil water content, and soil surface gas diffusivity were changed.	73
6.2	Parameters in the simulation of Fukuroyamaswa watershed.	89
6.3	Parameters used in the simulation of Kog-Ma watershed.	90

Chapter 1

Introduction

1.1 General background/Climate change and soil carbon

1.1.1 Climate change and soil carbon

Climate change is without doubt the most concern of mankind (IPCC, 1995; IPCC HP). IPCC estimates that the global temperature will rise, the precipitation will increase, and also the extreme events will occur more often. Sometimes the global warming is discussed alone; however, change in precipitation and the increase of extreme events are also critical.

Climate change has been induced by greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These gases have been released by human activities, such as fossil fuel consumptions, deforestation, particularly since the industrial revolution (eg. IPCC HP; Tans et al. 1990; Houghton and Hackler, 1999; Andres et al. 1999). Not only researchers but also politicians, citizens are now tackling decreasing the release of greenhouse gases in various ways (eg. IPCC HP; WWF HP; Japanese Forest Agency HP; United Nations, Framework convention on climate change HP; International Energy Agency, experience curves for energy technology HP; Bolin, 1998; IGBP Terrestrial carbon working group, 1998; Reilly et al. 1999; Schulze et al. 2000, 2003; De Leo et al. 2001; Manne and Richels, 2001; O'Neill and Oppenheimer, 2002).

Soil is the largest pool of terrestrial carbon (IPCC HP). Post et al. (1982) estimated global soil organic carbon pool at 1395×10^{15} gC. The value estimated by Eswaran et al. (1993) was about 1576×10^{15} gC. The study pointed out the large contribution of soils of the tropics. In respect of forest, Dixon et al. (1994) estimated forest vegetation and soils contain about 1146×10^{15} gC and 49 percent at high latitudes.

These values are more than twice the amount of carbon in the atmosphere. If even a small fraction of carbon in soil is released to atmosphere, it would significantly affects global warming (e.g. Jenkinson et al. 1991; Sundquist, 1993; Houghton and Hackler, 1999).

Carbon is released from soil through various forms such as CO_2 and CH_4 ; however, the most major form is CO_2 . The release of CO_2 from soil is called soil respiration. Soil respiration is a phenomenon that carbon dioxide which was produced by organic matter decomposition or root respiration is emitted from soil surface. It is known that soil respiration increases with increasing temperature, and then the response of soil respiration to global warming is concerned. Raich and Schlesinger (1992) reviewed measured rates of soil respiration and estimated the annual global CO_2 flux from soil at 68.4×10^{15} gC. Raich et al. (2002) used a climate-driven regression model and estimated soil- CO_2 emissions from the terrestrial land surface from January 1980 to December 1994. The estimate was about 80.4×10^{15} gC.

1.1.2 Forest carbon cycle and climate change

Forest is the major vegetation that contains a lot of carbon, and then how forest changes with climate changes is a big issue (Malhi et al. 1999). Carbon cycle in forest is complex (e.g Landsberg and Gower, 1997; Komatsu and Hashimoto, 2002). Forest includes soil and plant. Plant absorbs CO₂ through photosynthesis, and supplies organic matter to soil. Soil releases CO₂ produced by organic matter decomposition and root respiration. Forest plant also affects environments in forest, like temperature and water, which controls organic matter decomposition and root respiration (Liechty et al. 1992; Chen et al. 1993, 1999; Carlson and Groot, 1997; Morecroft et al. 1998; Potter et al. 2001a; Hashimoto and Suzuki, 2004).

Considering these cycles, I can consider some possible scenarios of each flow. Possible high CO₂ concentration and temperature may increase plant CO₂ absorptions (Kirschbaum, 1999b; Nemani et al. 2003). Possible high plant growth may increase the amount of carbon which is provided to soil. Possible increase of precipitation may increase plant growth and litter fall. On the other hand, possible high plant growth may lead to nutrient limitation. Moreover, possible increase of extreme climatic event may decrease plant growth.

Climate change also affects below ground processes. Possible high temperature may raise soil respiration, that is to say, releases of CO₂ to atmosphere (Kirschbaum, 1999b). Possible high decomposition may result in stimulating plant growth. Possible increase of precipitation may increase organic matter decomposition. On the other hand, possible extreme events may conversely inhibit the decomposition because it will cause too wet, dry or hot conditions.

Although these scenarios of each flows can be expected, the changes of the carbon budget of forest ecosystem is difficult to be answered. So far, some researches expect that global warming accelerates soil respiration more than other flows and increases the carbon release from forest ecosystems. Many researchers are now investigating how forest ecosystems, especially soil respiration, respond to global warming (Sundquist, 1993; Jones et al. 1998; Borken et al. 1999; Dixon et al. 1999; White et al. 1999).

Boreal forest is considered to be a key ecosystem to climate change (Oechel et al. 1993; Dixon et al. 1994). The boreal forest has relatively low temperature, which restrains organic matter decompositions. As a result, the boreal forest soil contains a lot of organic matter than other ecosystems. The organic matter would release much carbon responding to global warming. Moreover, the degrees of temperature rises are expected to be different among regions. The boreal forest (high latitude) would experience much more increase than the low latitudes (IPCC HP; Sellers et al. 1997). Many researchers investigate the carbon cycle of boreal forest and its responses to climate change (Baldocchi and Meyers, 1991; Bonan, 1991; Baldocchi and Vogel, 1996, 1997; Baldocchi et al. 1997; Lafleur et al. 1997; McCaughey et al. 1997; Suyker et al. 1997; Winston et al. 1997; Cienciala et al. 1998; Rayment and Jarvis, 2000; Kellomaki and Wang, 2000; Morén and Lindroth, 2000; Barr et al. 2002; Hirsch et al. 2002; Pypker and Fredeen, 2002).

However, tropical forest is also considered to be a very important ecosystem which affects climate changes. Townsend and Vitousek (1992) pointed out that tropical forests could dominate the short-term carbon cycle feedbacks to increased global temperatures because they have high sensitive to small changes in temperature. Also, Trumbore et al. (1996) showed the possibility of tropical regions' domination; tropical forest would respond more quickly and largely to a warming, even in case of relatively small changes.

Boreal and tropical forests are globally very concerned; however, temperate forests are significantly of interest as well. Under the Kyoto protocol, researchers in each country are now requested to evaluating carbon cycle in forests of each country (Schulze et al. 2000). In Japan, a temperate forest is the most major forest ecosystem, and then more studies on carbon cycle in temperate forest (both artificial and natural forest) are needed (Nakane, 1995; Ohashi et al. 1999, 2000).

1.2 Soil respiration

1.2.1 What is soil respiration? What controls soil respiration?

Let me explain what soil respiration is. As mentioned above, soil respiration is a phenomenon that carbon dioxide which was produced by organic matter decomposition or root respiration is emitted from soil surface. There are many factors that influence soil respiration, such as temperature and water (Wiant, 1967; Nyhan, 1976; Orchard and Cook, 1983; Glinski and Stepniewski, 1983; Schlentner and Van Cleve, 1984; Coxson and Parkinson, 1987; Naganawa et al. 1989; Howard and Howard, 1993; Bowden et al. 1998; Leiros et al. 1999; Fierer and Schimel, 2002), quality and quantity of organic matter (Franzluebbers et al. 2000), micro fauna (Wang et al. 2003), macro fauna (Binet et al. 1998), CO₂ or O₂ concentration (Luxmoore et al. 1970; Armstrong and Gaynard, 1976; Santruckova and Simek, 1997; Boone et al. 1998), vegetation, and so on. However, as numerous studies have shown, temperature and soil moisture are two major factors. Soil respiration is affected by temperature and soil moisture more strongly than by any other factors. In general, soil respiration increases with temperature and varies parabolically with soil moisture (Howard and Howard, 1993; Bowden et al. 1998). Soil respiration drops at too high temperature (Wiant, 1967; Nyhan, 1976). In most field studies, temperature is a main controller of soil respiration; however, there are some reports that soil water determined the seasonality of soil respiration or played important roles in a certain season. Although temperature and soil water are the main controllers of soil respiration, how and when each factor affects soil respiration differ among ecosystems or climates. Measuring soil respiration at each ecosystem is then very important.

There are several good introductions of soil respiration, which are the papers based on a symposium on "Controls on soil respiration: Implications for Climate Change", which was held at the annual meetings of the Soil Science Society of America in 1997 (eg. Hanson et al. 2000; Raich and Tufekcioglu, 2000; Rustad et al. 2000; Schlesinger and Andrews, 2000). Then, I still explain the history and the methodology of soil respiration below.

1.2.2 History of soil respiration studies

Soil respiration has been investigated from early 20th century. Gainey (1919) is one of the earliest studies of soil respiration. Lundegardh (1927) 's study is also an older one. Figure 1.1 shows the history of soil respiration studies last several decades. Soil respiration has been investigated by ecologists until early 1980's, with respect to ecology in forest and carbon cycle in forest. Soil respiration was started to be increasingly studied by many researchers from late 1980's, as global warming which is caused by greenhouse gases became a big issue.

1.2.3 Methods measuring soil respiration

Until late 1980's, the main method used was alkali absorption method with a closed chamber, which was set on the soil surface. As many researchers studied soil respiration, many kinds of methods of measuring soil respiration were proposed and used. Combinations are mainly about chambers and CO₂ detector. There are two types of chambers, open and closed, which CO₂ diffuses into. Then, there are roughly three types of CO₂ detectors, alkali absorption, a gas chromatograph and IRGA. In addition, SAT and IRGA were used in some studies. As many studies which compared these methods pointed out (eg. Freijer and Bouten, 1991; Norman et al. 1997; Davidson et al. 2002a-b; Yim et al. 2002), there are probably differences among these methods. So far, which method is best is not clear.

1.2.4 Approaches to soil respiration

Approaches to soil respiration are roughly classified into two types (Glinski and Stepniewski, 1983): laboratory core incubations (Soulides and Allison, 1961; Wiant, 1967; Orchard and Cook, 1983; Howard and Howard, 1993; Goncalves and Carlyle, 1994; Pohhacker and Zech, 1995; Bowden et al. 1998; Lomander et al. 1998; Scanlon

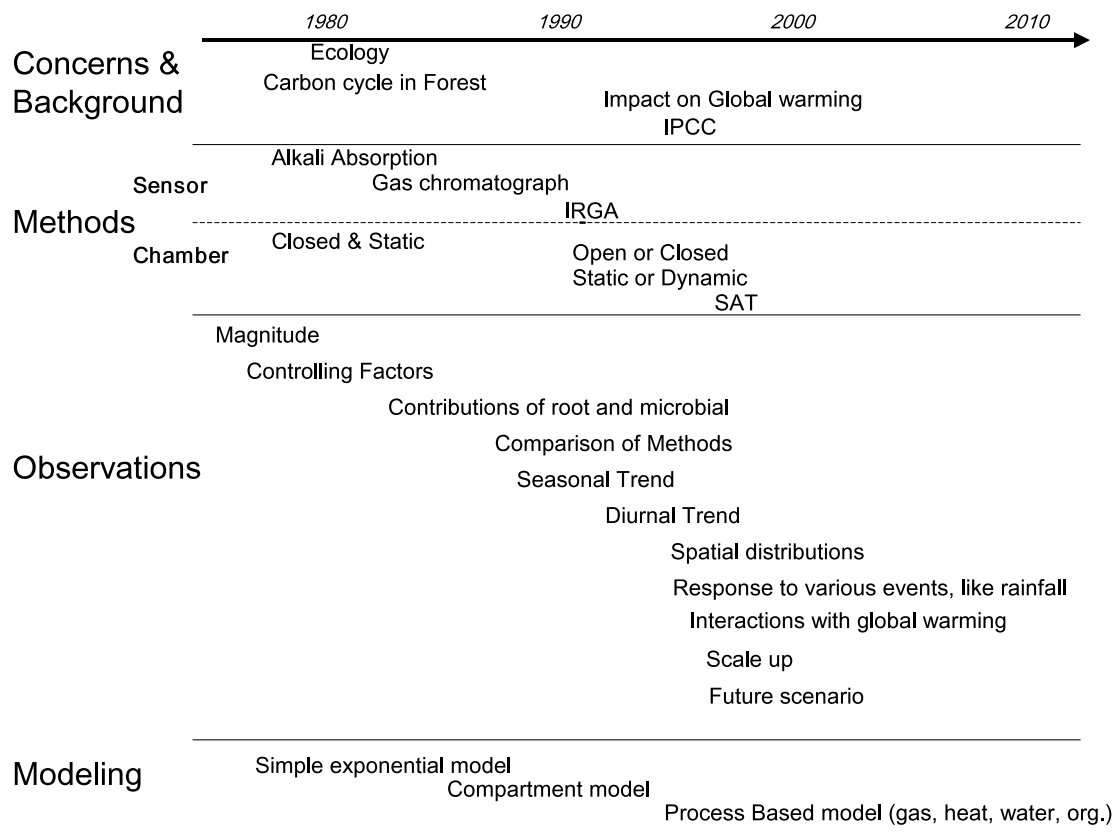


Figure 1.1: The history of studies on soil respiration. The background, methods, observation purpose, and models.

and Moore, 2000; Dalias et al. 2001a-b; Fierer and Schimel, 2002) and field observations (Nakane et al. 1983; Schlentner and Van Cleve, 1984; Keller et al. 1986; Hanson et al. 1993; Fernandez et al. 1993; Davidson and Trumbore, 1995; Davidson et al. 1998, 2000; Fang et al. 1998; Janssens and Barigah, 1998; Ohashi et al. 1999; Leiros et al. 1999; Rayment and Jarvis, 2000; Morén and Lindroth, 2000; Ishizuka et al. 2002). The laboratory core approach has the advantage of being able to measure the soil CO₂ production at each depth at various temperature and water conditions, but has the disadvantage of disturbing the soil system. The field observation approach, that is to say measuring the efflux from soil surface, has the advantage of being able to measure the soil CO₂ production without altering the soil; however, the vertical profile of the CO₂ production rate cannot be measured, and environmental conditions, such as soil temperature and soil water, cannot be controlled, so there are too many factors to consider.

1.2.5 Modeling of soil respiration

Modeling soil respiration is very important both to understand the mechanism of soil respiration and to predict the impact of and also to global warming. There are two kinds of models: compartment models and process based models. The compartment model is often, inversely, called process based model. The compartment model has various compartments of elements, and flows among compartments are controlled by environmental conditions (Foley, 1995; Tiktak and van Grinsven, 1995; Kimball et al. 1997; Hingston and Galbraith, 1998; Hingston et al. 1998; Chiba, 1998; Bergh et al. 1998; Kirschbaum, 1999a-b; Makela et al. 2000; Potter et al. 2001b). Century model (Parton et al. 1987, 1988; Townsend et al. 1995; Krishna et al. 2001; Kirschbaum and Paul, 2002; Wang et al. 2002) is one of major compartment models. This model includes carbon cycle, nitrogen cycle and water cycle, and can evaluate the interaction among them. CO₂ from organic matter decomposition is one of outputs that are calculated in these models. Biome-BGC (Running, 1994) is a model which is widely used.

The process based model calculates CO₂(carbon) gas production and its transfer in soil (Simunek and Suarez, 1993; Suarez and Simunek, 1993; Kumagai, 1998; Moncrieff and Fang, 1999; Hendry et al. 1999; Fang and Moncrieff, 1999). CO₂ is produced at each soil depth in response to soil temperature, soil water, and soil CO₂ concentration and is transported by mainly diffusion.

1.3 The lack of considering the vertical processes

Soil respiration is often dealt as if a homogeneous material is stimulated by homogeneous environments and produces CO₂ (Fig. 1.2). Nevertheless, the way of thinking would lead misunderstandings, and is very dangerous.

Considering the vertical process of soil respiration is required to understanding soil respiration correctly. Figure 1.3 shows the practical way of considering soil respiration. Potential which can produce CO₂ in response to the environment, that is to say roots and decomposable organic matter, distributes horizontally and heterogeneous. Environment conditions like temperature and water also differ at each depth. CO₂ is produced at each depth, in response to both potential and environments, and CO₂ produced at each depth is transferred, forms CO₂ profiles. CO₂ transferred to soil surface is observed as soil respiration. In short, it is important to consider that potential distribute horizontally, and environments conditions differ horizontally as well.

For example, some observation studies show the importance. Elberling and Brandt (2003) found that deep soil thawing and freezing affect soil respiration measured at soil surface in an arctic heath. Hirsch et al. (2002) measured deep soil respiration in a boreal forest soil and found that deep soil respiration varied linearly with 50 cm temperature. A hysteresis of diurnal soil respiration was reported by Janssens and Barigah et al. (1998), that is, from morning to noon and noon to night. The relationships between soil respiration and temperature were different between temperature rising process and decreasing process. This hysteresis should be explained by considering the vertical process. The time lag of temperature changes at depths and of CO₂ transfer probably caused the hysteresis.

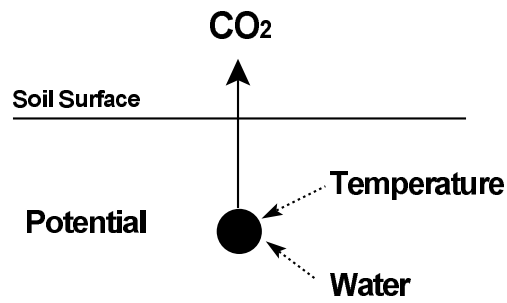


Figure 1.2: A conceptual diagram of soil respiration, which ignores its complex processes.

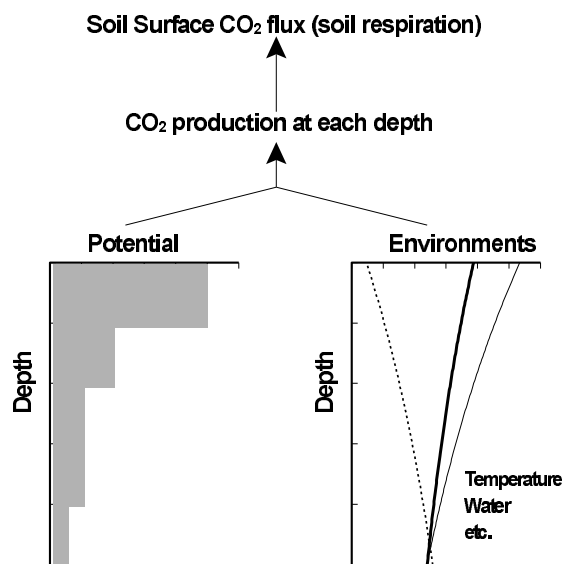


Figure 1.3: A conceptual diagram of soil respiration, which considers real processes.

Moreover, the lack of considering the vertical processes should cause more difficulties in discussing Q_{10} value. Q_{10} is the factor by which soil respiration rate increased when temperature increased by $10\text{ }^{\circ}\text{C}$. This index is widely used when you compare and discuss the temperature sensitivity of soil respiration. Raich and Schlesinger (1992) compiled a lot of field observation studies and shows that Q_{10} value was ranged from 1 to 6, and 2.5 on average. Let's consider calculating Q_{10} by seasonal field observation data of soil respiration and soil temperature. The point is that which depth of temperatures you compare with soil respiration will change Q_{10} value. The annual range of soil temperature, generally, decreases with increases depth (Hillel, 1980a-b). Even though soil respiration observed is the same, the temperature used to compare has a different range. As a result, Q_{10} value would be larger as the depth of temperature used is deeper. If a deeper depth is used, soil respiration at the site could be considered more sensitive to temperature. On the other hand, if a shallower depth is adopted, the soil respiration could be thought to be less sensitive to temperature. Thus, comparing Q_{10} values of field observation is very difficult.

The lack of considering the vertical processes probably causes errors when you predict the response of soil respiration to global warming. Considering the vertical process is probably essential for us to predict the response of soil respiration to global warming. Larger amplitude of temperature will result in larger soil respiration, even when an average soil temperature is the same, because soil respiration increases with increasing temperature exponentially. To be clarified, let's assume the three simple seasonality (Fig. 1.3).

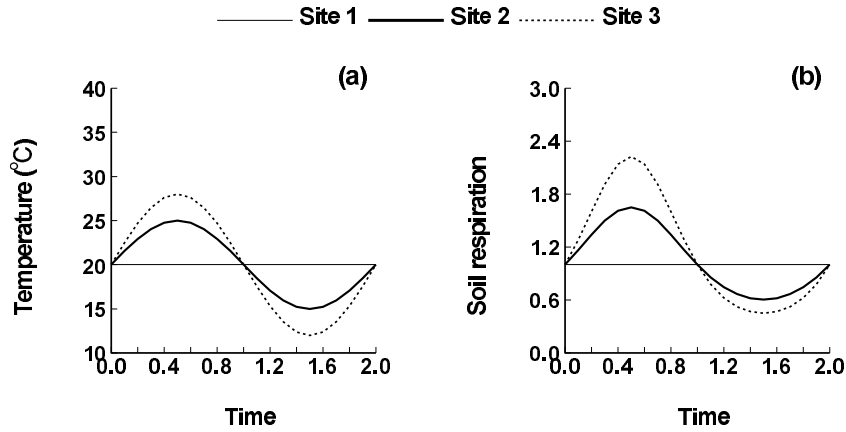


Figure 1.4: A simple model which explains the relationship between a seasonality of soil temperature and soil respiration.

The annual temperature is $20\text{ }^{\circ}\text{C}$ in each site. In site1, there is no seasonality, and the amplitude is $0\text{ }^{\circ}\text{C}$. In site2, there is sine-curve seasonality with $10\text{ }^{\circ}\text{C}$ amplitude, and in site3, a sine-curve seasonality with $16\text{ }^{\circ}\text{C}$ amplitude. Assuming that the relationship between soil respiration and temperature can be described as $y = e^{0.1(T-20)}$ in every site, the seasonality of soil respiration is as Fig. 1.4. Due to the exponential response of soil respiration to temperature, larger amplitude results in larger soil respiration. In this case, annual soil respiration in site 2 is larger than in site 1 by 6 %, and that in site 3 is by 16 %.

Thus, the range of soil temperature affects the soil respiration. And as mentioned above, the ranges of soil temperature differ among depths. Therefore, considering the vertical process would improve the accuracy of predictions of responses of soil respiration to global warming.

1.4 Gas diffusivity

1.4.1 Gas movement and gas diffusivity

Gas diffusion coefficient is the most important soil physical property for analyzing CO₂ gas movement in soil. Emissions of CO₂ from soil are the results of CO₂ produced in the soil and transported to the surface. Transport of CO₂ is mainly by gas diffusion and mass flow; when the difference in pressure is small, gas diffusion dominates mass flow. Identifying the gas diffusion coefficients of a soil is essential for analyzing and modeling gas diffusion in the soil as hydraulic conductivity is important for analysis of water flow (Kosugi, 1997a-b; Kosugi et al. 2001). There is a close correlation between gas diffusion and water flow. Gas diffusion occurs in non water-filled pores, and water movement occurs in water-filled pores. Larger empty pores enhance gas diffusivity and drop water flow, and vice versa.

1.4.2 Previous methods

Traditionally, gas diffusion coefficients have been evaluated in the laboratory, using non-steady-state methods and small soil cores (Reible and Shair, 1982; Shimamura, 1992; Xu et al. 1992; Washington et al. 1994; Freijer, 1994; Moldrup et al. 1996a). Such methods are suitable for handling large numbers of samples, and allow control of soil-water conditions. Methods using larger, undisturbed soil samples, or *in situ* testing, have been proposed (Lai et al. 1976; Rolston et al. 1991; van Bochove et al. 1998; Hashimoto and Suzuki, 2000), but none allows control of environmental factors, especially water conditions.

1.4.3 A new system

A new system then should meet requirements as follows:

a new system can

1. handle samples larger enough to take into account the heterogeneity of soil.
2. easily vary the environments (soil temperature and soil water).
3. measure not only gas movement but also gas production.

1.5 Objectives of this study

I approach soil respiration from a viewpoint which takes the vertical processes of soil respiration into consideration. The objectives of this study are (1) develop a new method for evaluating vertical profiles of CO₂ gas diffusivity and CO₂ production rate in soil sample, (2) examine the property of soil respiration of a temperate coniferous forest and a tropical evergreen forest using the new method, (3) measuring the CO₂ production rate at each depth through field observation data, (4) develop a process based model which simulates the CO₂ producing process and its transport process with results derived from the experiments, and apply the model to a temperate coniferous forest and a tropical evergreen forest.

In Chapter 2, a new apparatus for measuring gas diffusion coefficients in sandy soil was proposed. I measured a relationship between gas diffusion coefficients and soil water suction in sandy soil sample. Before handling forest soil sample, I tried in a more simple condition.

Chapter 3 developed a new system for measuring vertical distributions of CO₂ diffusion coefficients and CO₂ production rate in forest soil sample. The system is able to handle large, undisturbed soil sample and to control soil temperature and soil water.

Chapter 4 shows the soil respiration properties of a tropical evergreen forest in Thailand which was measured using a new apparatus developed in chapter 3.

Chapter 5 presents in situ analysis of CO_2 concentration and soil surface flux, measuring CO_2 production rate at each depth using field observation data.

Chapter 6 develops a model which simulates CO_2 concentration in soil and soil surface CO_2 flux with the results obtained in previous chapters.

I conclude this paper in Chapter 7.

Chapter 2

A new apparatus for measuring the gas diffusion coefficient in sand soil

2.1 Introduction

Knowledge of the gas diffusion coefficient in forest soil is necessary for analyzing water evaporation, the movement of pollutants, and various gaseous environments in soil.

Forest soils are much more heterogeneous than other soils. To measure the soil physical properties that typify the soil physical properties of each soil layer, a larger sample size is preferable (Ohte et al. 1989; Ohte and Suzuki, 1990).

The gas diffusion coefficient changes with air porosity and soil water content, which in turn is affected by the soil water suction. The relationship between the gas diffusion coefficient and soil water suction is necessary data for various simulations (i.e. water evaporation or CO₂ evolution above the soil surface).

Diffusion experiments involving readily soluble gases, such as CO₂, require an instrument that evaluates the diffusion under steady state conditions. Various instruments can measure gas diffusion coefficients in soil. In general, laboratory instruments usually measure gas diffusion coefficients using small samples at a non-steady state. For example, typical sample sizes are 7.6×5 -15 cm (diameter \times length) (Ball, 1981), 5×10 cm (Freijer, 1994), 7.6×7.6 cm (Xu et al. 1992), and 6.7×10 cm (Washington et al. 1994). Although some instruments have been developed that evaluate gas diffusion without removing soil from its natural location and without altering it (Rolston et al. 1991), a laboratory method of evaluating gas diffusion using less disturbed soil samples is also needed for experiments with gas diffusion under various conditions. To do this, any new gas diffusion apparatus should: (1) handle samples large enough to take into account the heterogeneity of soil, but not so large that it is difficult to transport an undisturbed soil sample from its natural site to the laboratory, (2) estimate the relationship between the gas diffusion coefficient and suction, (3) easily vary the soil water content, and (4) evaluate the gas diffusion coefficient after establishing a steady state gas concentration. The purpose of this study was to develop a new apparatus that satisfies these requirements for measuring gas diffusion coefficients in soil. I also proposed a new simple technique to analyze a small volume of soil CO₂ gas using an infrared gas analyzer. Accurate measurement of soil CO₂ gas is important in environmental, biological and agricultural studies. Especially, understanding the process of CO₂ production and diffusion in soil is essential. Compared with above ground, the air space in soil is very small and differences in CO₂ concentration between space are large. Therefore, a small volume of the sample gas is adequate for measuring the soil CO₂ profiles. Commonly, the sample gas is carefully transported from the field to the laboratory and is analyzed using a gas chromatograph (GC) or infrared gas analyzer (IRGA) in the laboratory (de Jong and Schappert, 1972; Nakayama and Kimball, 1988; Terhune and Harden, 1991; Wood et al. 1993; Osozawa and Hasegawa, 1995). These methods take a lot of time from sampling until analyzing the gas, and so degradation or escape of gas

is possible. Although an in situ method is necessary for rapid and accurate measurement of the soil CO₂ gas, few methods exist to measure a small volume of the CO₂ gas in the field. A method, in which the gas sample is injected into a flowing carrier gas (N₂ or CO₂-free air) that passes through an infrared gas analyzer, has been proposed (Clegg et al. 1978; Nakayama and Kimball, 1988; Fang and Moncrieff, 1998). This method is suitable for handling rapidly a large number of gas samples. But the adjustment of carrier gas, its flow rate and speed of gas sample injection are delicate.

This study investigated a simple method of measuring a small volume of the CO₂ gas using IRGA both in the field and in the laboratory. I here describe the experimental results using a large undisturbed soil sample.

2.2 Material and Method

2.2.1 Theory

This method evaluates the gas diffusion coefficient after establishing steady state gas concentrations in a soil sample. A steady CO₂ concentration gradient is established by keeping the CO₂ concentrations above and below the sample constant. The CO₂ concentration above the sample is equal to the atmospheric concentration of CO₂ and a higher CO₂ concentration is maintained below the sample. When the CO₂ concentration is at a steady state, the CO₂ concentration in water is also at a steady state and does not affect the measurement of the gas diffusion coefficient.

The gas flux in a given layer n is described according to Fick's first law

$$F_n = D_{s,n} \frac{\Delta C_n}{l_n} \quad (2.1)$$

where $D_{s,n}$ is the gas diffusion coefficient of layer n , ΔC_n is the difference in CO₂ concentration between each end of the layer, and l_n is the thickness of the layer. Under steady state conditions, the fluxes in each layer are equal; F_n is the same as the flux that is measured above the soil sample (F_0).

$$D_{s,n} = \frac{F_n}{(\Delta C_n/l_n)} = \frac{F_0}{(\Delta C_n/l_n)} \quad (2.2)$$

The gas diffusion coefficient in soil, $D_{s,n}$, is easily calculated by substituting the measured values of F_0 and $\Delta C_n/l_n$ into equation(2.2).

As the gas diffusion coefficient is effected by temperature and air pressure, the ratios of gas diffusion coefficients in soil and air (D_s/D_0) is presented in this study. The gas diffusion coefficient in free air, D_0 , is calculated by

$$D_0 = 0.139(1013/P)(T/273.16)^{1.75} \quad (2.3)$$

where P is atmospheric pressure (hpa), T is the absolute temperature (K) in soil (Campbell, 1985).

2.2.2 Apparatus and Experimental Method

Apparatus

The gas diffusing system is composed of a sample column, two chambers (upper and lower ends of the sample column) and a gas circulation device (Fig. 2.1).

The sample cylinder has an inner diameter of 19.5 cm and is 62.0 cm long. At each end of the sample cylinder, a 10 cm-long chamber with the same diameter is attached and sealed with silicone. The upper chamber has several holes in it to continuously supply fresh air, which is slowly pumped into one hole and leaves through the others. Air with a higher CO₂ concentration circulates in the lower chamber. The air in Box BA is kept

at a constant CO_2 concentration (ex. 10,000 ppm) and circulates in the lower chamber. The air in Box BB is kept at a higher CO_2 concentration than that in Box BA by being exchanged with fresh gas with a high CO_2 concentration at intervals of several hours. A CO_2 meter (TOA, type CGP-1) monitors the concentration in Box BA, and a data logger transmits the data to a personal computer. If the CO_2 concentration drops below the required concentration, fans (FB in Fig. 2.1) are turned on for tens of seconds.

Tensiometers and tubes for sampling gases are placed in the soil at 10 cm intervals, and three porous cups are placed 7 cm above the soil in lowest layer and connected to a water tank in order to absorb the soil water.

In this experiment, Toyora standard sand was used as the sample soil. 71 % of the sand particles are larger than 0.2 mm and smaller than 2.0 mm, and 29 % are larger than 0.02 mm and smaller than 0.2 mm. The sample is repeatedly saturated and drained by gravity and the sand is packed firmly. Average value of volumetric water content of saturated each layer is 0.46.

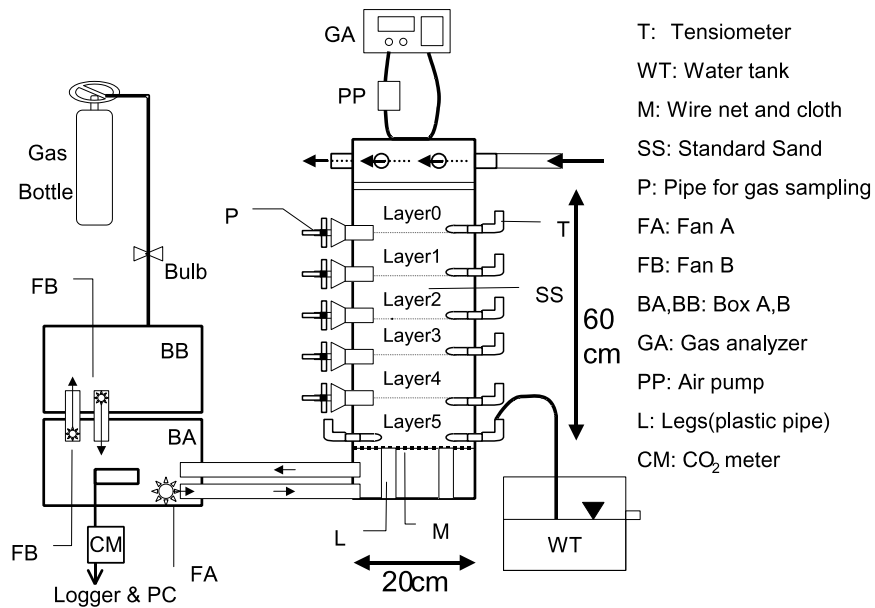


Figure 2.1: Diagram of the diffusion system.

Experimental Procedure

The procedure for measuring the gas diffusion coefficient of a sample with a given soil water condition is:

1. Begin regulating the CO_2 concentration in the upper and lower chambers.
2. Monitor the flux from the soil surface at 1 hour intervals.
3. After the flux becomes constant, measure the CO_2 concentration profile and calculate the gas diffusion coefficient.
4. Move the water tank to alter the soil water content for the next measurement.

The flux from the soil surface is measured with the chamber method. When measuring the flux, the upper chamber is closed, and the CO₂ concentration in the upper chamber is measured with a CO₂ analyzer (LI-COR Co. Ltd., type 6252). After the flux becomes constant, gas is sampled with a syringe and the CO₂ concentration profile is measured with the CO₂ analyzer.

The soil water content is controlled by absorbing the soil water into porous cups placed below the soil sample. The gas diffusion coefficient is measured at various soil water contents, which are regulated by changing the height of the water tank.

2.2.3 A simple technique to analyze a small volume of soil CO₂ gas using an infrared gas analyzer

An infrared gas analyzer can measure the CO₂ gas concentration flowing through a cell and has the range of 0-3000

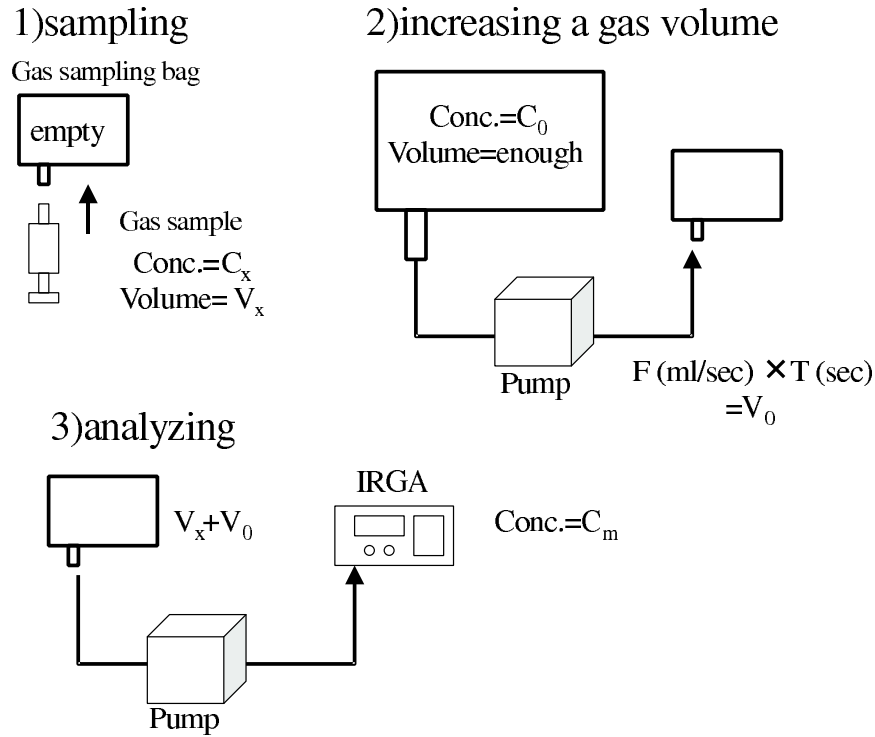


Figure 2.2: Procedure of analyzing the gas in small volumes.

Soil gas samples in small volume cannot be measured using infrared gas analyzer because the volumes are too small and have a high concentration. In this method, gas samples are analyzed after increasing the volume with air of known CO₂ concentration. Figure 2.2 shows the procedure to increase the gas volume and measure the concentration. Large and small gas sampling bags (*e.g.* 10 l and 1 l), a pump of accurately constant flow rate and infrared gas analyzer were prepared. A large bag was filled up with air using a pump and the CO₂ concentration in it (C_0) was measured by IRGA. The air in the large bag was well mixed and almost homogeneous. The gas in the small gas bag was all removed by the pump. 1) soil gas sample of unknown concentration (C_x) and known volume (V_x , *e.g.* 20 ml) was injected into the small empty gas bag. 2) Air of known concentration (C_0)

was pumped from the large bag to the small one for a known period of time (*e.g.* the flow rate of 23.8 ml/sec for 30 sec). The volume of the air pumped (V_0) was obtained from the product of the flow rate of the air pump and time of pumping air (*e.g.* 23.8 ml/s \times 30sec). 3) The volume of gas in the small gas bag ($V_0 + V_x$) was sufficient to be measured using IRGA. The relationships between the concentrations and the volumes are:

$$C_m = \frac{(V_x C_x + V_0 C_0)}{V_x + V_0} \quad (2.4)$$

The concentration of the gas sample in a small volume is calculated as follows:

$$C_x = \frac{(V_x + V_0)C_m - V_0 C_0}{V_x} \quad (2.5)$$

First, to check the validity, 20 ml of commercially prepared standards and air of known concentration were tested before applying them to the soil sample.

Second, this method was tested using the following soil incubation system with undisturbed forest soil. The system was composed of a sample column, two chambers (upper and lower ends of the sample column), a gas circulation device and a temperature control device. The sample cylinder had an inner diameter of 19.5 cm and was 40.0 cm long. A 10.5 cm-long chambers of uniform diameter were attached and were sealed at each end of the sample cylinder with silicone. The CO₂ concentration of the soil surface was kept atmospheric CO₂ concentration. The lower chamber was closed. The soil temperature was controlled by circulating water of fixed temperature in tubes around the sample column using a cooling thermo pump (EYELA, CTP-201). Through boundary and temperature controls, steady state CO₂ gas profile were maintained in this apparatus. Tubes for sampling gases were placed in the soil at 10, 20, 30, 40 cm depth. The steady state CO₂ profile are measured at various temperatures. Throughout the experiment the soil water suction was kept nearly constant. After adjusting the constant temperature bath, the soil was left for more than 12 hours, the constancy of soil temperature was checked and the measurements were started. The soil gas was sampled two or three times at 2-4-hour intervals and was analyzed. When analyzing a sample gas, a large gas bag of 10 l and a small gas bag of 1 l were used. 20 ml of soil gas sample was injected into the small bag and mixed with the air from the big bag. V_0 is about 715 ml, pumped at a flow rate of 23.8 ml/sec for 30 seconds by a pump (MP-2N, Sibata Scientific technology LTD, Japan). The mixed gas was then analyzed by an IRGA (Li-Cor 6262, Li-Cor, U.S.A).

Figure 2.3 shows results of the validity test. Twenty ml of standards of $411 \times 10^{-6} \text{m}^3/\text{m}^3$ (air measured by IRGA), $907 \times 10^{-6} \text{m}^3/\text{m}^3$ (commercially prepared) and $100700 \times 10^{-6} \text{m}^3/\text{m}^3$ (commercially prepared) were tested several times. The accuracy was sufficiently satisfactory ($R^2 = 0.999$). This method provided an accurate concentration of soil gas in a small volume.

Figure 2.4 shows the measured steady state CO₂ gas profiles of at 8 °C, 13 °C, 21 °C, 33 °C. Profiles measured at different times agreed well with each other. Soil CO₂ profile depends on gas diffusivity and CO₂ production within the soil. CO₂ production rate increases with increasing temperature. In this experiment, the soil water condition was nearly constant and hence the gas diffusion coefficient changed little. The increment of the CO₂ gas gradient with increasing temperature was caused by the increment of CO₂ production in soil.

2.3 Results and Discussion

2.3.1 Measurements

The soil water suction profile, the CO₂ concentration profile in soil, and the value of D_s/D_0 (the ratios of gas diffusion coefficients in soil and air) determined for two different soil water conditions (Condition A and B) are presented in Fig. 2.5.

Figure 2.6 shows the results of the gas concentrations in the upper and lower chambers and the flux above the soil surface for Condition A and B. The upper boundary condition is approximately the atmospheric CO₂ concentration and is stable. Although the lower boundary condition is a little variable, a steady state of gas

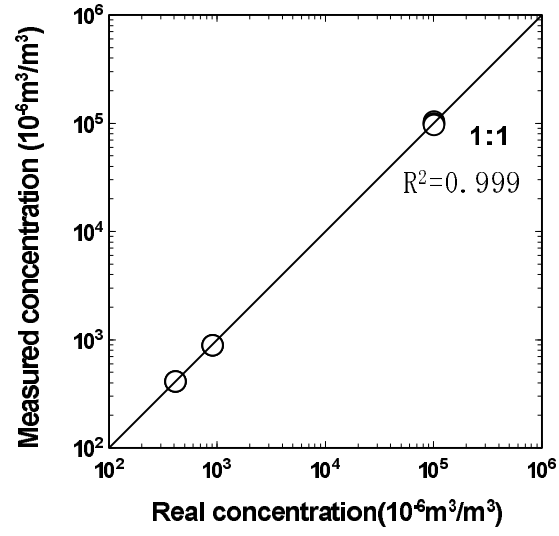


Figure 2.3: Comparison between standards and measured CO₂ concentration.

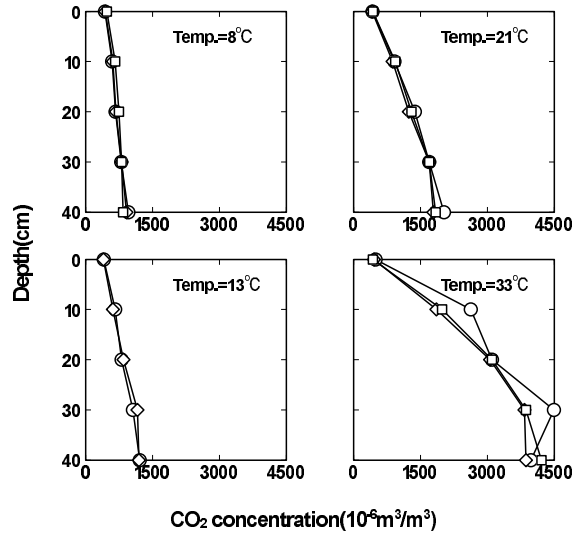


Figure 2.4: Measured CO₂ profiles at various temperature. Open circle: first measurement, open diamond: second measurement, open squares: third measurement

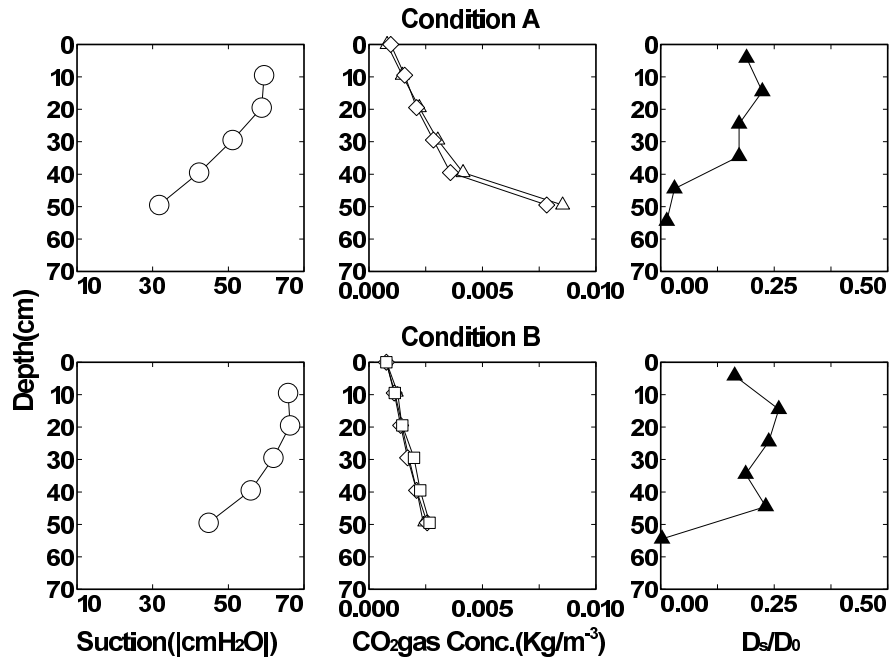


Figure 2.5: Soil water suction, CO₂ gas distribution under a steady state, and calculated D_s/D_0 under two different soil water conditions (condition A, condition B). Open triangle: measured at time 1 in Fig. 2.6. Open triangle: measured at time 2. Open square: measured at time3.

flux above the soil surface is observed beginning 10 hours after setting up the apparatus. The time required to reach a steady state and the values of the flux differ with the soil water content and the CO_2 concentration gradient.

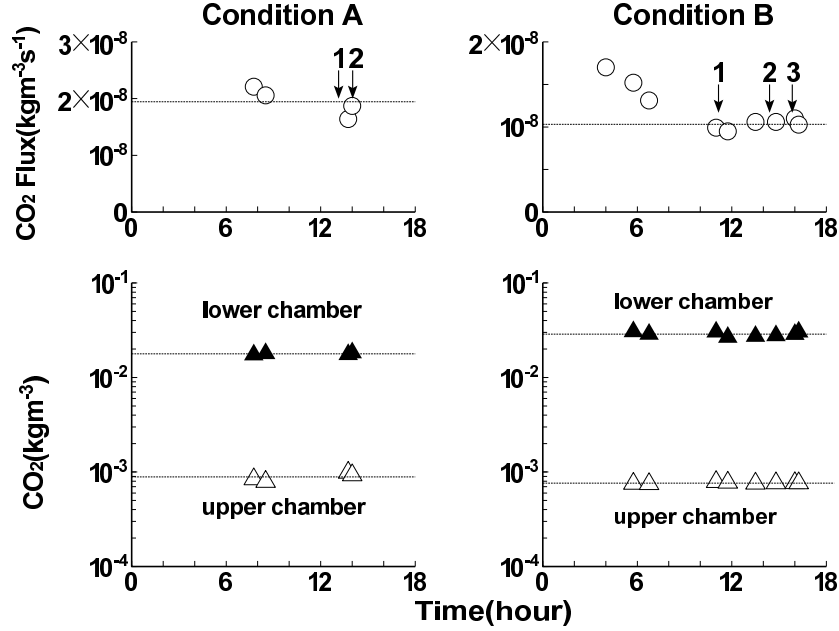


Figure 2.6: Results of measurements made under conditions A and B. The change in the CO_2 flux with time is measured above the soil surface.

Figure 2.5 shows that the soil in Condition B was drier than that in Condition A. In each column, the soil at the top of the column is drier than that at the bottom. The D_s/D_0 in deeper (wetter) soil shows more fluctuation than in shallower (drier) soil.

2.3.2 The relationships between soil water suction and D_s/D_0

Figure 2.7 shows the relationship between the relative gas diffusion coefficient and soil water suction. The measured values in each layer are similar. The relative gas diffusion coefficient suddenly increases between 30 and 50 $\text{cm H}_2\text{O}$ suction and then changes little when the suction exceeds 50 cmH_2O . The critical capillary suction of Toyora standard sand is about 30 cmH_2O , and the soil water content decreases suddenly in the range 30-50 cmH_2O and then changes little beyond 50 cmH_2O . The increment in the gas diffusion coefficient caused by the decrement in soil water is clearly observed. When the suction in a layer is less than 30 cmH_2O , the gas in the soil cannot be sampled because of saturation and hence the gas diffusion coefficient cannot be measured under these conditions. The gas diffusion coefficient in water is less than 1/1000 of the value in air, and the gas diffusion coefficient is very small when the capillary suction is less than a critical value (about 30 cmH_2O). The Milington-Qurk model was also plotted in Fig. 2.7. The Milington-Qurk model had a good fit for my results.

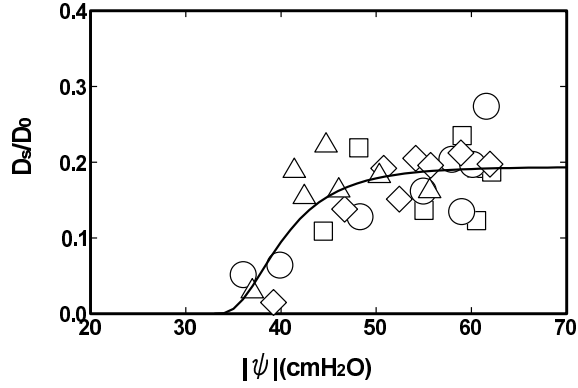


Figure 2.7: Relationship between suction and relative gas diffusion coefficient (D_s/D_0). Open square, layer 1 (9.5- 19.5 cm depth); open circle, layer 2 (19.5-29.5 cm depth); open diamond, layer 3 (29.5-39.5 cm); open triangle, layer 4 (39.5-49.5 cm).

2.4 Conclusions

A new apparatus was developed to measure gas diffusion coefficients in large soil samples while controlling soil water suction. Using this apparatus, the relationship between suction and the gas diffusion coefficient was examined. CO_2 can be used as the diffusing gas in this apparatus, because the apparatus evaluates the gas diffusion coefficient after establishing a steady state gas condition. If forest soil is used in this apparatus, inhibition of respiration by cooling or chemical treatments will be needed. When a long sample column is used, the suction of upper layers can't be prepared to be low. To lessen the dispersion of measured values, the stability of the boundary conditions and the accuracy with which the CO_2 concentration profile is measured should be increased.

Chapter 3

Vertical distributions of carbon dioxide diffusion coefficients and production rates in forest soil

3.1 Introduction

Accurate measurements of CO₂ emissions from soil are important for understanding the carbon cycle in forest systems. Emissions of CO₂ from soil are the result of CO₂ produced in the soil and transported to the surface. Transport of CO₂ is mainly by gas diffusion and mass flow; when the difference in pressure is small, gas diffusion dominates mass flow.

Identifying the gas diffusion coefficients of a soil is essential for analyzing and modeling gas diffusion in the soil. Traditionally, gas diffusion coefficients have been evaluated in the laboratory, using non-steady-state methods and small soil cores (Washington et al. 1994; Moldrup et al. 1996a). Such methods are suitable for handling large numbers of samples, and allow control of soil-water conditions. Methods using larger, undisturbed soil samples, or *in situ* testing, have been proposed (Lai et al. 1976; Rolston et al. 1991; van Bochove et al. 1998; Hashimoto and Suzuki, 2000), but none allows control of environmental factors, especially water conditions.

The CO₂ production in soil is strongly controlled by soil temperature and moisture (Howard and Howard, 1993; Zak et al. 1999; Morén and Lindroth, 2000). There are two major methods of evaluating the CO₂ production in soil. One is the laboratory core method, and the other measures the CO₂ efflux from the soil surface. The laboratory core method has the advantage of being able to measure the soil CO₂ production at each depth at various temperature and water conditions, but has the disadvantage of disturbing the soil system. Measuring the efflux has the advantage of being able to measure the soil CO₂ production without altering the soil; however, the vertical profile of the CO₂ production rate cannot be measured, and environmental conditions, such as soil temperature and soil water, cannot be controlled, so there are too many factors to consider. There are a few other methods that evaluate the CO₂ production in soil; these involve placing a solution in the soil or calculating the CO₂ profile using gas diffusion coefficients measured in advance (de Jong and Schappert, 1972; Campbell and Frascarelli, 1981). These methods are suitable for measuring the instantaneous CO₂ production, but are not reasonable for measuring the relationships between the CO₂ production rate and various environmental factors.

To overcome current limitations, any new method must be able to: (1) handle larger, undisturbed soil samples (2) obtain continuous vertical profiles of gas diffusion coefficients and CO₂ production, and (3) allow easy control of soil-water and soil-temperature.

In this study I developed a way of evaluating gas diffusion coefficients and CO₂ production rates in soil that satisfies these requirements. The proposed method was tested using an undisturbed soil sample, and some of the experimental results are presented. Also, the dependence of soil CO₂ production to soil temperature were measured.

3.2 Materials and Methods

3.2.1 Theory

This method evaluates diffusion coefficients after steady-state conditions have been established in a soil sample. One-dimensional CO₂ transport can be described by the following equation.

$$\frac{d(aC)}{dt} = -\frac{dq}{dz} + Y \quad (3.1)$$

where a is the volumetric air content (m³ m⁻³), C is the CO₂ concentration (kg m⁻³), z is the distance (m), q is the CO₂ flux (kg m⁻² s⁻¹), and Y is the CO₂ production rate in soil (kg m⁻³ s⁻¹). As $d(aC)/dt$ is zero when gas and soil water concentrations are at a steady state, equation 3.1 can be rewritten as:

$$Y = \frac{dq}{dz} \quad (3.2)$$

Assuming that the main form of CO₂ transport is gas diffusion, the gas flux q is described by Fick's Law as follows:

$$q = -D \frac{dC}{dz} \quad (3.3)$$

where D is the gas diffusion coefficient in the soil (m² s⁻¹). Figure 3.1 shows the discretization of the measuring system.

Equation 3.2 for each layer is approximated as:

$$Y_n = \left(q_n + D_{n-1} \frac{(C_n - C_{n-1})}{(\Delta z_n + \Delta z_{n-1})/2} \right) / \Delta z_n \quad (3.4)$$

⋮

$$Y_i = \left(-D_i \frac{(C_{i+1} - C_i)}{(\Delta z_{i+1} + \Delta z_i)/2} + D_{i-1} \frac{(C_i - C_{i-1})}{(\Delta z_i + \Delta z_{i-1})/2} \right) / \Delta z_i \quad (3.5)$$

⋮

$$Y_1 = \left(-D_1 \frac{(C_2 - C_1)}{(\Delta z_2 + \Delta z_1)/2} - q_0 \right) / \Delta z_1 \quad (3.6)$$

where Δz_i is the thickness of a layer and n is the number of layers.

In this method, two different boundary conditions are imposed, and the CO₂ gas concentration, C_i , and the upper and lower fluxes, q_0 and q_{n+1} , are measured. Soil temperature and soil water conditions are kept the same for the two measurements with the different boundary condition. The interval is too short for significant decomposition of organic matter, and the CO₂ concentrations in the soil do not differ enough to affect microbial activity. It can be assumed that CO₂ production and the gas diffusion coefficients are not different,

$$Y_i^a = Y_i^b \quad (3.7)$$

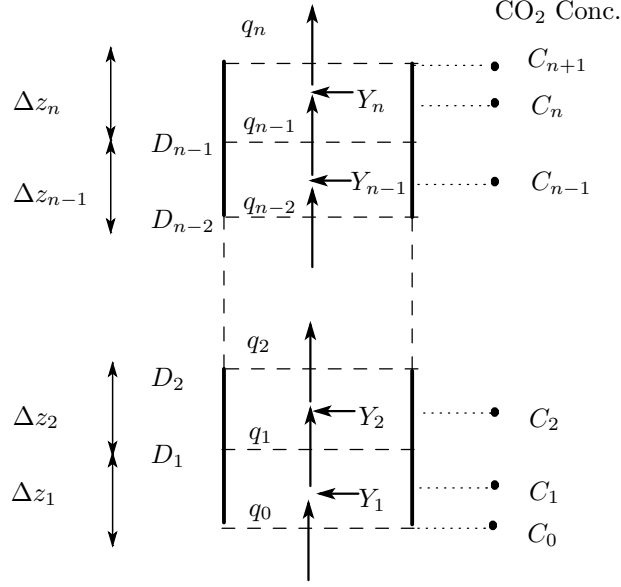


Figure 3.1: Model for the measuring system.

$$D_i^a = D_i^b \quad (3.8)$$

where X^a is the value of X at one boundary condition and X^b is the value at the other. The total CO_2 production in soil, $\sum_{i=1}^n Y_i$, is equal to the fluxes measured at the soil surface.

$$\sum_{i=1}^n Y_i \Delta z_i = q_n^a - q_0^a = q_n^b - q_0^b \quad (3.9)$$

Equation 3.7 cannot be checked directly, so the relationship, equation 3.9 was checked experimentally.

Substituting the measured values of q_n and C_0 in the two boundary conditions into these equations, simple equations for Y_1 - Y_n , D_1 - D_{n-1} are obtained and can be easily solved, as shown below.

$$D_i = \frac{(\Delta z_{i+1} + \Delta z_i)/2}{(C_{i+1}^a - C_i^a) - (C_{i+1}^b - C_i^b)} (q_n^b - q_n^a) = \frac{(\Delta z_{i+1} + \Delta z_i)/2}{(C_{i+1}^a - C_i^a) - (C_{i+1}^b - C_i^b)} (q_0^b - q_0^a) \quad (3.10)$$

These equations show that the gas diffusion coefficients can be calculated using the difference in the gradients of CO_2 concentration and CO_2 flux from the soil surface. The large differences in the gradients of CO_2 concentration are particularly important.

Y is described using the obtained gas diffusion coefficients (D_i) as

$$Y_i = \frac{q_{i+1} - q_i}{\Delta z} = \frac{1}{\Delta z} \left(-D_i \frac{C_{i+1} - C_i}{(\Delta z_{i+1} + \Delta z_i)/2} + D_{i-1} \frac{C_i - C_{i-1}}{(\Delta z_i + \Delta z_{i-1})/2} \right) \quad (3.11)$$

This equation shows that the CO_2 production in a certain layer is the difference between the flux of inflow and outflow. de Jong and Schappert (1972) also used this relationship to calculate the CO_2 production at each soil depth.

Using the gas diffusion coefficient ($D_x, \text{m}^2 \text{s}^{-1}$) for a certain temperature (T_x, K) and pressure (P_x, KPa), the gas diffusion coefficient ($D_n, \text{m}^2 \text{s}^{-1}$) at another temperature (T, K) and pressure (P, KPa) can be estimated

as (Campbell, 1985).

$$D_y = D_x(T/T_x)^{1.75}(P_x/P) \quad (3.12)$$

Consequently, under the same soil water conditions, measuring the steady CO₂ profile and soil surface flux at another temperature under only one boundary condition allows estimation of the vertical profile of the CO₂ production rate.

3.2.2 Apparatus

The system consists of a sample column with a chamber at each end, a gas circulator, and a temperature control (Fig. 3.2). The sample cylinder is 40.0 cm long, with an inner diameter of 19.5 cm. At each end of the sample cylinder there is a 10.5-cm-long chamber, of the same inner diameter, sealed with silicone.

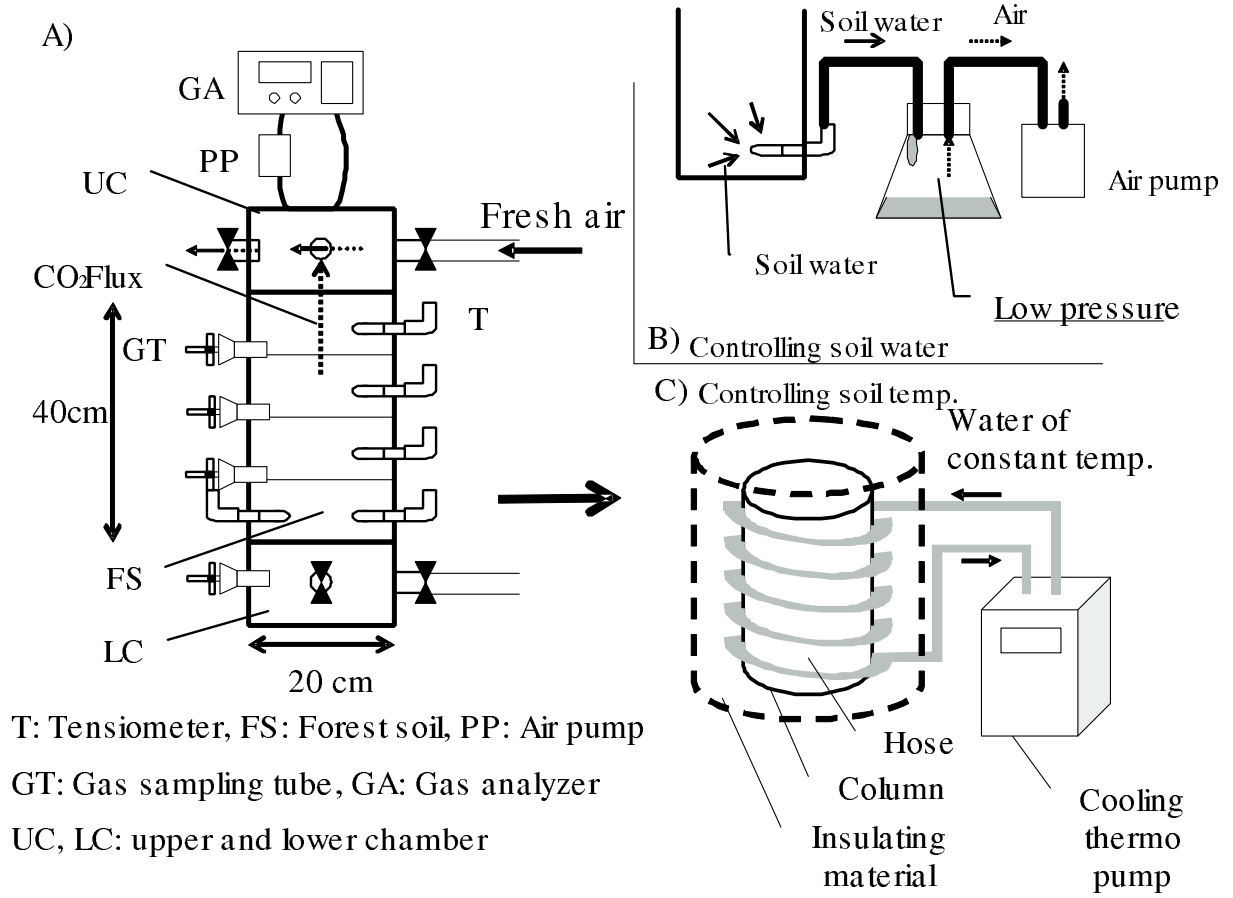


Figure 3.2: Schematic diagram of (A) the measuring system, (B) the system for controlling soil water, and (C) the system for controlling soil temperature.

There are several holes in the upper and lower chambers. Opening or closing holes can control the boundary conditions. When all of these holes are closed, the CO₂ concentration at the boundary is high. When at least two holes are open, fresh air pumped slowly into one hole leaves through the other. The atmospheric CO₂ concentration is maintained at the boundary. Two boundary conditions are as follows (Fig. 3.3):

Closed lower chamber condition The upper end of the soil sample is kept at atmospheric CO₂ concentration and the lower end is closed. ($C_n = \text{atmospheric CO}_2 \text{ concentration}$, $C_0 = C_{40cm}$, $q_0 = 0$)

Open lower chamber condition The upper and lower ends of the soil sample are kept at atmospheric CO₂ concentration. ($C_n = C_0 = \text{atmospheric CO}_2 \text{ concentration}$.)

Measurements are first taken with a closed lower chamber, followed within 24 hours by measurements with an open

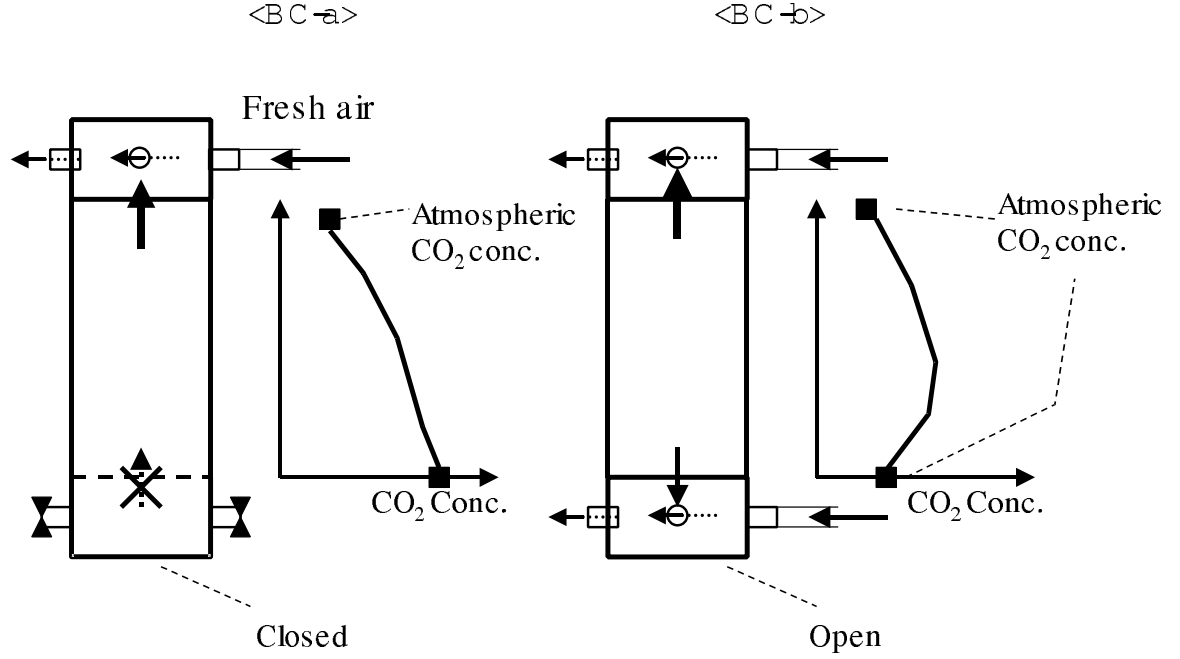


Figure 3.3: Schematic diagram of the boundary control.

There are ports for sampling the soil gases at depths of 10, 20, 30, and 40 cm, tensiometers (Daiki Co., Ltd. DIK-3151) at depths of 5, 15, 25, and 35 cm, and porous cups connected to flasks and an air pump, at a depth of 35 cm, to control soil-water drainage. When drying the soil, the air pump tries to pump out the air in the flasks and the air pressure in the flasks decreases. As a result, the soil water slowly drains into the flasks (Fig. 3.2 B). Soil temperature is controlled by circulating water at a fixed temperature in tubes surrounding the sample column using a thermo pump (EYELA, CTP-201) for keeping soil temperature (Fig. 3.2 C). The soil sample reaches thermal equilibrium within 12 h of starting the thermo pump.

The end chambers are used to find the flux from the soil surface; this is a closed dynamic chamber method (Blanke, 1996; Jensen et al. 1996; Norman et al. 1997; Striegl and Wickland, 1998). The CO₂ concentration in the chamber is measured using a CO₂ analyzer (LI-COR Co. Ltd., type 6252) and air pump (flow rate: 23.8 ml/sec) at 1-second intervals for 3-5 minutes. The CO₂ flux is calculated from the rate of increase in the CO₂ concentration in the chamber. Once the flux becomes constant, soil gases at various depths can be sampled using a syringe, and the CO₂ concentrations can be measured using a CO₂ analyzer (Hashimoto, 2002).

In this experiment, four layers were set as 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm depth. The CO₂ concentration of a certain layer (ex. C_{15cm}) is calculated from the average values of the CO₂ concentration at each end (ex. $C_{15cm} = (C_{10cm} + C_{20cm})/2$).

Location				
Latitude	35 ° 12'N			
Longitude	140 ° 06'E			
Climate				
Mean annual precipitation, mm	2300			
Mean annual temperature, °C	14			
Properties, m	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4
Rock (≥ 2 mm), g	193.0	357.0	1730.0	957.0
Large organic matter (≥ 2 mm), g	105.0	23.0	7.0	6.0
Small nonorganic particle(<2 mm), g	522.8	1202.4	652.4	1094.9
Small organic matter (<2 mm), g	155.2	181.6	89.6	130.1
Sand, % *	62.9	41.6	46.1	43.4
Silt, % *	33.0	50.3	44.6	47.5
Clay, % *	4.0	8.2	9.3	9.1
Texture *	Sandy Loam	Silt Loam	Loam	Loam
C/N ratio	18.1	12.2	9.8	7.1
Total porosity	0.850	0.750	0.690	0.720

* USDA basis

Table 3.1: Site location, climate, and soil properties. The layer 0-10cm contained the A₀ layer.

3.2.3 The dependence of soil CO₂ production rate on soil temperature

This apparatus can easily control the soil temperature by circulating water at a fixed temperature in tubes surrounding the sample column using a thermo pump (EYELA, CTP-201) for keeping soil temperature (Fig. 3.2 C). I measured the dependences of soil CO₂ production rate on soil temperature. I set soil temperature at 5, 10, 20, 35 °C in a rising process, and then 20, 10, 5 °C in decreasing process, and measured soil surface CO₂ flux. At each temperature, measurements were conducted after more than 12 hours after soil temperature change, under the equilibrium temperature condition.

3.2.4 Soil material and soil water retention curve

Soil material was collected at the University Forest in Chiba, Japan. The trees at the site were predominantly *Chamaecyparis obtusa*, *Cryptomeria japonica*, *Tsuga sieboldi*, and *Quercus glauca*. Undisturbed forest soil was collected by hammering a sample column with a sharpened rim into the soil. The A₀ layer was included without disturbing the fresh litter on the soil. Table 3.1 shows the forest's location and climate, and the soil samples' properties. Soil type is Brown forest soil.

After the experiments, the soil samples were cut into layers determined by the tensiometer positions (0-10, 10-20, 20-30, and 30-40 cm) and were well saturated. The relationships between soil-water suction (ψ , cmH₂O) and soil water content were obtained by gravimetric observations during the air-drying process. The gravimetric observations were conducted once to third a day for 7-17 days. However, it was difficult to measure the total weight when the soil was saturated ($\psi = 0$) because the soil samples were large. I calculated the saturated soil water content by assuming that the specific gravity of soil was 2.72 (Shuin, 1997) and the specific gravity of organic matter was 1.56 (Kawata and Kojima, 1979).

3.3 Results and Discussion

3.3.1 Measurements

Figure 3.4 A-1 and B-1 shows measurements made of one soil sample under two suction conditions: wetter (condition WT) and drier (condition DR). The measurements were made at approximately 20° C. The CO₂ gas concentration measurements used to determine the gas diffusion coefficient are presented in Fig. 3.4 A-2 and 4B-2. CO₂ profiles at each condition were measured 2-4 times at approximately 3-hour intervals. The average values were plotted. The interval between measurements under closed and open lower chamber conditions was about 24 hours. Under the closed lower chamber condition, the CO₂ concentration at the upper soil surface was the atmospheric CO₂ concentration. Under the open lower chamber condition, the CO₂ concentrations at the upper and lower soil surface were both the atmospheric CO₂ concentration.

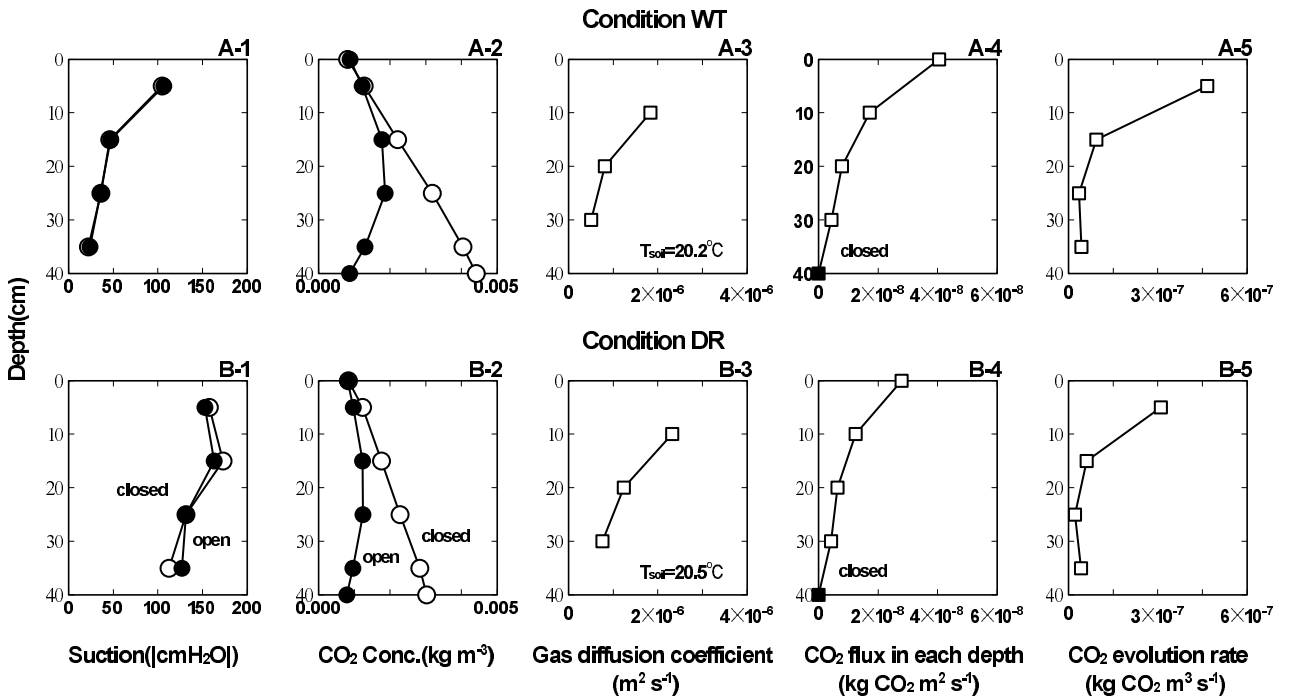


Figure 3.4: Average suction profiles for wetter conditions (condition WT) and drier conditions (condition DR) (A1, B1) and the measured CO₂ profiles used to determine the gas diffusion coefficients (A2, B2) and the obtained gas diffusion coefficients (A3, B3). The CO₂ fluxes were calculated at each depth from the CO₂ profile and the gas diffusion coefficient (A4, B4). The CO₂ production rate in a certain layer is the difference between the flux of inflow and outflow (A5, B5). The CO₂ profiles were measured at 0-, 10-, 20-, 30-, and 40-cm depths. I used the average values between these depths.

Fluxes from the surface of the soil are shown in Table 3.2. The CO₂ fluxes from the surface were measured two to four times, and the average values are shown with the standard error. The differences in the total CO₂ production under two boundary conditions were very small. The relationship of equation 3.9 was checked. This indicates that the CO₂ productions under both boundary conditions were the same. Moreover, the soil water suction was virtually the same under two boundary conditions. This indicates that the gas diffusion coefficients were also the same under both boundary conditions. Therefore, the assumption that the gas diffusion coefficients

	condition WT		condition DR	
	closed	open	closed	open
soil temp. (°C)	20.3	20.1	20.7	20.4
$q_n \times 10^{-8}$	4.05 (3, 0.03)	3.34 (3, 0.04)	2.80 (2, 0.10)	2.16 (2, 0.05)
$q_0 \times 10^{-8}$	0.0	-0.674 (3, 0.01)	0.0	-0.605 (2, 0.05)
$q_n - q_0 \times 10^{-8}$	4.04	4.01	2.80	2.77

Table 3.2: Measured CO₂ flux from the upper and lower surface, and the sum of them.(kg m⁻² s⁻¹, the number of measurements and standard error in parenthesis)

and CO₂ production rate were the same under closed and open lower chamber conditions (equation 3.7 and 3.8) was valid.

The gas diffusion coefficients were calculated using these values (Fig. 3.4 A-3, 3.4 4B-3). In conditions WT and DR, the gas diffusion coefficients in the upper layers were larger than those in the lower layers. There are few reports on the vertical distribution of gas diffusion coefficients in soil, especially in forest soil (Washington et al. 1994; Osozawa and Hasegawa, 1995; van Bochove et al. 1998). In both agricultural and forest soils, gas diffusion coefficients decrease with increasing depth, because the overall porosity of the upper layers of soil is generally higher than that of the lower layers, and consequently the soil-water suction is usually lower in the drier, upper soil. The gas diffusion coefficients obtained in this study decreased with increasing depth as expected. At each depth, the gas diffusion coefficients under condition DR were larger than those under WT. This is because the soil water was drained.

Figures 3.4 A-4 and 3.4 B-4 show the CO₂ fluxes at each depth under closed conditions, calculated from the CO₂ concentration profile and the obtained gas diffusion coefficients. Since the lower chamber was closed, the flux at a depth of 40 cm was assumed to be zero and that the CO₂ flux at each depth moved upwards. The flux at a given depth was the integral of the CO₂ production in the soil below that depth. Consequently, the flux is larger at shallower points than at deeper ones. The difference in the flux at each point is the CO₂ production rate in the layer (Fig. 3.1 and Equations 3.2 and 3.11). That is to say, the CO₂ evolution rate in the 0- to 10-cm layer was the difference between the flux at 0 cm and that at 10 cm. In both conditions, the CO₂ production rate also decreased with increasing depth and the CO₂ production rate at 0-10 cm was very large compared with other depths. This result agrees with previous reports (Ino and Monsi, 1969; de Jong and Schappert, 1972; Campbell and Frascarelli, 1981; Scanlon and Moore, 2000). The values of the CO₂ production rate per unit soil volume are of the same order of magnitude as published elsewhere (Howard and Howard, 1993; Bowden et al. 1998).

3.3.2 Comparison with empirical model

The gas diffusion coefficients obtained were compared with estimates from the Millington-Quirk model, which has been reported to give good estimates of gas diffusion coefficients (Moldrup et al. 1996b) and the new Moldrup model, which has been reported to give better estimates (Moldrup et al. 2000). The Millington-Quirk model is

$$\frac{D}{D_0} = \frac{\epsilon^{10/3}}{\Phi^2} \quad (3.13)$$

where D/D_0 is the relative gas diffusion coefficient, Φ is the total porosity (cm³ cm⁻³), and ϵ is the air-filled porosity (cm³ cm⁻³). The new Moldrup model is

$$\frac{D}{D_0} = (2\epsilon_{100}^3 + 0.04\epsilon_{100}) \left(\frac{\epsilon}{\epsilon_{100}} \right)^{2+3/b} \quad (3.14)$$

where ϵ_{100} is the air-filled porosity at -100 cmH₂O and b is the Campbell soil water retention parameter. The gas diffusion coefficient in free air can be obtained by equation 3.12 (Campbell, 1985) with values of $D_x = 1.39 \times 10^{-5} (\text{m}^2 \text{ s}^{-1})$, $T_n = 273.16(\text{K})$, $P_n = 101.3(\text{KPa})$.

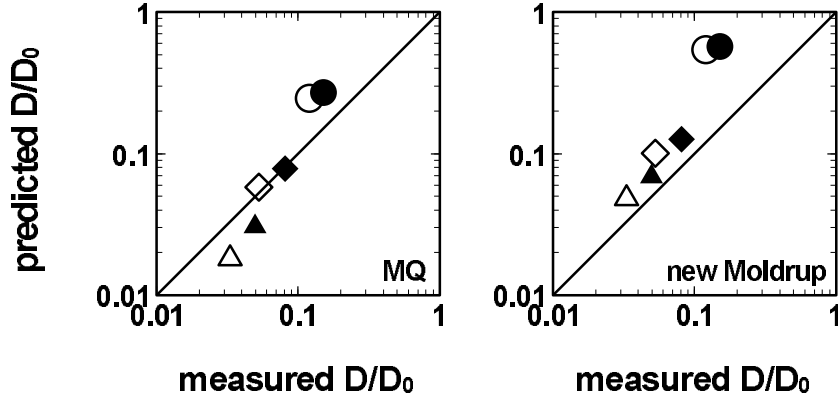


Figure 3.5: Comparison of the gas diffusion coefficient values measured in this study and values calculated from the Millington-Quirk model and new Moldrup models. Open and solid circles: 10 cm; diamonds: 20 cm, triangles: 30 cm. Open symbols are values under wetter conditions (condition WT), and solid symbols are values under drier conditions (condition DR).

Figure 3.5 compares the measured and estimated D/D_0 . Compared with the Millington-Quirk model, the measured D/D_0 at a depth of 20 cm was in good agreement with estimated values. However, the D/D_0 was overestimated at 10 cm and underestimated at 30 cm. The values estimated with the new Moldrup model were all larger than the measured values.

3.3.3 The dependence of soil CO₂ production rate on soil temperature

Figure 3.6 shows the relationships between soil surface CO₂ flux and soil temperature.

Soil surface CO₂ flux exponentially increased with increasing temperature. I fitted the relationships with an exponential equation as follows:

$$Y = Ae^{kT} \quad (3.15)$$

where A is a constant, defined as the soil surface flux at 0 °C, k is the constant and T is the temperature. With this model, I can calculate Q_{10} value as $Q_{10} = e^{(10k)}$. The fitted k values were similar to each other, although the fitted A value on condition A was about twice as large as on condition B. Then the Q_{10} values on condition A was 2.2 and those on condition B was 2.3, and almost same.

3.3.4 Simulation of unsteady CO₂ profiles and surface flux

To validate these values, I simulated the unsteady changes of gas production and movement in a soil column. Accurate evaluation of the vertical distribution of gas diffusion coefficients and the CO₂ evolution rate are

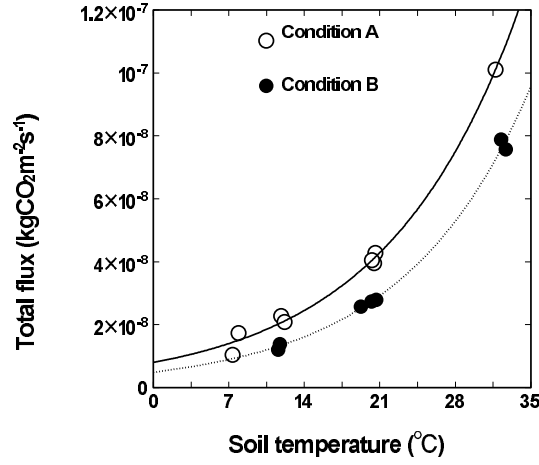


Figure 3.6: Soil surface flux (total CO₂ production) versus average soil temperature. The dependence of soil CO₂ production on soil temperature. Soil temperature is the average temperature of 10, 20, 30 cm depth.

essential for simulating gas transport. Soil temperature was changed from 20 °C to 33 °C (Fig. 3.9 A) with closed lower chamber. The profiles of CO₂ concentration and CO₂ flux from the upper soil-surface were measured.

The CO₂ transport in soil can be described by equation 3.1 and 3.3. This observation was carried out under condition DR. Figure 3.7 shows the relationships between soil depth and soil air content, the gas diffusion coefficient, and the CO₂ production rate. The soil air content (a) was calculated from the soil retention curve, and was approximated as shown in Figure 3.7. It was assumed that the air content (a) was constant during the measurement. The profile of the gas diffusion coefficients under condition DR was approximated as shown in Figure 3.7. The CO₂ production rate in each layer (0-10, 10-20, 20-30, 30-40 cm) was assumed to be constant. The relationship between the CO₂ production rate in soil (Y) and soil temperature was approximated by a linear equation (Fig. 3.8).

Figure 3.9 compares the simulated and measured (B) CO₂ flux from the soil surface and (C) soil CO₂ profile. Both the CO₂ concentration profile and the CO₂ flux at the soil surface were accurately simulated. The temperature of the water in the tube surrounding the soil column was changed from 20 °C to 35 °C at 22 h. The soil temperature changed slowly and stabilized at 32 °C after about 20 h. Corresponding with the change in soil temperature, the CO₂ concentration and CO₂ flux gradually rose and reached a stable state. The CO₂ concentration at deeper points changed more slowly and reached a steady state later. In particular, the CO₂ concentration at 30 cm temporarily became the same as that at a depth of 40 cm at about 30 h. These good results indicate that this apparatus can obtain adequate values of the gas diffusion coefficients and the CO₂ production rate.

3.4 Conclusions

A new method to evaluate the vertical distribution of gas diffusion coefficients and CO₂ production rates in undisturbed soil samples was proposed and tested using an undisturbed sample of forest soil. The advantage of this method is that it allows measurement of the vertical distribution of gas diffusion coefficients using undisturbed soil samples and controlled soil-water and soil-temperature conditions. Moreover, the sample size

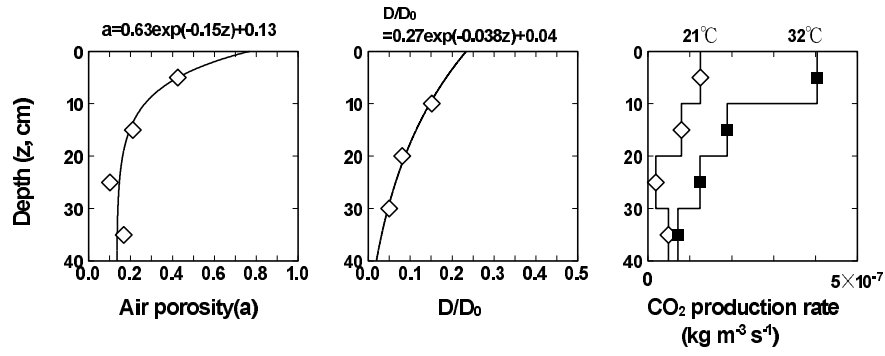


Figure 3.7: The relationships between soil depth and air porosity, the relative gas diffusion coefficient, and CO₂ production rate.

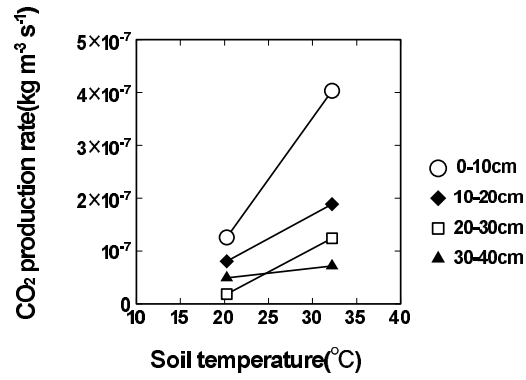


Figure 3.8: The relationship between soil temperature and the CO₂ production rate. These relationships were approximated as linear equations.

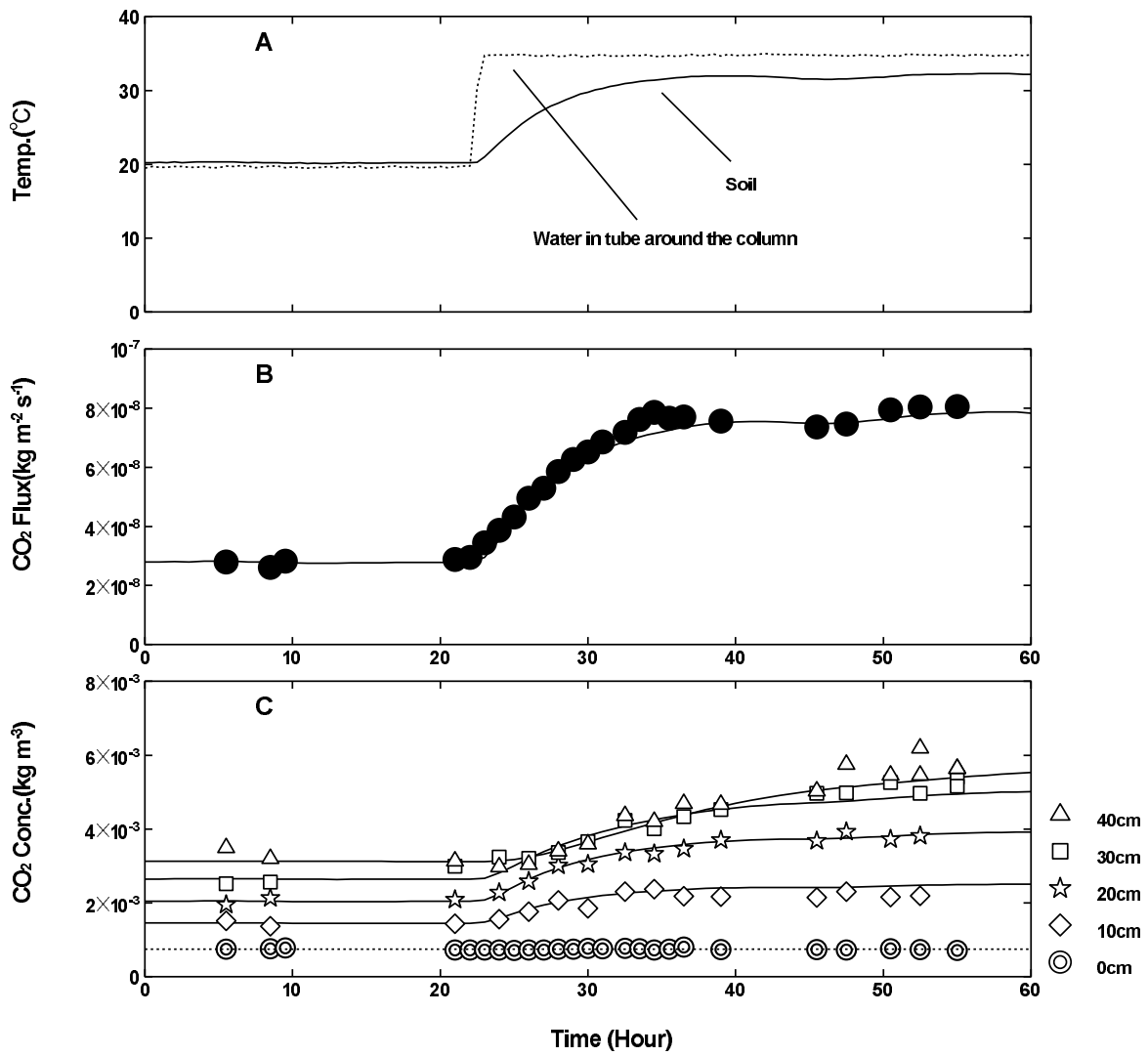


Figure 3.9: The change in soil temperature (A), and a comparison between simulated and measured CO₂ flux from the soil surface (B) and comparison of soil CO₂ profiles (C). The lines are the simulated values.

is considerably larger than was possible with previous methods. These advantages will allow this experimental system to be applied to other studies, such as the movement of gas at different temperatures or before and after rainfall, or the relationships between CO₂ gas diffusion coefficients and earthworm or micro-organism activity.

Chapter 4

Experiment in Thailand/Soil respiration properties in tropical forest in Thailand

4.1 Introduction

As discussed in Chapter 1, tropical forests are the key ecosystem in respect of global warming.

Shortage of studies in tropical region despite of its importance Nevertheless, there are few reports on soil respiration in tropical forest compared to the other climate regions, especially for Southeast Asia. The difficulty of accessing to these regions that have tropical forests is perhaps one of the reasons that have tropical forests is perhaps one of the reasons for the shortage of studies of soil respiration in tropical forests. Most tropical forests exist in developing countries in low latitudes. Then, traffic networks are not yet enough, and neither are observation systems. Also, there are so many types of tropical forest; various structures, diversities of species and climate (Whitmore, 1990), compared with boreal and temperate forests. Thus, the more studies of soil respiration in tropical forests are needed.

Introduction of evergreen forest There are vast forests across Thailand, Myanmar and Laos (Fires in Thailand and Cambodia in earth observatory, Nasa HP). The area is covered by dense evergreen forest and has a relatively constant seasonal temperature and experiences a clear dry and rainy season. The dry season is relatively longer than in other tropical forest.

Temperature sensitivity cannot be obtained by field observation As mentioned above, the carbon balance in tropical forest is needed. Soil respiration property, like temperature and water sensitivity, should be studied in this evergreen forest in Eastern Asia. There are two methods to obtain the soil respiration properties. Firstly, one is a method of measuring soil respiration in a field which has a clear temperature and water seasonality. Measuring soil respiration at various temperature and water conditions allow us to obtain the relationships between soil respiration and temperature, and water. Secondly, another is a method of measuring soil respiration in a laboratory-system which can control temperature and water.

Soil water sensitivity can be obtained In the evergreen forest in Eastern Asia, the relationship between soil respiration and soil water can be obtained because the forest has the explicit seasonality of soil water. However, the forest experiences very little temperature seasonality, and then it is impossible to obtain the

relationship between soil respiration and soil temperature. Hence it is needed to measure the relationship between soil respiration and soil temperature in a laboratory-system.

Importance of vertical distribution Soil respiration is a CO_2 flux from a soil surface. However, it is important to consider the process which CO_2 was produced and transported. CO_2 is produced at various depths and is transported to the soil surface mainly by diffusion. The source of CO_2 production vertically distributes in subsoil. In other words, the potential of CO_2 production varies at each depth and the environments which stimulate CO_2 production like soil temperature and soil water at each depth differ. CO_2 is produced at each depth responding to the potential and environmental stimulation. To understand the mechanism of soil respiration, it is important to investigate the vertical distribution of CO_2 production rate in soil and also that of gas diffusion coefficient.

Objectives of this study The objectives of this study were to obtain the temperature sensitivity of soil respiration under laboratory conditions; to measure the vertical distribution of soil CO_2 production rate and the gas diffusivity.

4.2 Material and Method

4.2.1 Site description

The study area, the Kog-Ma Experimental Watershed of Kasetsart University, is situated near the city of Chiang-Mai in northern Thailand, located at $18^\circ 48' \text{N}$, $98^\circ 54' \text{E}$, at an altitude of about 1300 m (Fig. 4.1). Detailed of this site are described by Hashimoto et al. (2004) and Tanaka et al. (2003). Thai researchers

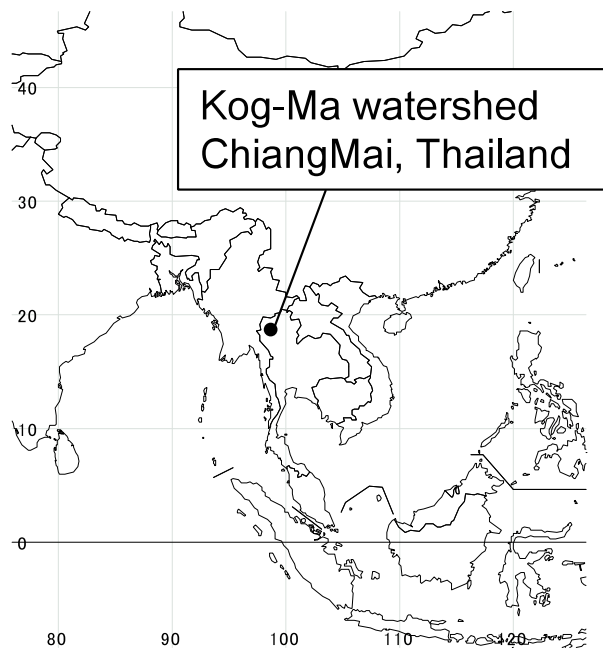


Figure 4.1: Location of Kog-Ma watershed.

have conducted many ecological and hydrological studies in this experimental watershed since 1965. Thai and

Location				
Latitude	18 ° 48'N			
Longitude	98 ° 54'E			
Climate*				
Mean annual precipitation, mm	2084.1			
Mean annual temperature, °C	20			
Properties, m	0-0.1	0.1-0.2	0.2-0.3	0.3-0.4
Rock (≥ 2 mm), g	69.9	82.6	91.5	224.7
Large organic matter (≥ 2 mm), g	7.0	3.5	4.4	3.7
Small nonorganic particle(<2 mm), g	1205.7	1759.8	2216.1	2354.9
Small organic matter (<2 mm), g	320.3	352.2	365.9	341.1
Sand, % **	45.0		42.1	
Silt, % **	28.9		27.1	
Clay, % **	27.1		30.8	
Texture **	Sandy Clay Loam		Clay Loam	
C/N ratio	13.1	12.3	11.7	10.6
Total porosity	0.735	0.730	0.620	0.595

* Chunkao et al. 1981 from 1966 to 1980

** Udomchock et al. 1983, USDA basis

Table 4.1: Site location, climate, and soil properties in Kog-Ma watershed.

Japanese hydrologists began cooperative research in 1997, to estimate energy and water budgets in hillside evergreen forests as a part of GAME (GEWEX-related Asia Monsoon Experiment). Soil respiration and soil CO₂ carbon dioxide concentration have been measured, together with soil temperature and soil moisture.

The Kog-Ma Experimental Watershed is covered by dense evergreen forest, mainly dominated by *Castanopsis*, *Lithocarpus*, and *Quercus* sp. The mean annual precipitation between 1966 and 1980 was 2084.1 mm (Chunkao et al. 1981). The rainy season usually starts in April and lasts through November, whereas the dry season occurs from December to March. January and February usually experience no rainfall. Six months of the dry season receive < 100 mm of precipitation (November to, April between 1966 and 1980, Chunkao et al. 1981). The mean annual temperature at the site is 20 °C. This kind of tropical forest, so called hill evergreen forest, is characterized by comparatively long dry season and low temperature (Whitmore, 1990). The average annual litter fall between 1968 and 1972 was 6.88 tonha⁻¹y⁻¹ (dry weight, Boonyawat and Ngampongsai, 1974; Thaitutsa et al. 1979). Monthly litter fall is generally largest in February and smallest in August (Boonyawat and Ngampongsai, 1974).

Soil type Soil properties were investigated by Udomchock et al. (1983). Soil type is Reddish Brown Lateritic. Soil texture of A layer (0-0.24 m) was Sandy clay loam. Total porosity of A layer was about 0.64. Soil texture of B layer (0.24-0.49 m) was Clay loamy. Total porosity of B layer was about 0.59. After the incubation, the soil sample was sieved and analyzed. Samples' properties are shown in Table 4.1.

4.2.2 Sampling

Sampling Undisturbed forest soil, of about 0.2 m diameter and 0.4 m long, was collected in 6th November 2002. Early November is just the end of rainy season and the beginning of the dry season in this region. The soil sample was collected by hammering sample column with a sharpened rim in to the soil. The process of obtaining the soil core was similar to the one which was described by Fang and Moncrief 2001. To obtain the soil core, the cylinder with sharpened rim was forces a few centimeters in to the soil and the soil around the rim was removed carefully with a knife. The cylinder was then pressed further into the soil by hammering the

upper end of the cylinder. This process was repeated.

Sampling position The sampling area was about 7 m west of the tower and about 6 m west of the soil respiration measurement point, point B. Fresh litters were removed before sampling. Before sampling, I measured the soil respiration from the surface. The value of soil respiration before sampling was about $1.33 \text{ kgCO}_2\text{m}^{-2}\text{s}^{-1}$. The surface temperature was about 15.3°C , and the soil temperatures at 0.05, 0.15, 0.25, 0.35, 0.45 m were 16.8, 17.3, 17.7, 18.3, 19.1°C , respectively. Soil water contents at 0.05, 0.15, 0.25, 0.35, 0.45 m were measured using TDR and were 0.28, 0.34, 0.34, 0.35 and 0.35, respectively.

4.2.3 Incubation system

The details of this experimental system are described in Chapter 3. The experimental system was developed by Hashimoto and Suzuki (2000) and Hashimoto and Suzuki (2002).

The system Figure 3.2 shows the system. The system consists of a sample column, a chamber at each end, a gas circulator, and a temperature control. The soil sample collected was attached a chamber at each end. Thermometers, tension meters and TDRs were installed. Tubes which each end was connected to a thermo pump (Tokyorikakikai Co. Tokyo., Japan) wrapped the sample column, which allowed us to change soil sample temperature and keep it. Soil sample temperature can be controlled by circulating water at a temperature in tubes surrounding the sample column using a thermo pump (Tokyorikakikai Co. Tokyo., Japan) for keeping soil temperature.

CO₂ flux measurement CO₂ flux from soil surface was measured by the dynamic closed chamber method. CO₂ concentration in the attached chamber was measured using CO₂ analyzer and air pump (flow rate: 27.3 cc/s), at 1-s intervals for 3-5 min. The CO₂ flux is calculated from the rate of increase in the CO₂ concentration in the chamber.

CO₂ concentration measurement Soil gases at each depth were sampled using a syringe, and the CO₂ concentrations were measured using a CO₂ analyzer. Generally, the CO₂ concentrations in soil are too high and the sample volumes are too small to be measured with CO₂ analyzer, like LiCor-6262, 6252. Then, Hashimoto (2002) proposed a method which the sample gas volume is increased with air of known CO₂ concentration and is analyzed using an infrared gas analyzer.

4.2.4 Incubation

Soil sample was conditioned at three different temperature conditions but a water condition, and soil CO₂ flux and soil CO₂ concentrations were measured.

Soil water Before incubation, the soil sample was saturated and then drained. Only one soil water content was applied to the soil sample. Soil suction at 0.35 m depth was set at -0.5 m using the soil water control device.

Temperature Soil temperature was controlled by the thermo pump. The circulating temperature was changed at 5, 20, 35°C . Soil sample temperature was affected by air temperature as well. So soil sample was conditioned at about 10, 21, 32°C . Soil temperature was increased from minimum to maximum and then back to minimum. Soil CO₂ fluxes were measured when the soil temperature reached a steady state after soil temperature was changed. Unsteady changes of soil CO₂ flux and soil CO₂ concentration profile were also measured when soil temperature had been changing from 21 to 32°C .

Boundary gas condition During the incubation, holes of upper chamber were open and CO₂ concentration in the upper chamber was kept at atmospheric CO₂ concentration. Holes of the lower chamber were closed. As mentioned below, only when measuring the vertical distribution of the gas diffusion coefficients and CO₂ production rates, the holes of the lower chamber were open and CO₂ concentration in the lower chamber was also kept at atmospheric concentration.

4.2.5 Vertical distribution of the gas diffusion coefficient and the CO₂ production rate

During the incubation, a measurement of the vertical distribution of the gas diffusion coefficients and CO₂ production rates of this sample was conducted. Hashimoto (2002) proposed a new method that evaluates the vertical distribution of the gas diffusion coefficients and CO₂ production rates. Details of this method are described in Chapter 3. They measured the CO₂ fluxes at the boundary of a soil sample and the steady-state CO₂ gas profile measured under two boundary gas conditions and calculated the gas diffusion and CO₂ production using the data and the differential form of Fick's second law. I applied this method when soil temperature was about 21 °C .

4.3 Results

4.3.1 Incubation

Temperature and water content controls Figure 4.2 shows the soil and air temperature, and soil water content during the incubation. Soil sample was saturated (7th and 8th November 2002) and then drained. Although, soil water contents changed during the incubation, the degrees were about 0.05 and not so large, which probably did not affect the CO₂ production during this incubation. The soil water content at 0.05 m, which was the shallowest depth, changed most. This is because the upper surface was always open in this system and soil water somehow evaporated. The average soil water content at each depth was 0.34, 0.41, 0.48, and 0.42, respectively. Soil temperature control was begun after the saturation (8th November 2002). I can see how long time it took for the soil sample to be in thermal equilibrium. When soil temperature changed from 22 °C to 10 °C , or 32 °C , it took about 18 hours. On the other hand, when soil temperature changed from 10 °C or from 32 °C to 22 °C , it took less time, about 12 hours to be in thermal equilibrium. This is because air temperature was about 22 °C and affected the temperature control performance. There were no differences in temperature among the thermometers at 22 °C and 32 °C , however, there were a little difference, about 1-2 °C , at 12 °C . In my incubation system, holes of the upper chamber were always open, and fresh air pumped slowly into one hole leaves through the other and the CO₂ concentration was kept at atmospheric condition. Hence, the control of the upper surface temperature is difficult in this system, which should be improved.

Flux and conc. Figure 4.2 (d) and (e) show the CO₂ fluxes measured at the upper soil surface and the CO₂ concentration at each depth. CO₂ flux increased with increasing temperature, ranging from about 0.5 to 2.6 kgCO₂m⁻²s⁻¹. CO₂ concentration at each depth also increased with increasing temperature. At 0.4 m depth, CO₂ concentration ranged from 0.0022 to 0.017 kgm⁻³.

4.3.2 Temperature sensitivity

Steady state

Relationship between average soil temperature and flux The relationship between soil temperature and CO₂ flux from the soil sample is shown in Fig. 4.3. Soil temperature is the average temperature of this soil sample. My system could not control the soil surface for the soil surface was open to be kept at atmospheric CO₂ concentration (Fig. 3.2). Average temperature was calculated as the average of the temperature of each

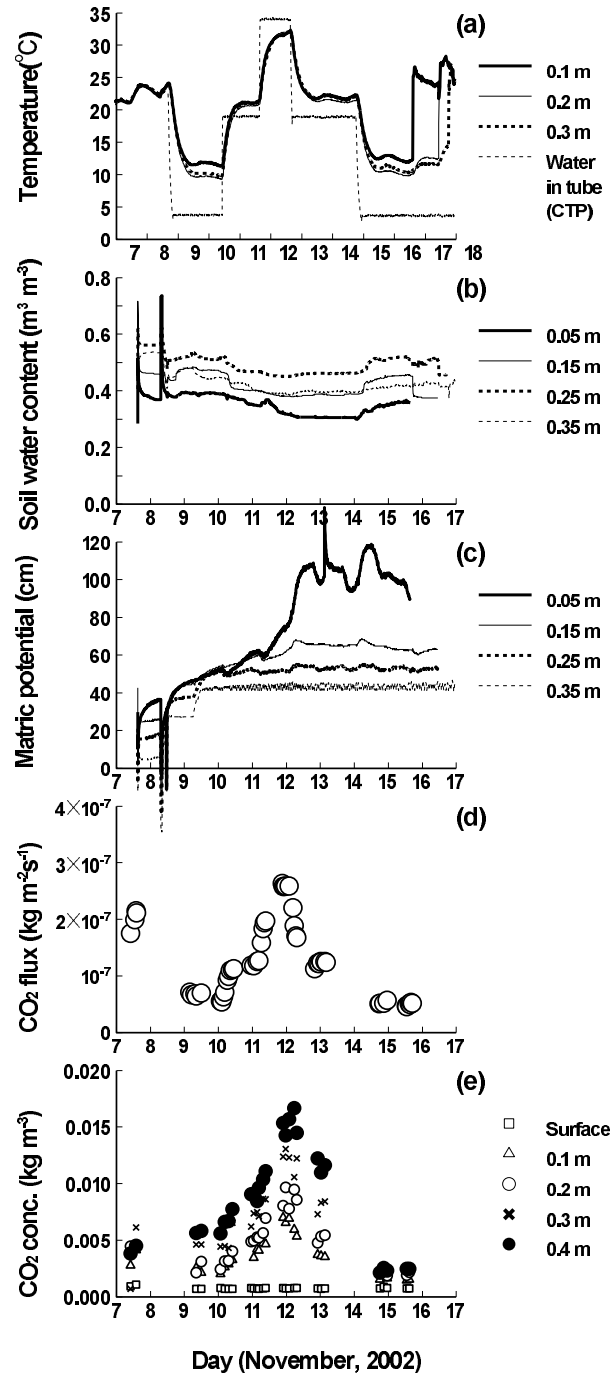


Figure 4.2: Soil, air, and CTP's temperature; soil water content; matric potential during the incubation period. Also, CO_2 flux measured at soil surface, which was the total CO_2 production from the soil sample, and CO_2 concentration at each depth in soil sample.

layer. CO₂ fluxes are the averages of the values measured when soil sample was both thermal and the gaseous

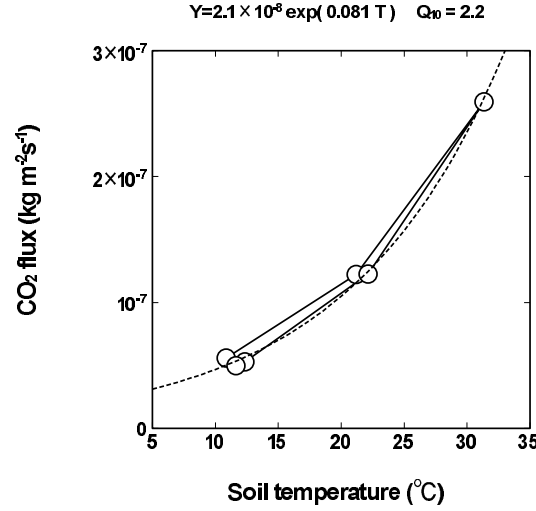


Figure 4.3: The temperature dependence of soil surface flux (total CO₂ production from the soil sample). Soil temperature near the surface was affected by the air temperature, although soil temperatures below the depth were almost the same. Then, I used average soil temperatures.

equilibrium. The gaseous equilibrium was defined as follows: After the thermal equilibrium, soil CO₂ flux also reached the constant values in a few hours and then, soil CO₂ profile in this soil sample also reach the equilibrium in a few hours.

Temperature-increasing process and temperature-decreasing process The influence of incubation time on measured CO₂ efflux was found in this study. Soil CO₂ effluxes in temperature-decreasing process tend to be smaller than those in temperature-increasing process.

Q₁₀ value The relationship between soil temperature and CO₂ flux was fitted with an exponential model,

$$SR = Ae^{kT} \quad (4.1)$$

where SR is the soil CO₂ flux, A and k are the constants, and T is the soil temperature (°C). The fit gives A of 2.1×10^{-8} and k of 0.081 , respectively. Q_{10} is the factor by which soil respiration rate increased when temperature increased by 10 °C. Q_{10} is a factor which indicates the temperature sensitivity of soil respiration and is widely used. Q_{10} value can be expressed with equation 4.1:

$$Q_{10} = (Ae^{k(T+10)})/Ae^{kT} \quad (4.2)$$

$$= e^{10k} \quad (4.3)$$

The value I obtained was $Q_{10} = 2.2$. My Q_{10} value was calculated using soil CO₂ flux data which were measured when soil sample was the thermal and gaseous equilibrium.

Unsteady state

How quickly soil respiration responds to changes of soil temperature Intermediate CO₂ flux changes between one equilibrium and next equilibrium were also observed (Fig. 4.4). This shows how quickly soil respiration responded to the soil thermal changes and CO₂ concentration profile changed. Soil sample was in thermal and gaseous equilibrium until T=15 h. Then the temperature in the tubes which rapped the soil sample was suddenly changed from 20 °C to 35 °C .

How long time are required to achieve thermal and gaseous equilibrium Soil sample temperature began to rise without a hourly delay from about 21 °C and reached the steady state at ca. 32 °C about 15 hours later after the change started (T=30 h). Soil CO₂ flux quickly responded to the change of soil temperature, without a hourly delay. Data between T=20 and 32 h were absent, however, soil CO₂ had reached the steady state about 16 hours later after the change started. On the other hand, soil CO₂ concentration did not respond as quickly as soil CO₂ flux. At the beginning, CO₂ concentration at 0.1 m depth seemed to be less sensitive. CO₂ concentration reached the steady state about 16 hours later after the change started.

4.3.3 Vertical distribution of gas diffusion coefficient and CO₂ production rate

Flux from each end/CO₂ concentration profiles The CO₂ gas concentration measurements used to determine the gas diffusion coefficient are presented in Fig. 4.5. CO₂ concentration profiles were measured when soil temperature was set about 21 °C . CO₂ flux measurements were conducted 3 to 5 times at -3-h intervals and CO₂ concentration profile measurements were made 3-5 times at -3 h intervals at open and closed conditions. The measurement at closed condition was made at first and then the lower chamber was opened and the measurement at open condition was made. The interval between measurements under closed and open conditions was about 24 h.

Vertical distribution of CO₂ production rate and gas diffusion coefficient Figure 4.5 shows the vertical distribution of the gas diffusion coefficient which was measured by this method. The gas diffusion coefficients decreased with increasing depth. The gas diffusion coefficient at shallowest depth was the largest. Figure 4.5 shows the vertical distribution of the CO₂ production rate. The CO₂ production rates also decreased with increasing depth, ranging from 0.8 to 7.2 kgCO₂m⁻³s⁻¹. The CO₂ production rate at shallowest depth (0-0.1 m) was the largest. The CO₂ production rate at second layer (0.1-0.2 m) was about half of the shallowest layer. The CO₂ production rates at third (0.2-0.3 m) and fourth layer (0.3-0.4 m) was the same level.

Comparison between measured gas diffusivity and empirical model Figure 4.6 shows the relationships between air-filled porosity and relative gas diffusion coefficient. The relative gas diffusion coefficient is the ratio of the gas diffusion coefficient in soils to that in free air. The gas diffusion coefficient in free air can be expressed by following equation.

$$D_0 = D_{standard}(1013/P)((273 + T)/273)^{1.75} \quad (4.4)$$

where D is the gas diffusion coefficient of CO₂ at standard condition (0 °C , 1013 hpa) T is the temperature (°C), P is the atmospheric pressure. P was assumed to be 1013 hpa in this study. The gas diffusion coefficient increased with increasing air-filled porosity. Measured gas diffusion coefficients were compared with other empirical model, which estimates the gas diffusivity and a function of air-filled porosity. Penmann model ($D_s/D_0 = 0.66\epsilon$) overestimates my results and Millington-Qurk model ($D_s/D_0 = \epsilon^{(10/3)}/\Phi(2)$) underestimates my results. The relationship between air-filled porosity and relative gas diffusion coefficient measured in this study was fitted with a Currie model equation:

$$D_s/D_0 = a\epsilon^c \quad (4.5)$$

where a and b are the constants. The fit gives the a of 2.03 and c of 2.78.

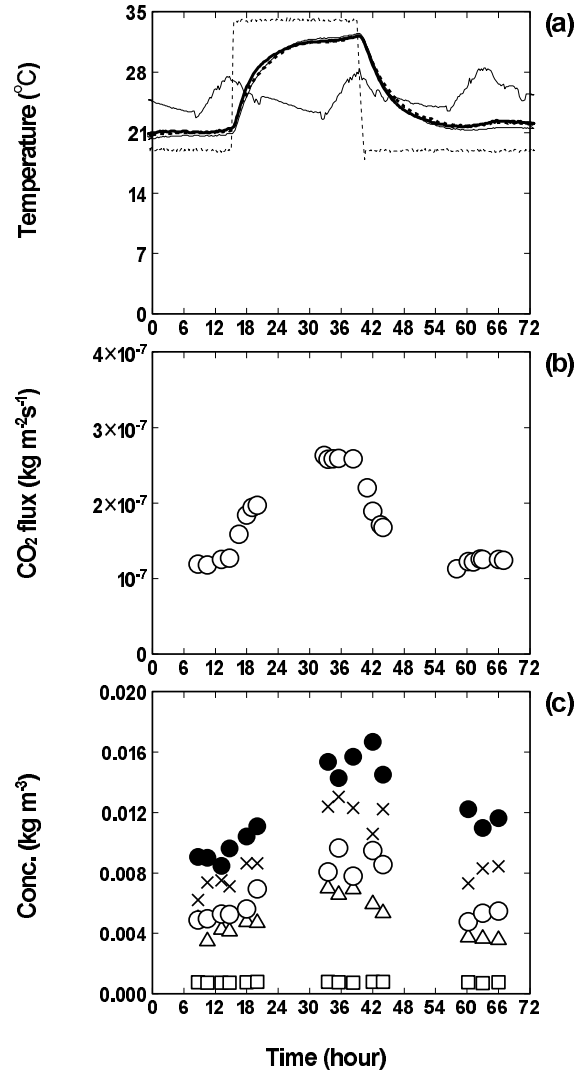


Figure 4.4: Unsteady change of soil temperature, and unsteady response of soil surface flux and CO_2 concentration in soil sample which were induced by the change of soil temperature. Temperature was changed suddenly when it was in steady state. See the Fig. 4.2 caption for explanation of symbols.

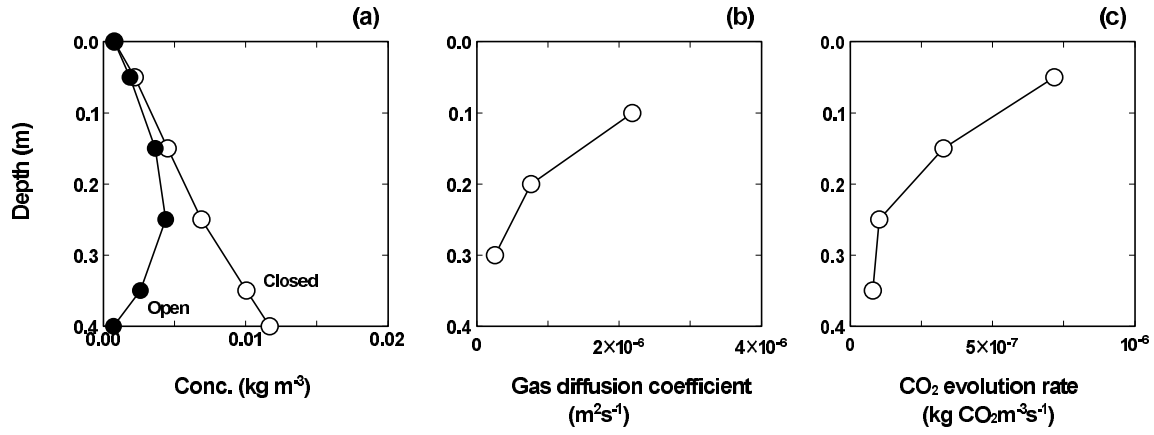


Figure 4.5: Vertical distributions of soil CO₂ concentration used for calculating vertical profiles of soil gas diffusion coefficients and CO₂ production rates, and obtained profiles. Measurements were conducted at 20 °C .

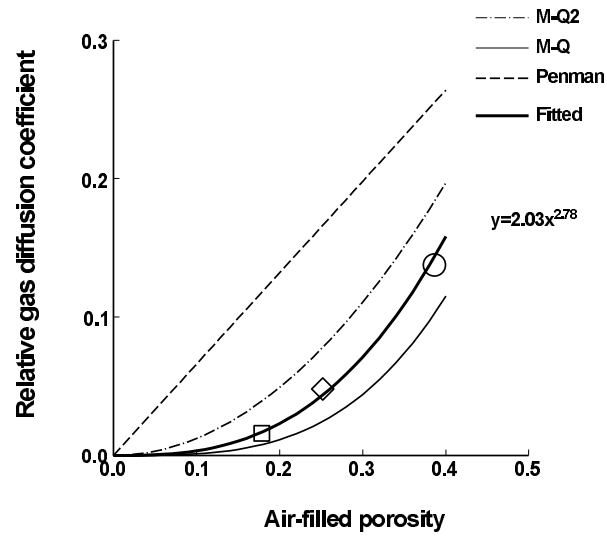


Figure 4.6: The relationship between air porosity and relative gas diffusion coefficient. Circle: 0.1 m depth; diamond: 0.2 m depth; square: 0.3 m depth. Solid lines are empirical models.

4.3.4 Influence of incubation

As mentioned above, a hysteresis was observed. That is, soil CO₂ effluxes in temperature-decreasing process tend to be smaller than those in temperature-increasing process (Fig. 4.7). The decomposition constant obtained in this study was about -0.028 d⁻¹.

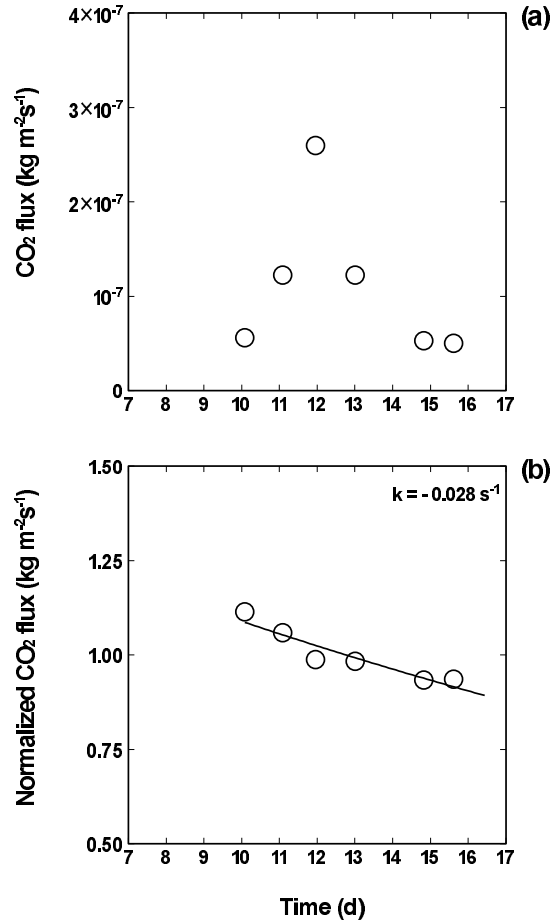


Figure 4.7: Soil surface flux (total CO₂ production of soil sample) during the experimental period, and flux normalized by the exponential relationships between soil temperature and soil surface flux in Fig. 4.3.

4.3.5 The relationships between soil properties and CO₂ production rate

Figure 4.8 presented the relationships between soil properties and CO₂ production rate at each layer on volumetric basis (kgm⁻³s⁻¹). I compared soil CO₂ production rate on volumetric basis with ratios of loss of ignition to total small soil (< 2 mm), the amount of loss of ignition, and C/N ratio. There were slightly linear relationships between soil CO₂ production rate and organic matter content, and between soil CO₂ production rate and C/N ratio. I could not find clear relationships between soil CO₂ production rate and the amount of soil organic matter in each layer; however, I could see that the soil in a layer in Thai contained more than twice

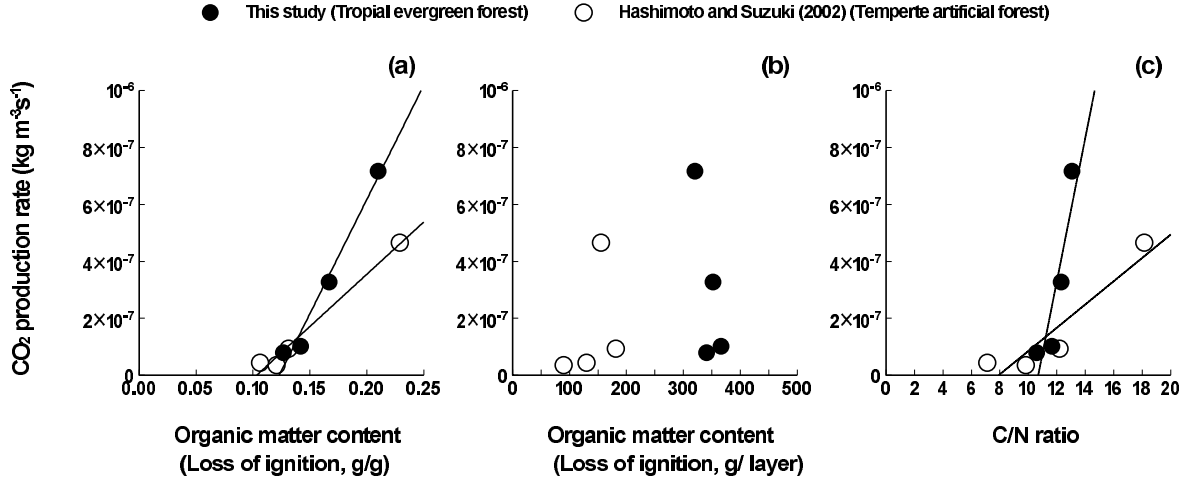


Figure 4.8: The relationships between soil CO₂ production rate on volumetric basis and soil properties (the ratio of organic matter in small particle, the amount of organic matter in small particle, and C/N ratio). Both are the results at about 20 °C .

as much as organic matter in a layer. Then I plotted soil CO₂ production rate on gravimetric basis (kgkg⁻¹s⁻¹) and soil properties (Fig. 4.9). I found a exponential relationships between organic matter content and soil CO₂ production rate on gravimetric basis. CO₂ production rate on volumetric basis can be calculated using the following equation.

$$y = 1.57 \times 10^{-9} e^{(26.6r)} d \quad (4.6)$$

where y is the CO₂ production rate on volumetric basis (kgm⁻³s⁻¹), r is the ratio of organic matter content and d is the soil density.

4.4 Discussion

4.4.1 Temperature sensitivity

Comparison of temperature sensitivity with those of other study/Comparison of Q₁₀ value My study reveals the strong relationship between soil respiration and temperature in hill evergreen forest in Thailand as other studies in other ecosystems have reported. Soil respiration increased exponentially with increasing soil temperature. The Q₁₀ value I obtained in this study is 2.2 and is comparable to other studies, although, as mentioned below, it is difficult to compare the Q₁₀ values. Raich and Schlesinger (1992) showed the Q₁₀ value for total soil respiration has a median value of 2.4, based on in situ measurements. The Q₁₀ value I obtained by the laboratory experiment is very similar to the average value. There are few reports on the temperature sensitivity of soil respiration in tropic regions. Meir et al. (1996) conducted field observations in a rainforest in Amazonia, investigated the seasonal relationship between soil respiration and soil temperature at 0.01 m with an exponential model and found that Q₁₀ was about 2.3. The value is the same as that of my study. Kiese and Butterbach-Bahl (2002) carried out laboratory-incubation after the failure of revealing a significant influence of soil respiration and soil temperature by field observations in three different tropical forest sites in the wet tropics, Australia, and studied the relationships between soil respiration and soil temperature for the temperature range 20-30 °C , and found that Q₁₀ values were 3.0, 3.6, 5.0. These values were higher than that of my study.

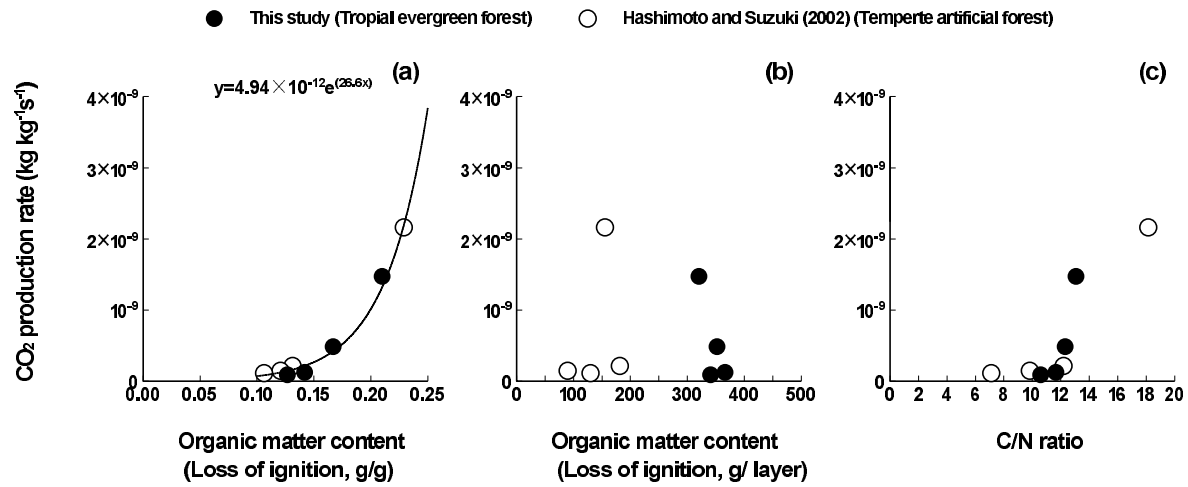


Figure 4.9: The relationships between soil CO₂ production rate on gravimetric basis and soil properties.

4.4.2 Unsteady temperature sensitivity

How quickly? It is very interesting how quickly soil respiration responds to the change of soil temperature and soil CO₂ profile is formed. These kinds of data were mainly observed in fields, not laboratory-incubations. Some diurnal field-observation of soil respiration and soil temperature shows the unsteady changes of soil respiration (Janssens and Barigah, 1998). Some incubation systems allow measurements of the unsteady-changes of soil respiration (Fang and Moncrieff, 2001; Murthy et al. 2003), so my system can do. My measurements indicated the quick response of soil respiration to temperature change, without hourly delay. When considering the response of soil respiration to temperature change, the response of CO₂ production to temperature change and the time which CO₂ produced at each depth is transported should be taken into consideration. If the contribution of soil layer which is deeper is high, it would take more time for the CO₂ to be transported to the soil surface.

4.4.3 The vertical distributions of CO₂ production rate and gas diffusivity

Comparison of vertical distribution of CO₂ production There are few studies on the vertical distributions of CO₂ production rate. Little is known, in particular, about tropic forests. de Jong and Schappert (1972) measured the gas diffusion coefficients and soil CO₂ profile in situ and calculated the CO₂ production rate at each depth under virgin prairie in Canada. Ino and Monsi (1969) collected soil samples at several depth (0-0.3 m) in seven ecosystems (forests and grasslands) in Japan and incubated them. Hashimoto (2002) measured the vertical distribution of CO₂ production rates in a coniferous forest soil in Japan using the same system as us. These studies demonstrated that CO₂ production rates decrease with increasing depth. My results agree with these studies. It is often assumed that the soil is poor and the main source of CO₂ in tropical forest is the shallowest layer because of the first turnover. On the other hand, it is also considered that soils in tropical forests may be many meters in depth, well mixed, and high in soil organic content, because they have developed over millions of years without disturbances such as glaciations and mixed well by active earthworms (Waring and Running, 1998). My results showed the layer of 0.1-0.2 m depth contributed about half as much as the shallowest layer (0-0.1 m), which probably indicated the well mixed soil.

The vertical distribution of CO₂ production rate in this study was measured when the soil temperature was about 21 °C at each depth and the soil water contents were 0.35-0.45. These water conditions are neither too dry

nor too wet. In the field, the contributions of deeper layers would be sometimes larger, because the shallower soil experiences severer droughts than deeper soil.

Comparison of the value of CO₂ production rate The values of the CO₂ production rates measured in this study were comparatively higher than those of other studies. Compared to the temperate coniferous forest, the value was almost two times higher. Soil respiration measured in this field is also larger than other studies. There may be different processes or mechanisms in tropic forest soils.

Comparison of gas diffusion coefficient The soil gas diffusivity is the most important property in analyzing soil CO₂ gas movement in soil. The gas diffusion coefficients also decreased with increasing depth. A gas diffusion coefficient is a function of air porosity. Shallower soils tend to have more total porosity than deeper soil, and also to be dryer and then to have larger gas diffusion coefficients. There are many kinds of gas diffusion-air porosity models. It is because the gas diffusivity is affected by not only the quantity of air porosity but also the connection property.

4.4.4 The relationships between soil properties and soil CO₂ production

In this study, soil organic matter content was descriptive of soil CO₂ production rate. There are many studies on the relationships between soil properties and soil CO₂ production rate, or decomposition. Ino and Monsi (1969) found linear relationships between organic carbon content and CO₂ production rates. But the relationships differed among sites. Franzluebbers et al. (2000) also presented linear relationships between organic matter content and C mineralization. In the study, C mineralization of one soil quadratically increased with increasing soil organic C, and was concave. This result is similar to my exponential relationship. Kiese and Butterbach-Bahl (2002) measured N₂O and CO₂ emissions from three different tropical forest sites. They explained site differences in only N₂O -emissions with C-to-N ratio of the organic matter, not site differences in CO₂ emissions.

4.4.5 Q₁₀ value

Definition of Q₁₀ value/Steady state?/Sources exist vertically and Environmental factors also vary Q₁₀ value is very simple and helpful index when comparing temperature sensitivities of soil respiration. However, Q₁₀ has been said to be carefully handled (Kirschbaum, 1995; Fang and Moncrieff, 2001). As Fang and Moncrieff (2001) and Davidson et al. (1998) pointed out, comparing the Q₁₀ values determined by different studies are difficult because Q₁₀ values may be different depend on which model was used. Kirschbaum (1995) showed the temperature dependence of Q₁₀ value. Moreover, what matters is whether soil respiration was measured at temperature-steady state. The source of CO₂ production rates distribute horizontally. The soil at each depth produces CO₂ by responding to the environmental factors at each depth. CO₂ is produced at each depth and is transported to the soil surface. When soil temperature changes more rapidly than CO₂ is transported, the relationship between soil respiration and soil temperature is affected by the temperature diffusivity and the vertical distribution of CO₂ production rate. This should occur in diurnal measurements. Janssens and Barigah et al. (1998) reported a hysteresis when plotting a complete diurnal cycle of soil respiration versus soil temperature. Also, the depth of soil temperature which is related to soil respiration is important. Generally, the range of soil temperature decrease with increasing depth and then the deeper the depth which is compared to soil respiration is, the larger the Q₁₀ value is. The depths of soil temperature were arbitrarily chosen in each study. Q₁₀ value is very convenient index for considering the temperature sensitivity of soil respiration. However, Q₁₀ values must be carefully used.

4.4.6 Environmental control limitation of this apparatus and its effect

Soil surface temperature/Control of soil water condition My system allows soil temperature control and, to some extent, soil water control. However, these controls are not perfect. The soil surface is always kept at

atmospheric CO₂ concentration. This cause soil temperature changes according to the difference in temperature between soil sample and air temperature. When soil temperature is kept at a temperature which is about the same as air temperature, it does not matter. But when soil temperature is cooler than air temperature, soil surface is hotter than soil temperature by the effect of the air temperature. This should be improved. In some studies which dealt with large soil samples, soil temperatures were controlled by changing and keeping the air temperature in the rooms. This method does not have such a difference of temperature. But the method may take more time to change soil temperature. Soil water control has much difficulty. Soil water control is much more difficult than soil temperature control in handling a large soil sample. It is, in particular, difficult to dry a large undisturbed soil sample. To control soil water content of a large undisturbed soil sample for a wide range is left as a future problem.

4.5 Conclusions

Temperature sensitivity of soil respiration in tropic evergreen forest was measured in a laboratory condition, which had been unclear. The soil respiration in tropic evergreen forest responded exponentially to temperature as well as in other ecosystems. The sensitivity was fitted by an exponential equation ($Y = 2.1 \times 10^{-8} \exp(0.081T)$), and the Q_{10} value was about 2.2. I also revealed the vertical distributions of soil CO₂ production rate and gas diffusion coefficient. These results should improve the accuracy of global carbon cycle model, which tropical forests play important roles. However, the studies on soil respiration in tropic regions are lacking as ever compared to other regions, and then more and more studies are needed, especially studies under laboratory conditions. Tropic regions have generally very small temperature seasonality, and moreover some tropic regions have even no water seasonality. To evaluate the response of soil respiration to environmental factors, measurements of soil respiration under environmental conditions which are strictly controlled are essential.

Chapter 5

Direct measurements of CO₂ production in each depth

5.1 Introduction

Forest soil contains lots of carbon Soil stores enormous amount of C, more C than plants and the atmosphere. The amount of soil organic carbon (SOC) was estimated about more than 2000 Pg C (Jobbagy and Jackson, 2000). The change of SOC is one of key issues for understanding the impact of and on climate change.

Soil respiration is the result of the processes of production and transport Soil respiration, emissions of CO₂ which produced by soil organic matter decomposition and root respiration, is one of the largest process of soil organic carbon release from soil to atmosphere. Since the global warming induced by greenhouse gases was a serious concern, many researchers have investigated the soil respiration. However, fewer researchers had taken the vertical process of soil respiration into consideration; only measuring soil surface efflux and soil temperature and soil water content at one depth. Nonetheless, the source of soil respiration distributes with depth, and the environments which stimulate the source vary with depth as well. As discussed in Chapter 1.4, I can see possible errors which would be caused by the lack of considering the vertical process of soil respiration.

Previous studies which tried to evaluate the CO₂ production rate Experimental approaches have advantages, like being able to control environmental conditions, and allow accurate measurements and various treatments. Ino and Monsi (1969) collected soil samples of various depths from 7 sites, incubated them, and measured soil respiration. Hashimoto and Suzuki (2002) investigated the vertical process of soil respiration, like vertical distributions of soil CO₂ production rates and gas diffusivity.

Some studies investigated the vertical processes of soil respiration through field observations. de Jong and Schappert (1972) measured soil respiration at each depth by measuring soil CO₂ concentration and gas diffusion coefficient. Campbell and Frascarelli (1981) measured soil CO₂ production rate at several depths by absorbing CO₂ at each depth directly with an absorbent solution. With the similar method to de Jong and Schappert (1972) method, Osozawa and Hasegawa (1995) investigated diel and seasonal changes in CO₂ flux in an andisol. Davidson and Trumbore (1995), also in the same way, measured production of CO₂ in deep soils of the eastern Amazon, and found that about 70-80 % of CO₂ production in forest and pasture in Amazon occurs within the top 1 m of soil. Hirsch et al. (2002) investigated deep soil respiration in a boreal forest and found that soil respiration varied linearly with 50 cm temperature. Gaudinski et al. (2000) calculated CO₂ flux at each depth by Fick's first law and radiocarbon inventory and found that 63 % of soil respiration took place in the top 15 cm of the soil in a temperate forest. Hendry et al. (1999) simulated soil CO₂ concentration and soil surface CO₂ flux and quantified the CO₂ production rate at each depth by its parameterization and sensitivity analysis.

Trumbore (1993) compared carbon dynamics in tropical and temperate soils using radiocarbon measurements and showed that the majority of the organic carbon in the upper 22 cm of the tropical soil has residence times of 10 years or less; on the other hand, equal amount of carbon with residence times of 10, 100, and 1000 years in temperate forest.

The difficulty of studying subsoil/Soil with matrix (structure), high heterogeneity, extremely different environmental conditions (high CO₂, poor O₂, temperature regime, water regime) Soil is a porous material which has a structure. Soil is not a mixture of various particles and material, i.e. a mixture of organic matter, water, sand; but a mixture with a structure. When the structure is changed, the soil is not the same and shows different physical properties. Therefore, a risk of disturbing soil structure accompanies to sampling soil and doing experiments with them. Moreover, environmental conditions would be changed by sampling, in particular, soil CO₂ concentration which probably affects CO₂ production in soil. In general, soil CO₂ concentration in soil is significantly higher than that is in atmosphere. Hence, investigating the vertical process of soil respiration through field observation is important as well as experimental approaches.

Objectives of this study My objectives are to (1) evaluate the vertical distributions of CO₂ production rate through field conditions, (2) examine their seasonality and contributions, and (3) quantify the relationships between soil CO₂ production rate and soil temperature or soil water. I calculate the soil gas diffusivity, evaluate soil CO₂ flux at each depth with Fick's first law, and obtain the CO₂ production rates at each depth. Two observation data were used: Fukuroyamasawa watershed, a temperate coniferous forest in Japan; Kog-Ma watershed, a tropical evergreen forest in Thailand. In former watershed, soil temperature controls soil respiration; on the other hand, in latter watershed, soil water content does.

5.2 Material and Method

5.2.1 Sites

This study has conducted in two different types of forest: Fukuroyamasawa watershed, a temperate deciduous forest in Japan, and Kog-Ma watershed, a tropical evergreen forest in Thailand. Table 3.1 and 4.1 show the climate and vegetation properties of Fukuroyamasawa watershed and Kog-Ma watershed. Figure 5.2 and 5.3 show the seasonality of air temperature and rainfall in each watershed. The two watershed have contrasting seasonality. In Fukuroyamasawa watershed, air temperature changed largely but rainfall varied little. On the other hand, in Kog-Ma watershed, air temperature changed little but rainfall varied largely. Figure 5.1 shows the locations of Fukuroyamasawa watershed and Kog-Ma watershed.

Details of the Fukuroyamasawa watershed is described in Chapter 3 and Hashimoto and Suzuki (2004), and those of the Kog-Ma Watershed was described in Chapter 4 and Hashimoto et al. (2004).

Fukuroyamasawa watershed in Japan

Fukuroyamasawa watershed was located in the University Forest of the University of Tokyo, in Chiba prefecture, Japan (35 °12'N 140 °06'E). The elevation of the watershed is about 170 m.

Kog-Ma watershed in Thailand

The Kog-Ma watershed is located in the forest of Kasetsart University, near Chiang-Mai, in northern Thailand.

5.2.2 Field measurements

I used similar methods for measuring soil respiration, soil CO₂ concentration and environments.

Table 5.1 shows the details of measurements.

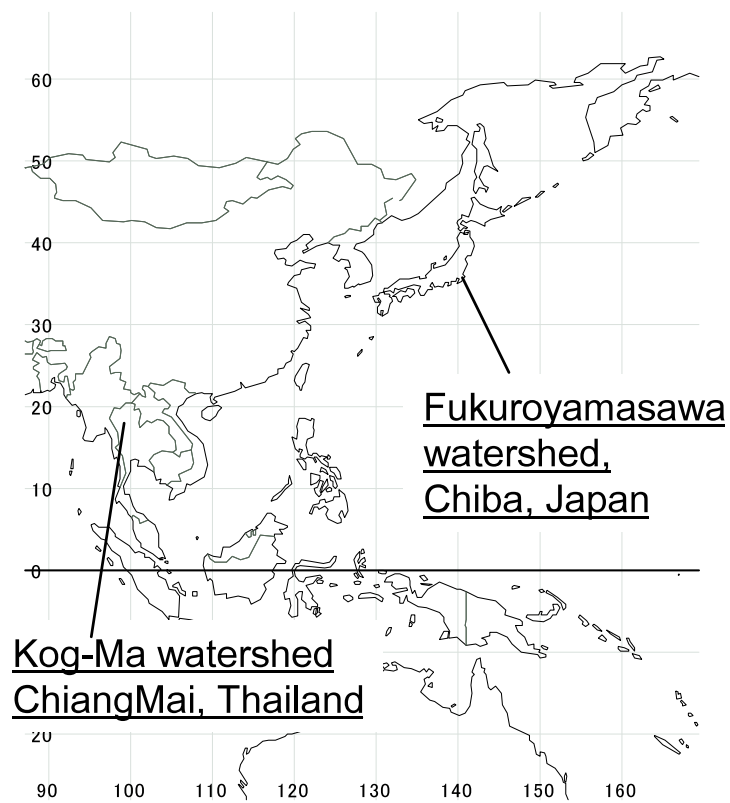


Figure 5.1: Locations of two watersheds.

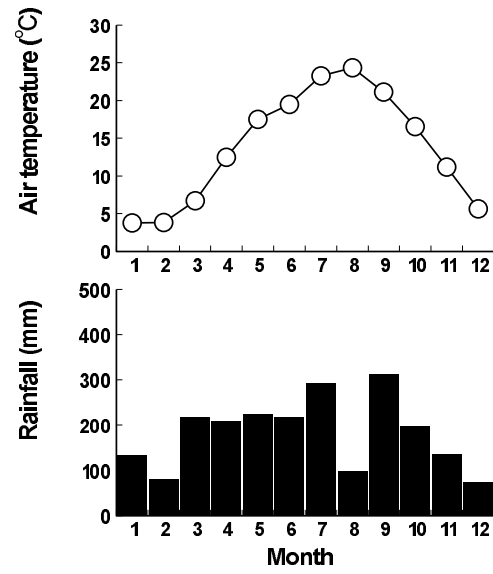


Figure 5.2: Seasonality of air temperature and rainfall in Fukuroyamasawa watershed.

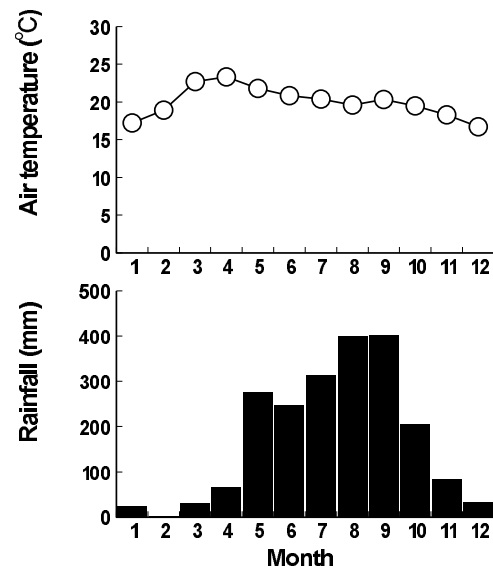


Figure 5.3: Seasonality of air temperature and rainfall in Kog-Ma watershed (Chunkao et al. 1981).

	Fukuroyamazawa	Kog-Ma
Location and Climate		
Latitude	35 ° 12'N	18 ° 48'N
Longitude	140 ° 06'E	98 ° 54'E
Elevation, m	180	1300
Mean annual precipitation, mm	ca. 2000	ca. 2000
Mean annual air temp., °C	ca. 14	ca. 20
Forest type		
Vegetation	Temperate deciduous	Tropical evergreen
Dominante species	Cryptomeria japonica, Camaecyparis obtusa	Castanopsis, Lithocarpus, and Quercus spp.
Artificial/Natural	Artificial forest	Natural forest
Measurements of Soil respiration		
Method	Closed dynamic chamber method	Closed dynamic chamber method
Chamber volume	0.0012	0.00155
Flow rate	0.017 (0.02)	0.017
Log interval	30 sec	10 sec
Obs. interval	1 wk	3 month
Measurements of CO₂ concentration		
Method	Gas detector tubes with a gas sampling pump (Gastec, Japan)	Gas detector tubes with a gas sampling pump (Gastec, Japan)
Depths, m	0.1, 0.2, 0.3, 0.5, 0.8, 1.0	0.1, 0.2, 0.4, 0.6
Obs. interval	1 wk	1 wk
Obs. started	1997	1998

Table 5.1: Comparison in location, climate, vegetation, and observations. See the locations in Fig. 5.1.

Soil respiration The closed-chamber method was used in both watersheds. When measuring soil respiration, I pressed the chamber on the soil surface firmly, but not so firmly that I disturbed the soil surface structure. The chamber edge was not pushed into the soil surface but on the soil surface (Hanson et al. 1993; Striegl and Wickland, 1998). I monitored the CO₂ concentration in the chamber and calculate the value of soil respiration. Measurements of soil respiration were conducted once a week in Fukuroyamasawa watershed, and 3-month intervals in Kog-Ma watershed.

Soil CO₂ gas concentration Soil CO₂ gas concentration was measured using gas detector tubes with a gas-sampling pump (GV-100S, Gastec, Japan). The CO₂ concentration in the air was indicated by the length of the color-changed zone in the gas detector tubes after a few minutes. This method is widely used in Japan (Hamada and Tanaka, 2001). Measurements of soil CO₂ gas concentration were conducted once a week in both watersheds.

Soil water In Fukuroyamasawa watershed, tensionmeters were installed at each depth, and soil matric potentials were measured once a week. When calculated soil water content, I used the relationships between soil matric potential and soil water content measured by Kumagai et al. (1996). TDRs were installed at each depth in Kog-Ma watershed, and soil water contents were measured. The value of soil water content measured by TDR was compared with the value measured by oven-dry sample method, and corrected.

Soil temperature Deep soil temperature was measured using an armored thermometer (Yoshino, type S251) in Fukuroyamasawa watershed. The thermometers were suspended from the cap of the hole with a chain to each depth. When measuring soil temperature, I opened the cap, quickly pull up the chain and take the reading. Shallower soil temperature was measured using a thermo recorder (TR71S, T & D corp.) on 15 minutes intervals from 1999. In Kog-Ma watershed, measure ring soil temperature was conducted using thermistor (CT-UU-A10-2A, Grant Ltd) with a logger (SQ1259, Grant. Ltd).

5.2.3 Theory of direct measurements

CO₂ flux in soil/Fick's law Soil CO₂ flux in soil can be easily written using Fick's first law:

$$f = -D \frac{dC}{dz} \quad (5.1)$$

where D is the CO₂ gas diffusion coefficient in soil, C is the soil CO₂ concentration and z is the distance, respectively. $\frac{dC}{dz}$ is the gradient of soil CO₂ concentration. The difference form of equation 5.1 is as follows.

$$f = -D \frac{\Delta C}{\Delta z} \quad (5.2)$$

In this study, CO₂ flux at each depth was calculated using this equation. The values of D at each depth were calculated with relationships between soil water content and D . The gradients of CO₂ concentration, $\frac{\Delta C}{\Delta z}$, were obtained with observation data. Assuming that CO₂ concentration profiles were almost under steady state, the difference in fluxes at each depth indicated the CO₂ productions at each depth.

$$Y\Delta z = f_i - f_{i+1} \quad (5.3)$$

Figure 5.4 and 5.5 shows the diagram of this calculations.

Soil surface flux Although soil CO₂ flux at each depth except for soil surface can be calculated using equation 5.1, soil CO₂ flux at shallowest layer can not be estimated because soil water content (i.e. gas diffusion coefficient) was not measured at the depth. It should be possible to use the value of soil water content of adjacent layers in

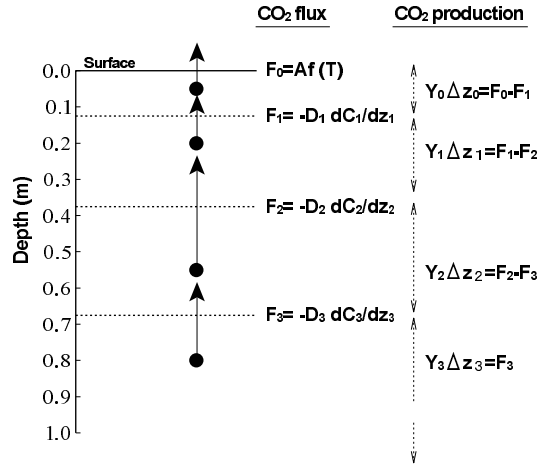


Figure 5.4: Diagram of model used for evaluating CO₂ production rate at each depth in Fukuroyamasawa watershed. F_i is the soil CO₂ flux, D_i is the gas diffusion coefficient, dC_i/dz_i is the gradient of soil CO₂ gas concentration, and $Y_i\Delta z_i$ is the CO₂ production rate.

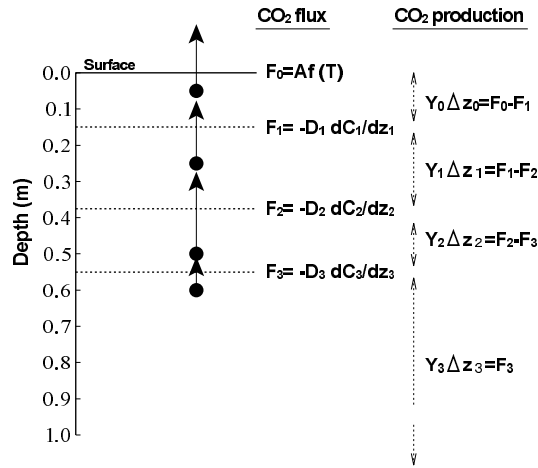


Figure 5.5: Diagram of model used for evaluating CO₂ production rate at each depth in Kog-Ma watershed. See the Fig. 5.4 caption for explanation of symbols.

case of at deeper layer; however, the difference of soil property and soil environmental conditions at shallower depth is generally large. Hence, I estimated soil surface fluxes with the relationships between soil water, soil temperature and soil surface fluxes measured using chamber method. These relationships were shown in Table 5.2.

Fukuroyamasawa	A	k			
1999	1.73E-08	0.0974			
2000	1.59E-08	0.1181			
2001	3.47E-08	0.0552			
Kog-Ma	A	l	m	o	p
1998-1999	1.21E-06	3.169478	-0.26779	1.084333	0.088129
2000-2001	8.43E-07	2.725513	-0.09021	1.118839	0.034433

Table 5.2: The fitted parameters of the relationships between soil respiration, and soil temperature and soil water content. In Fukuroyamasawa watershed, the function is $y = Ae^{kT}$, where y is the soil respiration and T is the soil temperature at 0.1 m depth. In Kog-Ma watershed, the relationship is the $y = A(l\theta + m)(oT^p)$, where θ is the soil water content at 0.1 m depth and T is the soil temperature at 0.1 m depth.

The gas diffusion coefficient Relationships between soil water content and gas diffusion coefficient were used to estimate the gas diffusion coefficient. The relationship measured experimentally was used in analyzing Kog-Ma watershed (Chapter 4). The Millington-Qurk model(M-Q model), an empirical model of soil water content and gas diffusion coefficient, was used in analyzing Fukuroyamasawa watershed, because the relationship between soil water content and gas diffusion coefficient could not be obtained experimentally due to the lack of TDR sensor. The M-Q model is a simple but reported to provide better estimations.

$$D_s/D_0 = \frac{\epsilon^{10/3}}{\Phi^2} \quad (5.4)$$

The gas diffusion coefficient in free air is affected by temperature and pressure and can be estimated as follows (Campbell, 1985):

$$D_0 = D_{stand} \left(\frac{T + 273}{273} \right)^{1.75} (1013/P) \quad (5.5)$$

where D_{stand} is the CO₂ gas diffusion coefficient in free air at standard condition, T is the temperature (°C), and P is the pressure(hpa), respectively.

5.3 Results

5.3.1 Fukuroyamasawa watershed

Field observation data

I used data from 1999 to 2001. Soil respiration ranged from to and shows clear seasonality. Soil respiration was high in summer season and low in winter season. Soil temperature showed clear seasonality and controlled soil respiration in Fukuroyamasawa watershed (Fig. 5.6).

Figure 5.7 shows the relationships between soil respiration and soil temperature. Soil respiration increased exponentially with increasing soil temperature. On the other hand, soil water content did not change clearly, except for the summer drought or wet condition after rainfall (Fig. 5.6). I did not see a clear correlation between

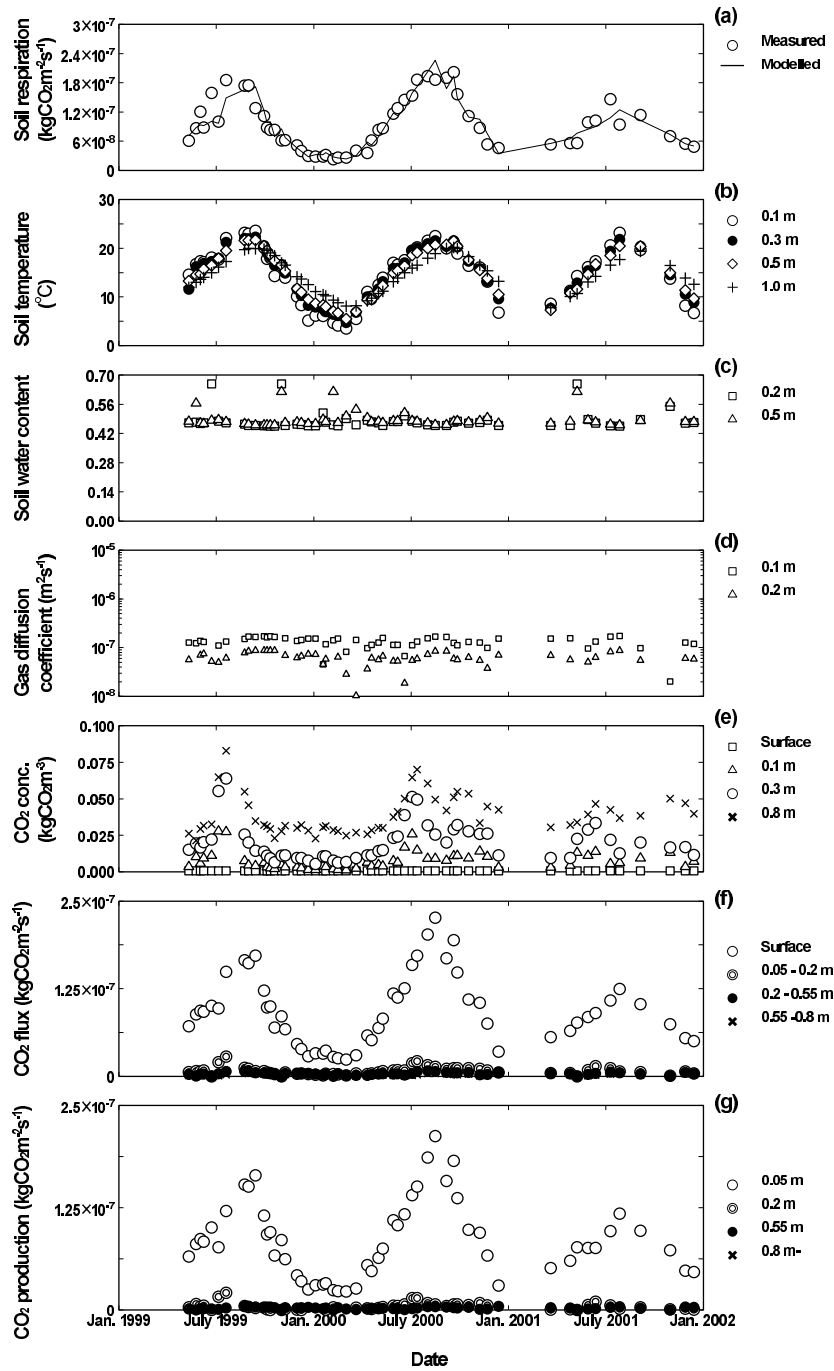


Figure 5.6: Seasonal variation of soil respiration, soil temperature, soil water content, gas diffusion coefficient, CO_2 concentration, CO_2 flux at each depth, and CO_2 production rate at each depth in Fukuroyamasawa watershed.

soil respiration and soil water content. A gas diffusion coefficient is significantly affected by soil water content; and then the gas diffusion coefficient in Fukuroyamasawa did not change largely. Soil CO₂ concentrations at each depth were large in summer season and small in winter season. Soil CO₂ concentration increased with increasing depth. Soil CO₂ concentration at deepest depth, 0.8 m, ranged from 0.022 to 0.083 kgCO₂m⁻³.

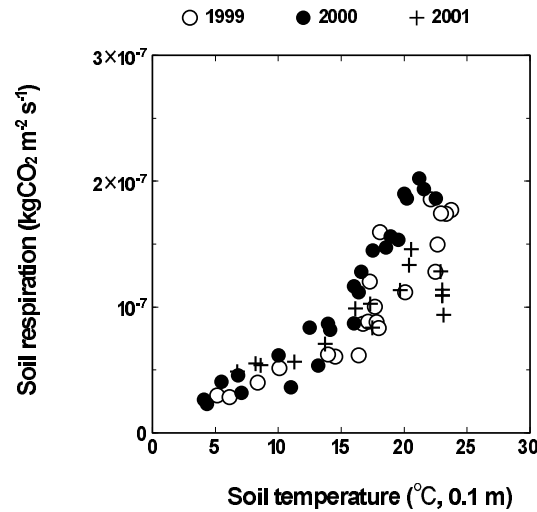


Figure 5.7: The relationships between soil respiration (soil surface CO₂ flux) and soil temperature.

Seasonality of CO₂ production at each depth

Figure 5.6 shows the CO₂ flux at each depth. CO₂ production rates at each depth were shown in Fig. 5.6. The degree of CO₂ production rate at shallowest depth was largest around the year. The value of CO₂ production rate at 0.05 m depth was large in summer season, small in winter season, and was more than ten times as large as those of deeper depths.

Contribution of CO₂ production at each depth

Contributions of CO₂ production at each depth to total soil respiration were calculated (Fig. 5.8). The contribution of shallowest soil, 0.05 m, was largest all the year round and ranged about 0.9.

Relationships between CO₂ production rate and soil temperature

The relationships between soil temperature and calculated CO₂ production rate were investigated (Fig. 5.9), because, in this watershed, soil temperature changed largely; on the other hand, soil water content changed little. At each depth, CO₂ production rates increased with increasing soil temperature. Although the deviations were large, CO₂ production rates tended to rise exponentially.

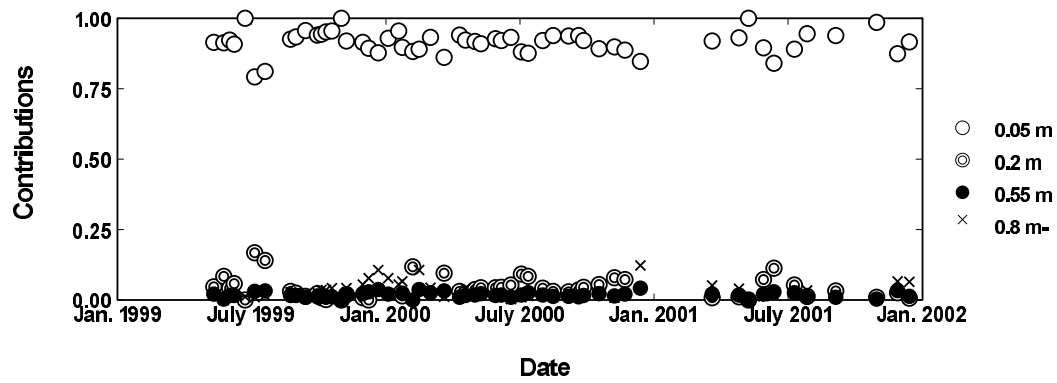


Figure 5.8: Seasonal variations in contributions of each depth to CO₂ production.

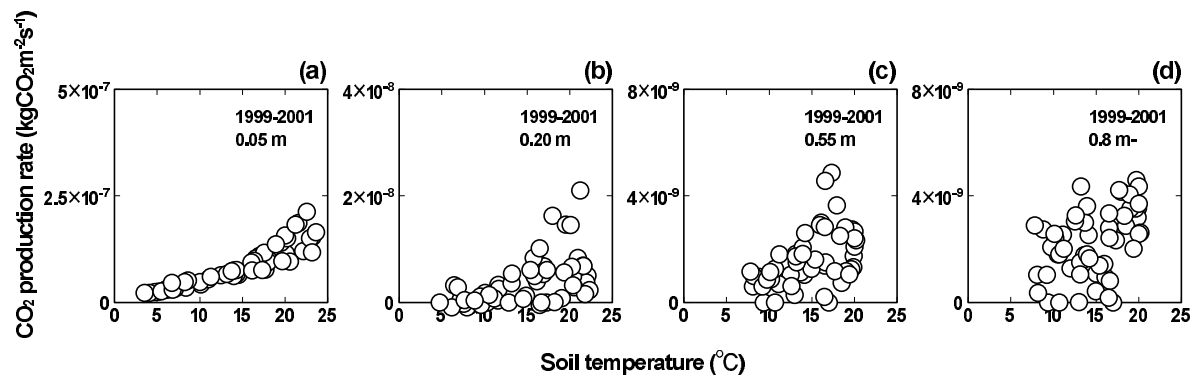


Figure 5.9: Seasonal temperature dependence of soil CO₂ production at each depth.

5.3.2 Kog-Ma watershed

Field observation data

I used data from 1998 to 2001. Soil respiration was relatively high in rainy season, and relatively low in dry season; however, interannual differences were large. Soil respiration in 1998 and 1999 was comparatively larger than those of in 2000 and 2001. Soil temperature did not change clearly (Fig. 5.10). So I did not see clear relationships between soil respiration and soil temperature. On the other hand, soil water content changed dramatically, and then controlled soil respiration. Figure 5.11 shows the relationships between soil respiration and soil water content. Soil respiration increased with increasing soil water content. As mentioned above, soil gas diffusivity is significantly affected by soil water content. So the gas diffusion coefficient changed dynamically. The gas diffusion coefficient was small in rainy season and large in dry season. Soil CO₂ concentrations were large in rainy season, and small in dry season. Soil CO₂ concentrations increased with increasing soil depth. Soil CO₂ concentration at deepest depth, 0.6m, ranged from 0.010 to 0.071 kgCO₂m⁻³.

Seasonality of CO₂ production at each depth

CO₂ production rate at shallowest depth showed a distinct seasonality, large in rainy season and small in dry season. The value was significantly larger than those of deeper depths, especially in rainy season. However, in dry season, the CO₂ production rate at shallowest depth decreased significantly, and was at the same degree as deeper depths. CO₂ production rate at 0.25 m depth show less clear seasonality compared with other depths. Inversely, CO₂ production rate at 0.5 m depth, increased in dry season and decreased in rainy season.

Contribution of CO₂ production at each depth

In Fig. 5.12, the calculated contributions of each depth were shown. The contributions of each depth changed with seasons. The contribution of the shallowest depth was high in rainy season and was about 0.9. Then, it decreased to less than half in dry season. The contributions of deeper depths were large in dry season and low in rainy season. In dry season, these contributions were about 0.25 at highest rate.

Relationships between CO₂ production rate and soil water content

The relationships between CO₂ production rate and degree of saturation were different among depths. At shallowest depth, CO₂ production rate increased with increasing the degree of saturation, although the degree of saturation at adjacent depth (0.1m) was used because of the absence of the same depth (0.05 m). This was very similar to the relationships of soil respiration measured at soil surface. Probably, the degree of saturation at 0.05 m was smaller than that of 0.1 m depth, because a shallower soil tended to have a larger saturation content.

The relationships at 0.25 depth was parabolic and had a peak at around 0.5-0.6, although the data scattered a little. The degree of saturation ranged from 0.3 to 0.8. The CO₂ production rate at deepest depth decreased with increasing the degree of saturation. The degree of saturation ranged from 0.4 to 1.0.

5.4 Discussion

5.4.1 Interpretation

Temperate forest in Japan

Temperature mainly controls the soil respiration/Seasonality was similar at each depth/CO₂ production at shallower depth is dominant through the year As measured at soil surface, soil CO₂ production rates increased with increasing soil temperature at each depth (Fig. 5.9). To the depth of 0.5 m, the time lags of temperature transfer were small; and soil temperature at each depth was high in summer season

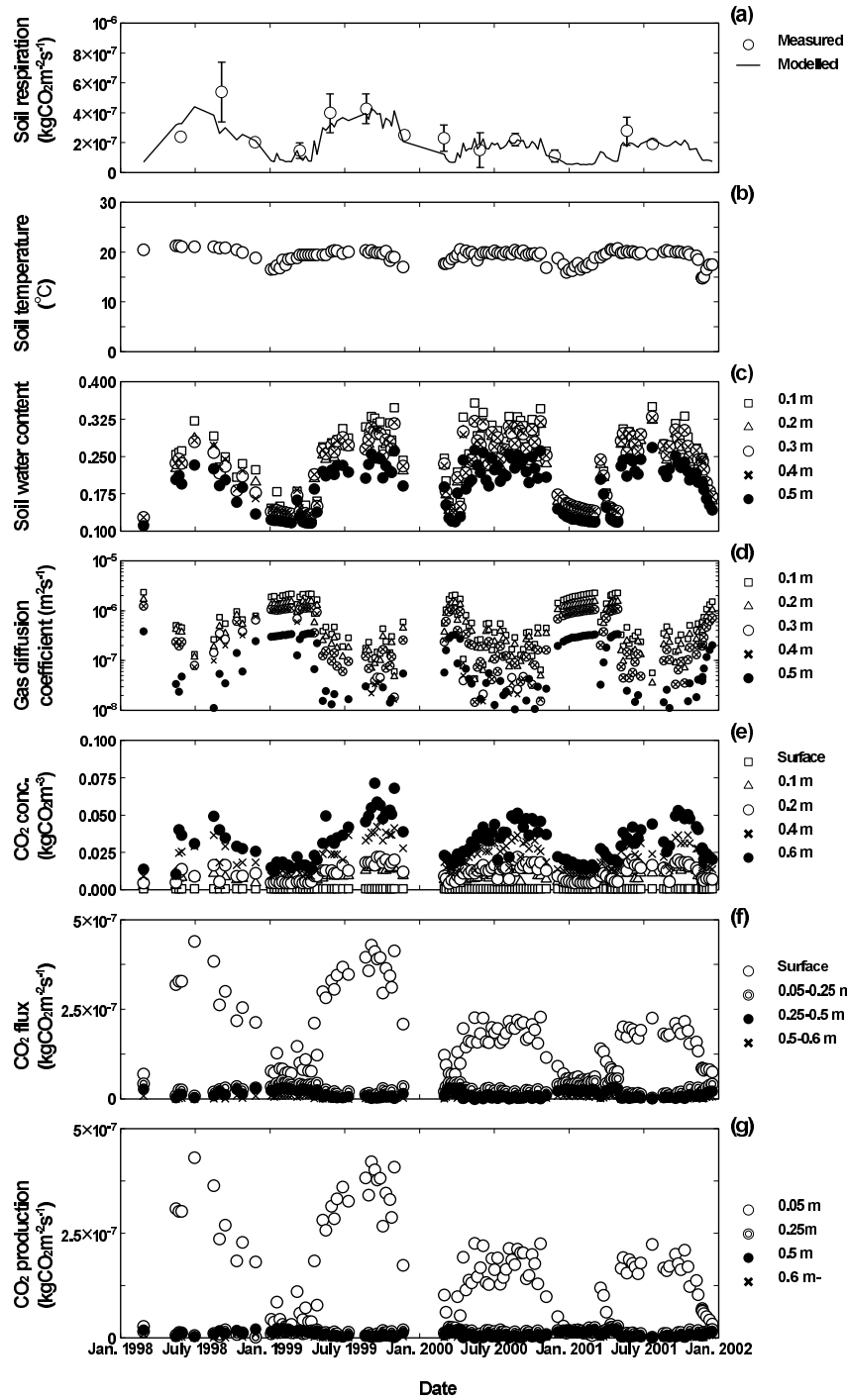


Figure 5.10: Seasonal variation of soil respiration, soil temperature, soil water content, gas diffusion coefficient, CO_2 concentration, CO_2 flux at each depth, and CO_2 production rate at each depth in Kog-Ma watershed.

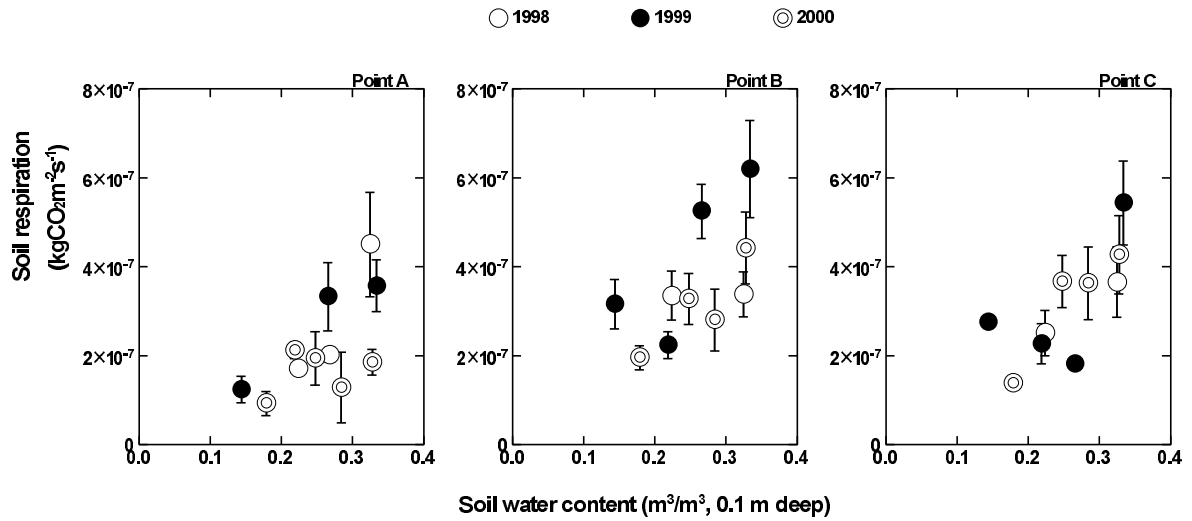


Figure 5.11: The relationships between soil respiration and soil water content.

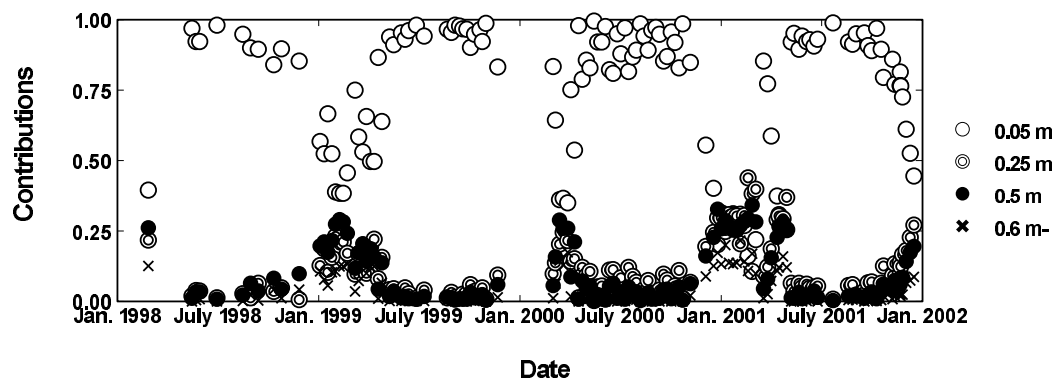


Figure 5.12: Seasonal variations in contributions of each depth to CO₂ production.

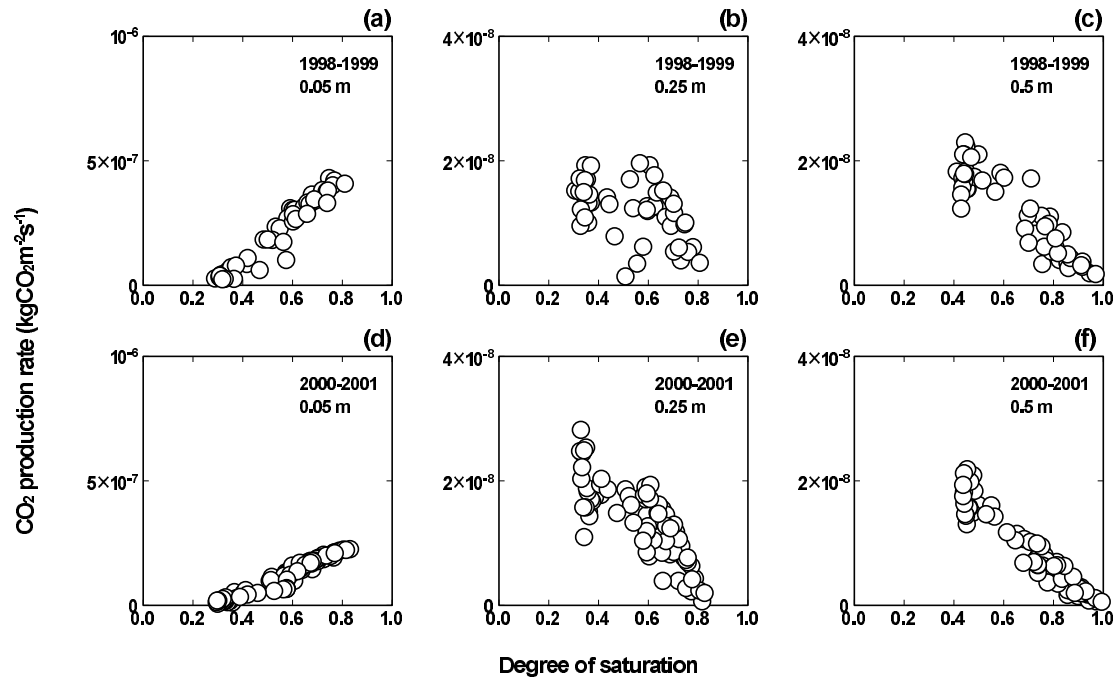


Figure 5.13: The relationships between CO₂ production rate and degree of saturation. Degree of saturation was the ratio of soil water content to saturated soil water content. I separate into two (1998-1999 and 2000-2001) because the CO₂ production at shallowest layer was different between the two intervals. Vertical scales are different between shallowest depth and other depths.

and low in winter season. As a result, the seasonality of soil CO₂ production at each depth were similar to each other, and then the contributions of each depth did not change all the year round. The contribution of the shallowest depth was significantly larger than other depths and around 0.9. This was probably due to rich organic matter and root density.

Tropical forest in Thai

Soil water mainly controls the soil respiration/Seasonality and Contributions were different at each depth/Contribution of deeper depths On the other hand, soil water changed significantly in Kog-Ma watershed and controls soil water content (Fig. 5.10). In general, soil CO₂ production rates respond to degree of saturation (or water-holding capacity, e.g. Howard and Howard, 1993; Bowden et al. 1998). Soil CO₂ production rate shows a parabolic response, decreased both at too wet conditions and too dry conditions, and had a peak at intermediate degree of saturation. My results also showed similar tendency at 0.25 m depth. At 0.05 m, CO₂ production rate increased with increasing the degree of saturation; the decrease of soil CO₂ production rate was not observed. This is probably because shallower soil has large capacity of soil water holding, that is, the saturated soil water content was large. Then, the saturation of shallowest soil rarely occurred. Meanwhile, CO₂ production rate decreased with increasing the degree of saturation. This is, more likely, because the degree of saturation at the depth was comparatively larger all the year around due to the low saturated soil water content, even in dry season. In other word, soil at deeper soil was too wet in rainy season, and soil CO₂ production was inhibited; however, soil CO₂ production increased because of the adequate degree of soil water content (Fig. 5.14).

The seasonality of the degree of saturation was similar at each depth; large in rainy season and small in dry season. As a result, the seasonality of CO₂ production rate at shallowest depth and that at deepest depth were different. Because of the difference of seasonality at each depth, the contributions of each depth changed through seasons. In rainy season, the degree of shallowest depth was adequate for soil CO₂ production; that of deeper depth was inadequate. Then, the contribution of shallowest depth was significantly large. Meanwhile, in dry season, the degree of shallowest depth was inadequate because of being too dry; that of deeper depth was adequate. Then, the contribution of shallowest depth decreased largely, and that of deeper depth rise.

5.4.2 Comparison between Fukuroyamasawa watershed and Kog-Ma watershed

The constant contribution and the variable contribution Comparing the CO₂ production rates in two watersheds, there were some differences and similarities. Soil at the shallowest depth was the main source of soil CO₂ production in both watersheds. This agreed with other studies (de Jong and Schappert, 1972; Campbell and Frascarelli, 1981). Soil organic matter is supplied mainly by litter fall from above-ground plant. As Jabbagy and Jackson showed, shallower soil contains more soil organic matter. Moreover, another source of CO₂, roots, also exists at shallower depth (Jackson et al. 1996). For example, 80-90 % of roots are in top 0.3 m of soil in tundra, boreal forest, and temperate grasslands, and 50 % in deserts and temperate coniferous forest (Jackson et al. 1996). Roots also supply organic carbon to soil.

On the other hand, there were a difference between Fukuroyamasawa watershed and Kog-Ma watershed. In Fukuroyamasawa, the contributions of each depth to soil CO₂ production were constant all the year round; however, those in Kog-Ma watershed changed significantly between seasons. The seasonality of soil CO₂ productions at each depth were different. Consequently, the contribution of shallowest depth significantly decreased in dry season, and those of deeper depth increased. This is because soil respiration in Kog-Ma watershed was controlled by soil water, not by soil temperature. In general, soil respiration increases with increasing temperature, and time lags of soil temperature up to 0.5 m below are small; then, the seasonality of CO₂ production at each depth should be parallel. On the other hand, soil respiration respond parabolically to the degree of saturation, and the degree of saturation depends on both soil water content and saturated soil water content; then, the seasonality of CO₂ production at each depth should not be always parallel as is controlled by soil temperature.

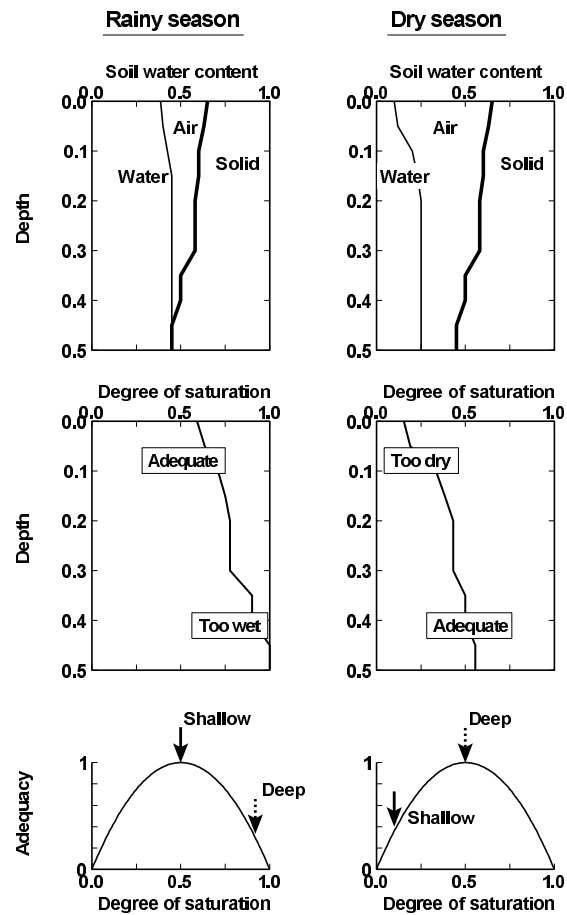


Figure 5.14: An explanatory diagram showing the different performances among layers in rainy and dry season. To clarity, plotted values are not observed data.

5.4.3 Comparison with other studies

Comparison with the studies of Gaudinski et al. 2000, Hirsch, et al. 2002, Davidson et al. Goulden et al. 1998 Giardina and Ryan (2000) compiled data of organic carbon decomposition in forest mineral soil, 82 sites on five continents, and indicated that the decomposition of organic carbon in mineral soil were insensitive to temperature. Deeper soil contains significant amount organic carbon (Jobbagy and Jackson 2000). For example, more than half of soil organic carbon, relative to the first meter, exist below 0.2 m (Jobbagy and Jackson, 2000). Considering top 3 meter soil, soil between 1 to 3 m contains about 44 % of soil organic carbon, 842 Pg C. Then, the response of soil organic carbon decomposition in deep soil to temperature is a critical issue for my understanding the impact of global warming.

In contrast to mineral soil, organic matter decomposition above mineral soil is surely sensitive to temperature. Goulden et al. (1998) found a high sensitivity of deep soil respiration to deep soil temperature in a black spruce forest in Canada. Hirsch et al. (2002) directly measured deep soil respiration at the BOREAS northern old black spruce site in Canada with a similar method I used. They found that deep soil respiration increased linearly with 0.5 m temperature, with a slope of $0.2 \text{ kgCha}^{-1}\text{d}^{-1}\text{°C}^{-1}$. My results agreed with above two studies. In my results of Fukuroyamasawa watershed, soil CO_2 production rates at each depth increased with increasing temperature. Soil CO_2 production at shallower depth did exponentially, and that at deeper depth linearly.

5.4.4 Evaluation the gas diffusion coefficient

This method depends on the accurate evaluation of gas diffusion coefficients This method, which evaluates soil CO_2 flux at each depth with Fick's first law, has advantages, like undisturbing soil and allowing us to observe directly the CO_2 production rate and its seasonality. The key is, as pointed out by Hirsch et al. (2002), the accurate estimation of gas diffusion coefficient. For the better estimation of gas diffusion coefficients, air-filled porosity or water-filled porosity and maximum porosity should be measured. The relationships between air-filled porosity and gas diffusion coefficient are different among soils and sites, then measuring the relationships at each site would improve.

Measuring soil CO_2 concentration is also a key. Although many methods measuring soil CO_2 concentration were proposed (e.g. Clegg et al. 1978; Nakayama and Kimball, 1988; Fang and Moncrieff, 1998; Hamada and Tanaka, 2001), measuring soil CO_2 concentration is cumbersome, and most studies focused only on soil surface flux, and not on soil CO_2 concentration. However, measuring soil CO_2 concentration provides a lot of information about CO_2 production in soil and then improves the prediction of soil organic carbon response.

5.5 Conclusions

Vertical distributions of soil CO_2 production rate were measured in temperate artificial forest and tropical evergreen forest for several years. In both forests, the shallowest layers had greatest roles. However, there were some significant differences between the two forests. In temperate artificial forest, soil temperature controlled soil CO_2 production rate, and the CO_2 production rate at shallowest depth was largest. On the other hand, in tropical evergreen forest, soil water dominated soil CO_2 production, and the CO_2 production rate at shallowest depth dropped in dry season, and the contributions of deeper depth increased. These differences between two forest sites indicate the importance of considering soil vertical processes. These considerations will improve my understandings of soil CO_2 production and allow us to predict the possible changes of soil carbon caused by climate changes.

Chapter 6

Modeling of CO₂ production and transport in soil

6.1 Introduction

Importance of soil subsurface carbon Carbon in soil is a great concern because the enormous amount of carbon is stored in soil and would have significant impacts on global warming, through a possible feedback (Kirschbaum, 2000). CO₂ is the main form of carbon emission from soil, and then deep understanding and accurate prediction of CO₂ emission from soil are required. Modeling soil CO₂ must help the understanding and prediction.

Statistical model In many studies, soil surface CO₂ flux was described using statistical regression models with specific parameters (Schlentner and Van Cleve, 1984; Hanson et al. 1993; Lloyd and Taylor, 1994; Dilly and Munch, 1996; Davidson et al. 1998; Londo et al. 1999; Rayment and Jarvis, 2000; Morén and Lindroth, 2000). Soil surface CO₂ flux is known for being strongly affected by temperature and water, and then some studies described annual soil surface CO₂ flux with annual mean temperature and precipitation, others adopted soil temperature and soil moisture content.

These models provided good estimations; however, the lacks of subsurface processes limit my understanding what really happened in soil.

Importance of soil subsurface carbon Soil surface CO₂ flux is the result of various processes under the soil surface, CO₂ production, its transport, its storage, CO₂ profile forming, etc. Even in an ecosystem, soil CO₂ production varies vertically, and environmental factors like soil temperature and soil moisture differ as well. These differences are also temporally and horizontally large.

For example, Jobbagy and Jackson (2000) investigated vertical distributions of soil organic carbon under various climate and vegetations and showed the variety. Root distributions also differ between biomes, as Jackson et al. (1997) showed by compiling a database of 250 root studies. Goulden et al. (1998) pointed out that soil thaw at deep soil affects soil surface CO₂ flux. Elberling and Brandt (2003) reported that trapped CO₂ in deep frozen soil was released after soil thawing, which increased soil surface CO₂ flux. In contrast to organic carbon in shallower organic soil, the decomposition rates of organic carbon in mineral soil might not vary with temperature (Giardina and Ryan, 2000). Hanson et al. (1993) reported spatial distributions of soil CO₂ flux, and these differences can be explained only by soil temperature, soil water content and soil's coarse fraction. However, there were some differences which cannot be explained by above mentioned factors. Evaluating subsurface processes would explain the differences.

In tropic regions, larger deviations between points were reported (Yoda and Nishioka, 1982; Meir et al. 1996; Ishizuka et al. 2002; Hashimoto et al. 2004). These differences cannot be explained by environmental factors.

Thus, nonempirical models which are not just statistical regressions but include subsurface processes are also needed for us to understand the mechanism of soil CO₂ flux.

Nonempirical models The nonempirical models proposed can be roughly classified into two types; compartment model and process-based model. Compartment model describes C and N cycling of plant growth and organic decomposition using many compartments (see Chapter 1.2.5). Century is one of the major compartment models. Parton et al. (1987) developed the Century, and now many researchers use the Century to predict carbon cycle during decades and centuries (e.g. Vitousek et al. 1994; Krishna et al. 2001; Kirschbaum and Paul, 2002). In Century model, soil surface CO₂ flux which is derived from organic matter decomposition is obtained.

Process-based model is a model which describes CO₂ production at each depth and CO₂ transport in soil with physical law like a mass balance equation and Fick's law. Simunek and Suarez (1993) developed a process based model (SOILCO₂) to predict the production, transport and spatial distribution of CO₂ in soil. They consider one-dimensional water flow in partially saturated porous media and multiphase transport of CO₂ and described soil CO₂ production with functions of depth, pressure head, temperature, CO₂ concentration, osmotic head and time. Fang and Moncrieff (1999) advanced a process based model (PATCIS) as well. The CO₂ production in this model includes the factors for the dependence on temperature, water content and O₂ concentration. These models evaluate CO₂ production rate at each depth, CO₂ profiles formed and soil surface CO₂ flux.

Objectives of this study The objective of this study was to develop a process-based model for predicting the CO₂ production, transport and distribution in soil. This model described one-dimensional CO₂ processes with an adequately simpler way, eliminating negligible processes. I validated this model against field data from two watershed, Fukuroyamasawa watershed and Kog-Ma watershed. Parameters of CO₂ production at each depth were determined by the results in Chapter 5.

6.2 Material and Method

6.2.1 Model description

Two processes: production and diffusion As described in Chapter 1.2, CO₂ emission from soil is a result of several processes which affect each other. Yet, roughly say, CO₂ flux from soil mainly consists of two major processes: CO₂ production and its transport. CO₂ is produced at each depth corresponding to the potential and the environmental factors, and CO₂ is transported to soil surface through forming soil CO₂ profiles.

What are included and what are not included Figure 6.1 shows a diagram of this model.

In this study, some processes were simplified. Some studies separated CO₂ production potential into two, root respiration and microbial respiration (soil organic matter decomposition); others did not. Contributions of root respiration and microbial respiration differ among ecosystems and between seasons, and are not yet clear. Also, the response of root respiration to environmental factors, like temperature and water content, is not yet known sufficiently. Here I did not separate the two processes and described CO₂ production potential as one term.

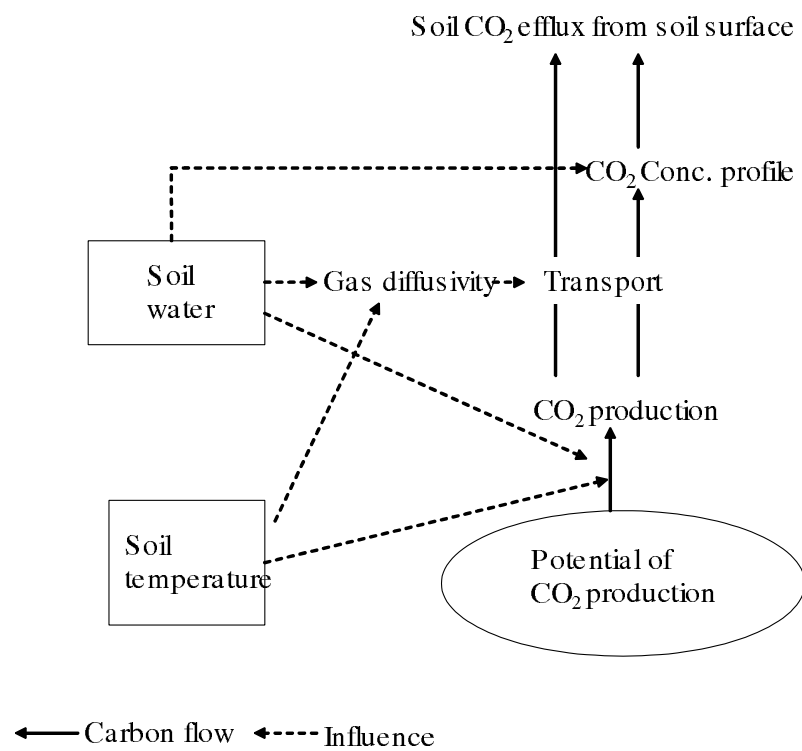


Figure 6.1: Diagram of CO₂ production and transport model.

6.2.2 Gas movement and mass balance

Fick's first law/Mass balance Assuming that CO₂ is transported only by diffusion, CO₂ flux in soil can be written by Fick's first law:

$$F = -D \frac{dC}{dz} \quad (6.1)$$

where F is the soil CO₂ flux, D is the gas diffusion coefficient in soil, and C is the CO₂ concentration and z is the depth in the soil. This equation shows that soil CO₂ flux is larger when the gas diffusion coefficient is larger or the gradient of soil CO₂ concentration. In some studies, CO₂ is often transported by advection, other than gas diffusion, like after rainfall; however, soil CO₂ is mainly transported by gas diffusion.

One-dimensional CO₂ transport is described by the following mass balance equation:

$$\frac{d\epsilon C}{dt} = -\frac{dF}{dz} + Y \quad (6.2)$$

where ϵ is the air porosity, t is the time, Y is the CO₂ production in soil. The left part indicates the change in CO₂ concentration, and the first term of the right part means the difference between influx and outflux, and the second term of the right part shows the yielding of CO₂ at the depth.

6.2.3 Gas diffusivity

Environmental factors In general, a gas diffusion coefficient is affected by temperature (T) and pressure (P):

$$D_0 = D_{std}(T/273)^{n_1}(1013/P)^{n_2} \quad (6.3)$$

where D_{std} is the gas diffusion coefficient at standard condition, and n_1 and n_2 are the constants. CO₂ has 1.25 of n_1 and 1 of n_2 . In considering gas diffusion coefficients in soil, relative gas diffusion coefficients (D/D_0), that is the ratio of a gas diffusion coefficient in soil to that in free air, are usually used. The relative gas diffusion coefficient is affected by soil air porosity. There are various models between the relative gas diffusion coefficient in soil and air porosity (Campbell, 1985; Jin and Jury, 1996; Moldrup et al. 1996a, 2000). For example, Penman model,

$$D/D_0 = 0.66\epsilon \quad (6.4)$$

Currie model,

$$D/D_0 = m\epsilon^b \quad (6.5)$$

where m and b are the fitted constants, Troeh model,

$$D/D_0 = \left\langle \frac{a-u}{1-u} \right\rangle^v \quad (6.6)$$

where u and v are soil-specific parameters. Millington-Quirk model,

$$D/D_0 = \frac{\epsilon^{10/3}}{\Phi^2} \quad (6.7)$$

and so on. Millington-Quirk model is reported to provide better estimations (Moldrup et al. 1996a). In Fukuroyamasawa simulation, Millington-Quirk model was used, because of the lack of the relationship between relative gas diffusion coefficients and air porosity. In Kog-Ma simulation, a relationship between relative gas diffusion coefficients and air porosity measured experimentally (see Chapter 4). The relationship is as follows

$$D/D_0 = 2.03\epsilon^{2.78} \quad (6.8)$$

6.2.4 CO₂ production

Influences of environmental factors on CO₂ production In this study, CO₂ production caused by soil organic matter decomposition and that from root respiration were not separated. The CO₂ production is given as just a potential of CO₂ production, without the distinguishing, at each depth. Various environmental factors affect the CO₂ production in soil. I assumed the influences of soil temperature and soil water content, and defined as

$$Y = \alpha f(T)g(\theta) \quad (6.9)$$

where $f(T)$ is the response of soil CO₂ production to soil temperature, and $g(\theta)$ is the response of soil water.

Soil CO₂ production increases exponentially with increasing soil temperature, and respond parabolically to soil water content.

$$f(T) = e^{k(T-T_0)} \quad (6.10)$$

$$g(\theta) = a(\theta/\theta_{max})^2 + b(\theta/\theta_{max}) + c \quad (6.11)$$

where a , b and c is the parameters, and θ_{max} is the maximum soil water content or maximum porosity. I used the relationships between soil CO₂ production rate and soil temperature, and between soil CO₂ production rate and soil water, measured in Chapter 5 (Fig. 6.1 and 5.13). These relationships were normalized; $f(T)$ is 1 when soil temperature is 20 °C. $g(\theta)$ has maximum of 1, and minimum of 0, varies between 0 and 1.

6.2.5 Data

I validated this model to two dataset; one was obtained in temperate artificial forest, another is in tropic evergreen forest. Details of the site and measurements are described in Chapter 5.

Temperature and Water content Observation data of soil temperature and water content were used. The interval of temperature was weekly in Fukuroyamasawa watershed and was 15 min interval in Kog-Ma watershed. That of soil water data was also weekly in Fukuroyamasawa watershed and was 15 min in Kog-Ma watershed. These data were interpolated when used in this model.

Soil respiration and soil CO₂ concentration Soil surface CO₂ flux was measured at one week interval in Fukuroyamasawa watershed and at three months intervals in Kog-Ma watershed. I used the dynamic chamber method in both watersheds. Soil CO₂ concentration was measured at one week interval in Fukuroyamasawa watershed and at half week intervals in Kog-Ma watershed. I used gas detector tube with a sampling pump in both watersheds (Hamada and Tanaka, 2001).

6.2.6 Running conditions

Boundary conditions and assumptions The assumptions of this model are as follows:

1. CO₂ is transported only by diffusion, without considering convective flux.
2. Dissolving CO₂ into water and CO₂ emission from water are neglected because the effect is considered to be small.
3. Response of CO₂ production to O₂ concentration or CO₂ concentration are not included. These relationships are not yet clear.
4. CO₂ diffusion through soil water is not included. In other words, a gas diffusion coefficient in saturated soil is 0.

The boundary conditions are as follows:

1. CO₂ concentration at soil surface is assumed to be 0.0061 kgCO₂m⁻³.
2. The gas diffusion coefficient at the bottom is assumed to be 0, and then CO₂ does not cross over the bottom boundary.

Time step, grid size, solving matrices I used the Crank-Nicholson implicit method for solving the diffusion equation (see Appendix A.). I adopted 3600 sec time step and 0.01 m grid size. I solved matrixes by Thomas algorism.

6.3 Sensitivity analysis

In this section I present a sensitivity analysis of the model parameters. A sensitivity analysis helps my understandings of model performance and finding errors, for factors affect each other in complicated ways and their significance to model outputs are different. I conducted a sensitivity analysis on (1)maximum air porosity, (2)CO₂ production rate in soil, (3)soil temperature and water content, and (4)the gas diffusion coefficient at upper boundary (6.1). For clarity I assumed the constant temperature and water content, and calculated under each condition for 360000 sec and obtained equilibrium soil surface flux and soil CO₂ concentration profile.

Case	Run	How
Case 1	Run 1-3	Production rates vary except at the shallowest layer
Case 2	Run 4-6	Production rates vary at every layer
Case 3	Run 7-9	Production rates vary at the shallowest layer
Case 4	Run 10-12	Maximum porosities vary with constant θ/θ_s and ϵ/θ_s
Case 5	Run 13-15	Maximum porosities vary with constant θ
Case 6	Run 16-18	Maximum porosities vary with content ϵ
Case 7	Run 19-23	Soil temperatures vary with vertically constant
Case 8	Run 24-29	Soil water contents vary with vertically constant
Case 9	Run 30-36	Soil temperatures at shallower depth change larger
Case 10	Run 37-39	The depth with large and constant gas diffusivity changes
Case 11	Run 40-42	The value of the gas diffusion coefficient at soil surface changes

Table 6.1: Sensitivity analyses conducted in this study. Production rate, maximum air porosity, soil temperature and soil water content, and soil surface gas diffusivity were changed.

6.3.1 Production rate

I examined the dependence of soil CO₂ profile and soil surface CO₂ flux to CO₂ production rate in soil by changing CO₂ production rate in three different ways (Fig. 6.2):

Case1 CO₂ production rates except for shallowest layer were changed (Run1-3)

Case2 CO₂ production rates at every layer were changed (Run4-6)

Case3 CO₂ production rate at shallowest layer was changed (Run7-9)

In all runs, I assumed that soil temperature was 20 °C and soil water content was 0.5 at each depth.

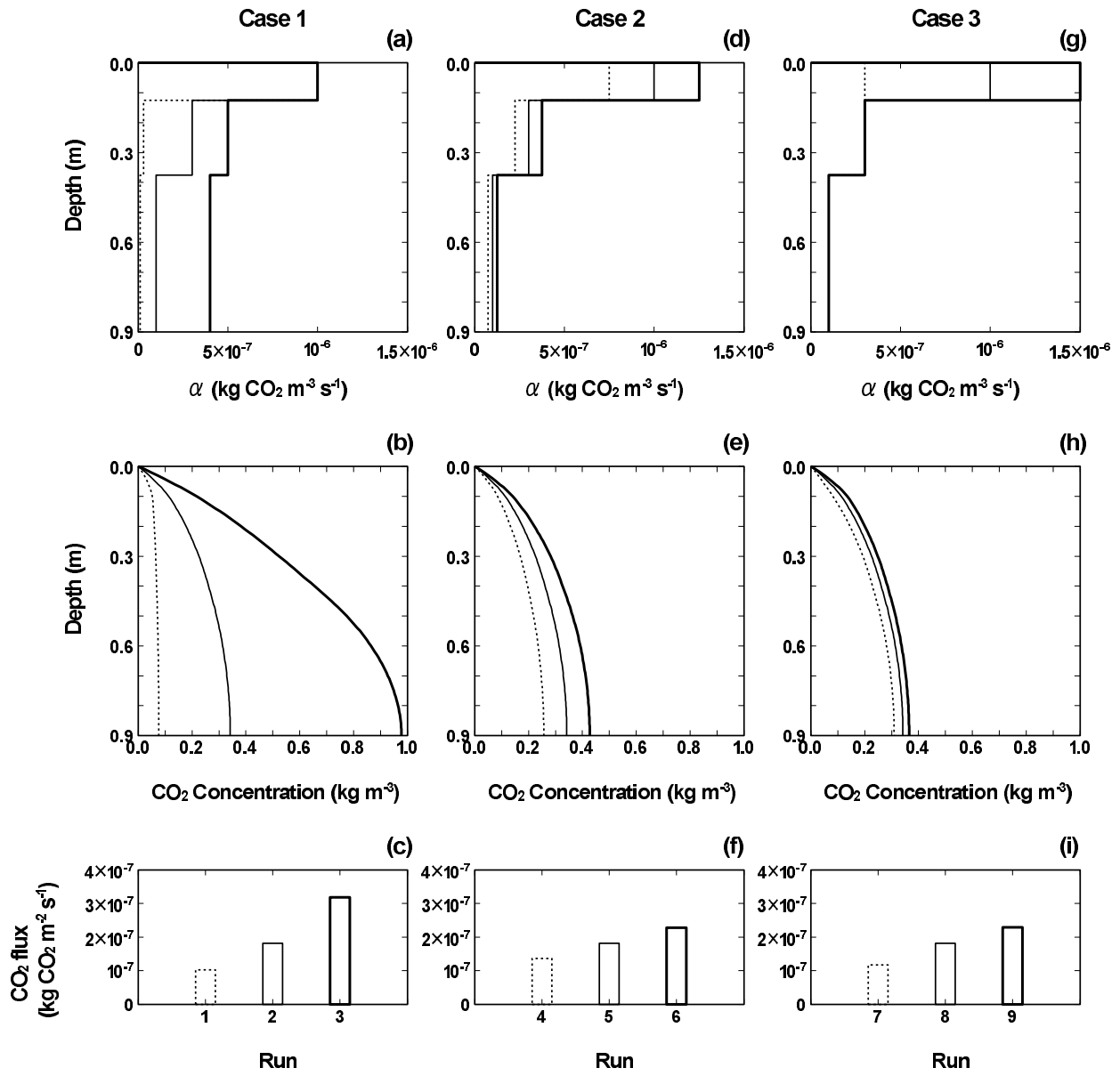


Figure 6.2: Sensitivity analysis: assumed various vertical profiles of CO₂ production rate, and simulated CO₂ gas concentration profile and CO₂ flux.

Case 1(Run1-3): CO₂ production rates at deeper layer change Generally, soil organic matter content and root density decreased with increasing depth. So, probably, CO₂ production rate decreased with increasing depth. The contributions of CO₂ production at deeper depth are, however, different among ecosystems. From Run1 to Run3, CO₂ production rates at deeper layer were increased. Both soil CO₂ concentration and soil surface CO₂ flux increased with increasing deep soil CO₂ production; however, the increments of soil CO₂ concentration was larger than those of soil surface CO₂ flux. Soil surface CO₂ flux increased about twice from Run1 to Run2 and from Run2 to Run3, soil CO₂ concentration at deepest depth became about increase three-fold. The increment of CO₂ concentration, however, decreased with decreasing depth. At 0.1 m, the differences in soil CO₂ concentration among three Runs were similar to that in soil surface flux.

Case 2 (Run4-6): CO₂ production rates at each layer change In case 2, CO₂ production rates at each layer increased from Run4 to Run6. Soil CO₂ concentration and soil surface CO₂ flux rise almost linearly. The ratios of CO₂ concentration among three runs were similar at each depth. Compared to case1, soil CO₂ concentration at each depth increased linearly.

Case 3 (Run7-9): CO₂ production rate at shallowest layer change Litter fall from above ground biomass is supplied to the shallowest soil layer, and the root density is largest at shallowest layer. Then, the CO₂ production rate at shallowest layer would, easily and significantly, vary with seasons and years. Only CO₂ production rate at shallowest depth was changed in case 3. Even in the deepest depth, soil CO₂ concentration increased with increasing CO₂ production rate at shallowest layer; however, the increments are smaller than those of soil surface CO₂ flux and those are similar at each depth. Compared with case2, the performances of soil CO₂ concentration were different although the increments of soil surface flux were similar.

6.3.2 Maximum porosity

Maximum porosity affects soil CO₂ concentration and CO₂ flux from soil surface. However, even in the same changes of maximum porosity, the effects to CO₂ concentration and soil surface flux change with soil water and air porosity. Because the ratio of θ to θ_s controls CO₂ production at each depth, ϵ affects CO₂ concentration in soil (equation 6.11), and also gas diffusivity changes with ϵ or maximum air porosity. By setting three different cases, I examined how maximum air porosity affects soil CO₂ profile and soil surface flux (Fig. 6.3).

Case4 maximum air porosity changes with constant θ/θ_s and ϵ/θ_s (Run10-12)

Case5 maximum air porosity changes with constant θ (Run13-15)

Case6 maximum air porosity changes with constant ϵ (Run 16-18)

In all runs, I assumed that soil temperature was 20 °C at each depth.

Case 4 (Run10-12): The ratios of θ/θ_s is constant Firstly, θ and ϵ changed with maximum air porosity under the condition that θ/θ_s and ϵ/θ_s are constant. In this case total CO₂ productions are the same in three runs and hence soil surface CO₂ flux are the same as well. Soil CO₂ concentration decreased with increasing maximum air porosity. This was caused by only change of gas diffusivity.

Case 5 (Run13-15): θ is constant, ϵ changes with maximum porosity Secondly, ϵ changed with maximum air porosity with constant θ . Soil surface flux increased with increasing maximum air porosity. This is because θ/θ_s became close to 0.5 from 1 with increasing maximum air porosity. Soil CO₂ production rate respond parabolically to the degree of saturation. In the condition I conducted this sensitivity analysis, I assumed the accurate condition as $\theta/\theta_s = 0.5$. Then total CO₂ production increased with increasing maximum air porosity. Although the dependence of CO₂ flux to maximum air porosity is simple, the dependence of CO₂ concentration to maximum air porosity is complicated. Below about 0.25 m, CO₂ concentration increased from Run13 to

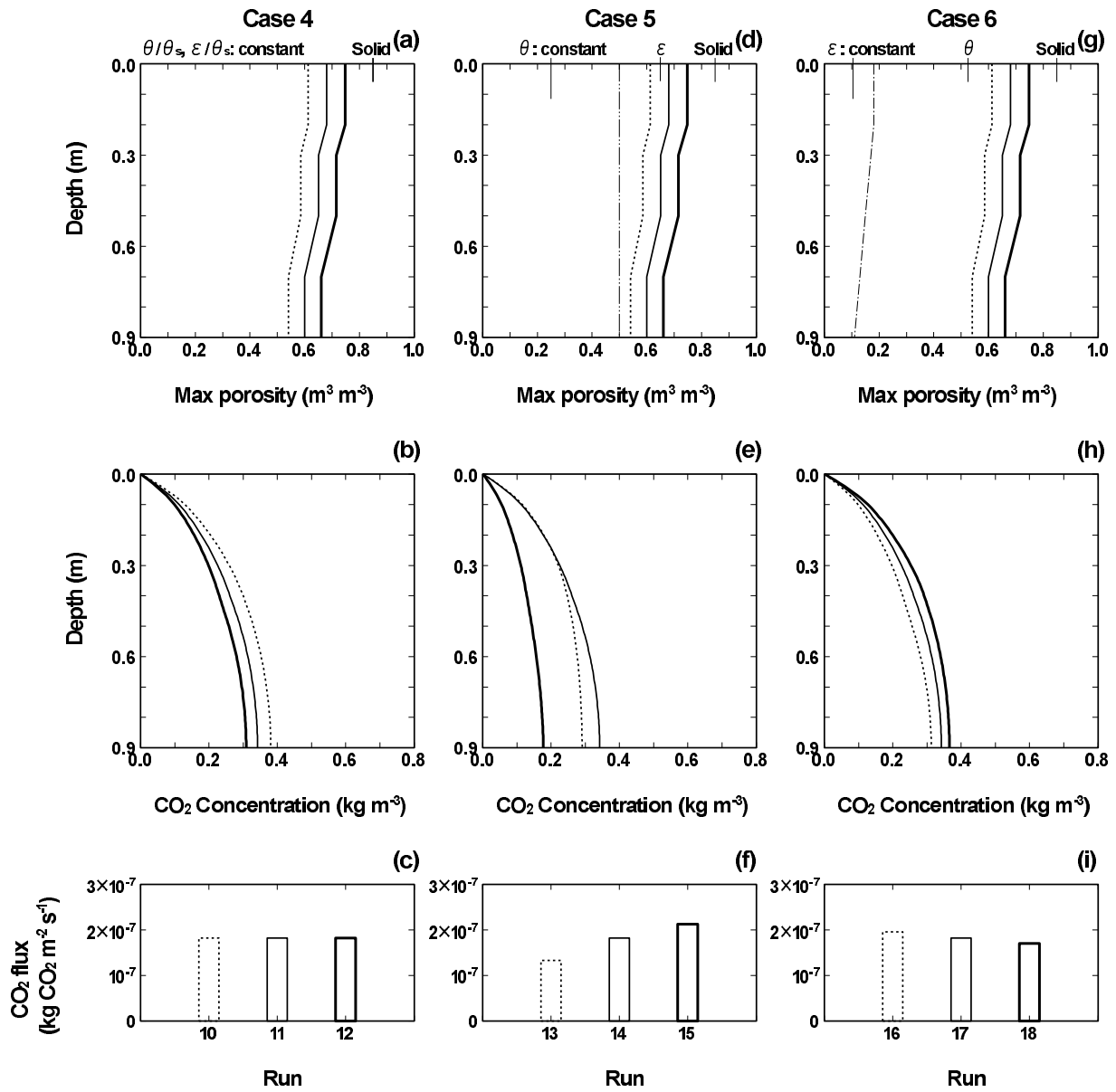


Figure 6.3: Sensitivity analysis: given vertical profiles of soil air, water, solid content, and simulated CO₂ gas concentration profile and CO₂ flux.

Run14 and then decreased to Run15. On the other hand, above about 0.25, CO₂ concentration decreased from Run13 to Run15, although the difference between Run13 and Run14 is different. These performances were not universal and would depend on the adequate degree of saturation. The complicated performance of soil CO₂ concentration was caused by the change of the air porosity (ϵ), the change of gas diffusivity and the change of CO₂ production. Compared with case4, the change of CO₂ concentration was larger.

Case 6 (Run16-18): ϵ is constant, θ changes with maximum porosity Thirdly, θ changed with maximum air porosity with constant ϵ . Soil surface flux decreased with increasing maximum air porosity. Because, in this case, θ/θ_s decreased with decreasing maximum air porosity and became close to 0.5 (i.e. $(\theta - \delta/(\theta_s - \delta)) < \theta/\theta_s < (\theta + \delta/(\theta_s + \delta))$). In contrast to soil surface CO₂ flux, CO₂ concentration increased with increasing maximum air porosity. This is because of the gas diffusivity. In this sensitivity analysis, I used Milington-Quirk model. The gas diffusion coefficient in the MQ model increases with increasing air porosity and decreasing maximum air porosity. In case5, increment of maximum air porosity under constant air porosity caused the decrease of gas diffusivity, and which dominated the performance of soil CO₂ profile. Even though the total CO₂ production decreased, the CO₂ concentration increased. If I used a relationship between the gas diffusion coefficient and air porosity which is insensitive to maximum air porosity, CO₂ concentration decreased with decreasing soil surface flux because of constant gas diffusivity.

Case 4'-6': A relationship between the gas diffusion coefficient and air porosity which is insensitive to maximum air porosity In simulation of Kog-Ma watershed, I used a relationship between the gas diffusion coefficient and air porosity which is insensitive to maximum air porosity. Then I examined the dependence of CO₂ concentration and soil surface flux to maximum porosity. Maximum porosity was changed under same three conditions as case 4, 5 and 6 (case 4.2, case5.2, case6.2). Soil surface flux did not change between case 4 and case 4.2, between case 5 and case5.2, and between case 6 and case 6.2 because all running conditions except for the function of gas diffusivity were the same. The performances of soil CO₂ concentration were, however, different among cases. In case4.2, soil CO₂ concentration decreased with increasing maximum air porosity, there were no difference between case4 and case4.2. Soil CO₂ concentration in case 5.2 were also similar to in case 5; however, soil CO₂ concentration decreased, at each depth, with increasing maximum porosity in case 5.2. On the other hand, in contrast to case 6, CO₂ concentration at each depth decreased with decreasing maximum porosity in case 6.2, though slightly. This change was caused by only the decrease of CO₂ production rate in soil because of constant gas diffusivity.

6.3.3 Soil temperature and water conditions

Soil temperature and soil water are major controller of soil respiration. I examined the performance of soil surface flux and soil CO₂ concentration profile (Fig. 6.4).

Case7 soil temperature, vertically constant, changed from 10 °C to 30 °C (Run19-23)

Case8 soil water content, vertically constant, changed from 0.1 to 0.5 (Run24-29)

Case9 soil temperature changed vertically; when it is hot, shallower layer is hotter. When it is cool, shallower layer is cooler (Run 30-36)

Case 7 (Run19-23): Soil temperature change 1. vertically constant This vertically constant soil temperature occurs in experimental conditions in laboratory rather than in field conditions. Soil surface CO₂ flux increased exponentially with increasing temperature. Also, soil CO₂ concentration increased with increasing temperature, and the increment of soil CO₂ concentration induced by increasing 5 °C tend to be larger at larger temperature. These trends were the same at each depth.

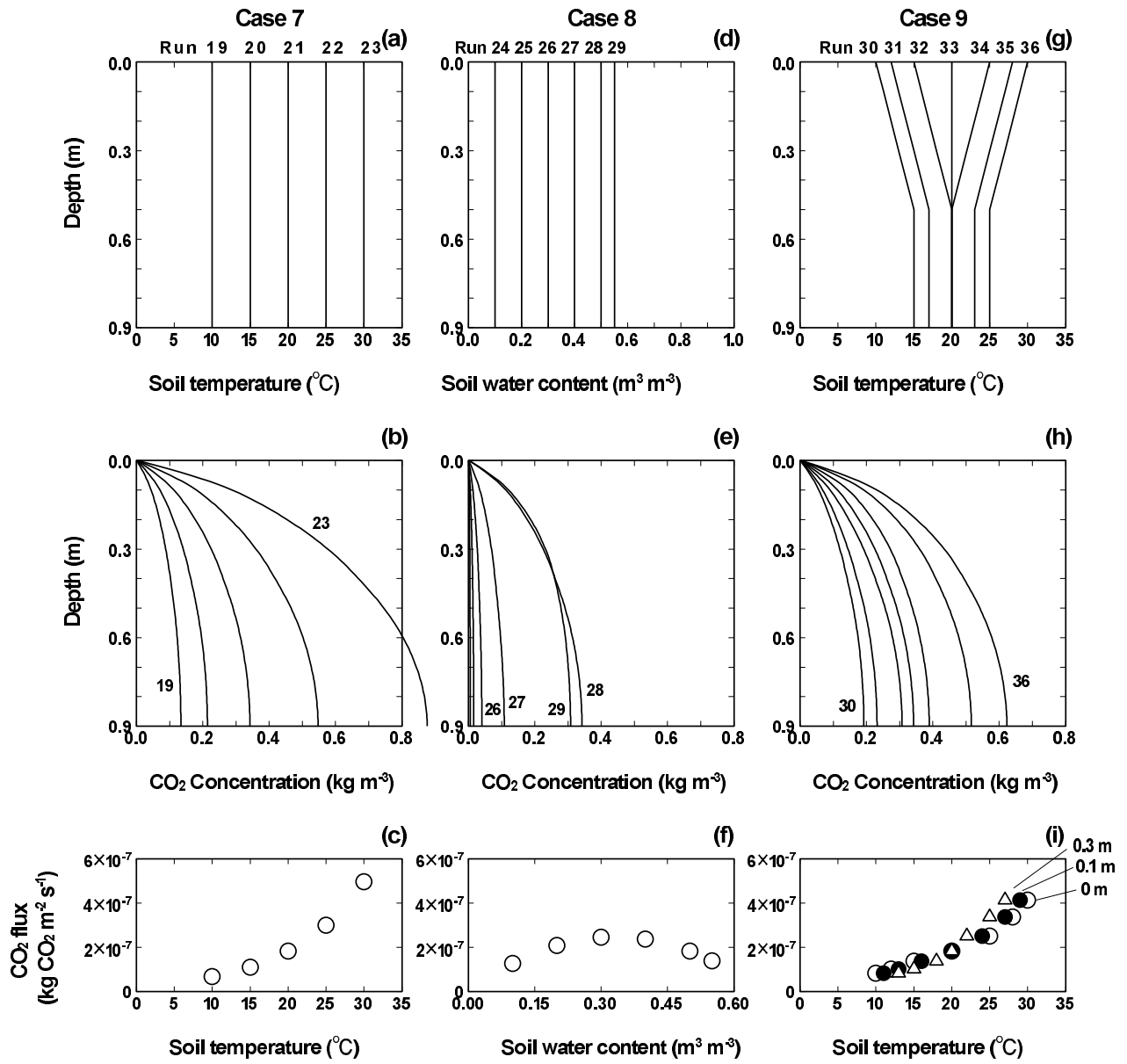


Figure 6.4: Sensitivity analysis: given vertical profiles of soil water or soil temperature, and simulated CO₂ gas concentration profile and CO₂ flux.

Case 8 (Run24-29): Soil water content changes The vertically constant soil water content is possible in area with distinct wet and rainy seasons. Soil water content at every depth is higher in rainy season and is lower in dry season. Soil surface CO₂ flux responded parabolically to soil water content. It agrees with CO₂ production rate. However, the performance of CO₂ concentration was complicated. Until Run28, CO₂ concentration increased with increasing soil water content, and the increment of CO₂ concentration was larger at higher soil water content. But, from Run28 to Run29, the performance was different from others. Soil water content slightly decreased below 0.4 m, increased a little above 0.4 m. The decrease of CO₂ concentration at deeper depth was because the decrease of soil CO₂ production at the depth dominated the decrease of gas diffusivity. The CO₂ concentration tends to increase with increasing CO₂ production rate and decreasing gas diffusivity. On the other hand, the increase of CO₂ concentration at shallower depth was caused by the dominance of the decrease of gas diffusivity. As in case5 and case6, soil CO₂ concentration profile performs in complicated manners. This is because soil CO₂ production responds to soil water content parabolically and air porosity controls gas diffusivity.

Case 9 (Run 30-36): Soil temperature change 2. vertically different In field conditions, a shallower soil tends to have a larger seasonality. That is to say, soil temperature at shallower depth is larger than deeper depth in hot season; on the other hand, soil temperature at shallower depth is smaller in cool season. In case9, I assumed 7 different temperature profiles and examine the model performance. Soil surface CO₂ flux increased with increasing temperature; however, the relationship between soil surface flux and soil temperature depended on the depth of soil temperature compared. The shallower depth the temperature used was at, the steeper the relationships were. This is, as mentioned above, because amplitudes of soil temperature decreased with depth. This result indicates the difficulty of comparing Q₁₀ values measured at field conditions in various ecosystems. Even in a same ecosystem, the relationship between soil surface flux and soil temperature is different due to the depth of soil temperature compared. I need to recompile various studies which reported Q₁₀ values with considering the depth of soil temperature. Soil CO₂ concentration increased with increasing soil temperature (From Run30 to Run36). Soil CO₂ concentration at deeper depth increased parallel from Run32 to Run34, and increased linearly from Run30 to Run32 and from Run 34 to Run36. These differences depended on whether CO₂ production rate at deeper depth rose or not, and were similar to the performances in case2 and in case3.

6.3.4 The gas diffusion coefficient at soil surface

Strictly say, modeling soil surface is very difficult. There are many reasons for this. For example, measuring soil water content or maximum air porosity is technically difficult because of the difficulty of installing probes and litter layer, although soil properties and soil environmental conditions change dramatically at shallowest depth. Soil surface receives litter fall from above ground biomass. This causes dramatic change of soil surface conditions. Activities of plant root at shallower soil would alter soil property every so often. Not only input of litter fall, litter fall decomposition also changes soil surface property. Soil surface also receives rainfall or throughfall directly and the variation of temperature is largest at soil surface. The transport form of soil CO₂ gas might be various although the main transport form in soil is considered as diffusion. It is known that wind speed affects soil CO₂ flux measurement (Hanson et al. 1993; Ohashi et al. 1995; Kutsch et al. 2000). In this model, I assumed constant and large gas diffusion coefficient at soil surface and changed the depth with the assumed diffusivity. It is reasonable because soil surface has larger porosity and greater gas diffusivity, and even in rainfall the air porosity is kept due to high water permeability. I conducted a sensitivity analysis about the boundary gas diffusivity as follows (Fig. 6.5):

Case 10 The depth with large and constant gas diffusivity changes (Run37-39)

Case 11 The value of the gas diffusivity change (Run 40-42)

In all runs, I assumed that soil temperature was 20 °C and soil water content was 0.5 at each depth.

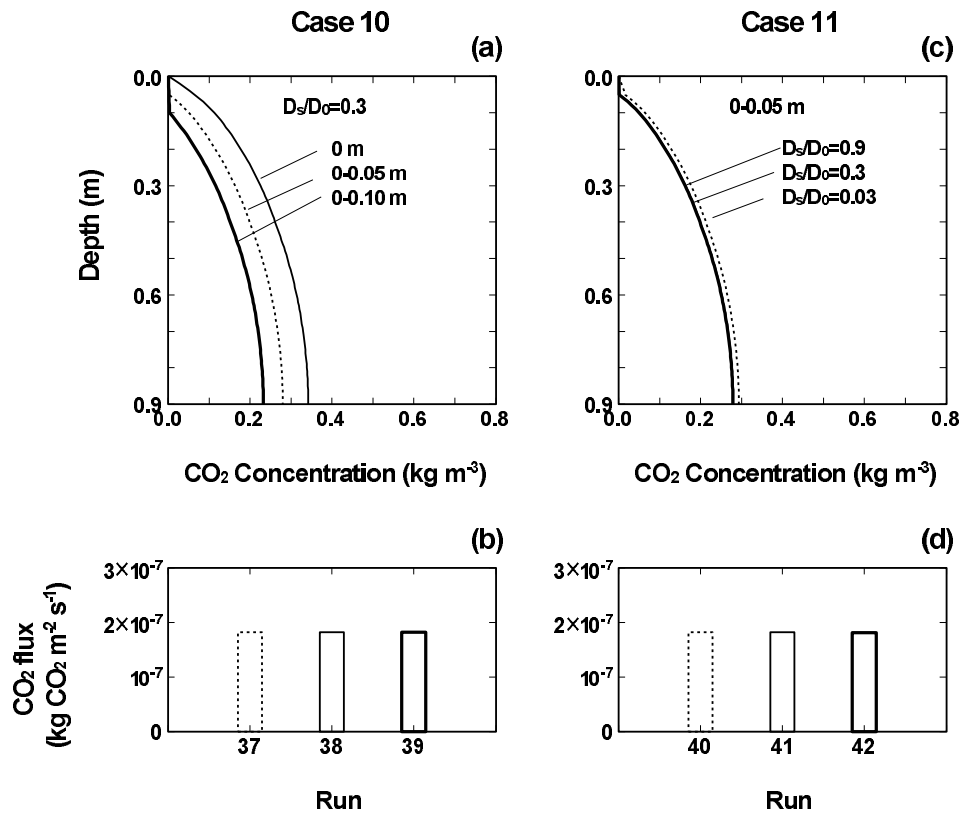


Figure 6.5: Sensitivity analysis: simulated CO₂ gas concentration profile and CO₂ flux with different soil surface gas diffusivities.

Case 10 (Run37-39): Depth of constant gas diffusion coefficient I examined the dependence of the depth which was assumed to have a large and constant gas diffusion coefficient. I assumed 0m, 0-0.05 m and 0-0.1 m depth as $D_s/D_0 = 0.3$. Soil surface flux did not change among Run 37 to Run39 because soil surface gas diffusivity did not affect the CO₂ production. On the other hand, soil CO₂ concentration at each depth decreased in parallel, with increasing the depth of constant and large gas diffusivity. Soil CO₂ concentrations at shallower depth (above constant gas diffusivity) were very small compared to Run38, almost the same as atmospheric concentration.

Case 11 (Run40-41): The degree of the gas diffusion coefficient at soil surface The value of the gas diffusion coefficient at shallower depth was changed, and its dependence to soil CO₂ concentration was examined. I changed three gas diffusion coefficient at 0-0.05 m, $D_s/D_0=0.03$, 0.3 and 0.9. When D_s/D_0 was 0.9, it indicated the gas diffusivity was almost as large as atmospheric gas diffusivity. As case 10, soil surface CO₂ fluxes were the same among three runs due to the insensitivity of soil CO₂ production to surface gas diffusivity. Soil CO₂ concentration decreased slightly from Run40 to Run41, and hardly from Run41 to Run42. The change of CO₂ concentration was quite small compared to Case 11. These results in case 10 and 11 indicate that the CO₂ concentration in soil is more sensitive to the depth of large and constant gas diffusion diffusivity at shallowest layer.

6.4 Results and Discussion

6.4.1 Temperate forest

Parameters Parameters value used in simulation of Fukuroyamasawa watershed are shown in Table 6.2.

Seasonality of soil respiration/CO₂ concentration profile Simulated soil surface flux agreed well with measured data (Fig. 6.6). Soil surface flux increased in summer season and decreased in winter season. Although the simulated soil surface flux models the measured data well, it overestimated in late summer to fall (September to October). This is probably caused by the lack of data of soil water measured at each depth and at shorter intervals.

Figure 6.6 shows the simulated and measured concentrations of CO₂ for individual depths. The simulated CO₂ concentration showed good agreement with observed data. CO₂ concentrations at each depth increased in summer season and decreased in winter season. The fluctuations at deeper depth were larger. In each depth, CO₂ concentrations in early summer (July, August) were underestimated and those in late summer and fall (September to October) were over estimated. At deepest depth of 0.8 m simulated CO₂ concentration in winter season tended to be smaller than observed values.

Possible causes of discrepancy The simulated soil surface flux and soil CO₂ concentration were a little higher than those of measured. This is probably because low intensity of soil water data. From late summer to fall, this site experienced less rainfall, and it would cause a decline of soil CO₂ production rate and an increase of gas diffusivity. They bring the decrease of soil surface flux and CO₂ concentration. However, my data of soil water was measured at one week interval with tensionmeters, and more intense data would be required. In other studies, these declines of soil surface CO₂ flux and CO₂ concentration were reported (Moncrieff and Fang, 1999). Soil surface CO₂ flux is often predicted only with temperature as a controller, and which brings, to some extent, good results; however, in this way, including soil temperature and soil water is essential for better estimation.

Vertical distributions of CO₂ concentrations, CO₂ production rates and gas diffusivity in high-soil respiration and low soil respiration season As mentioned above, the simulated CO₂ concentrations did not always match the measured ones well. However, there were some days on which the simulated CO₂

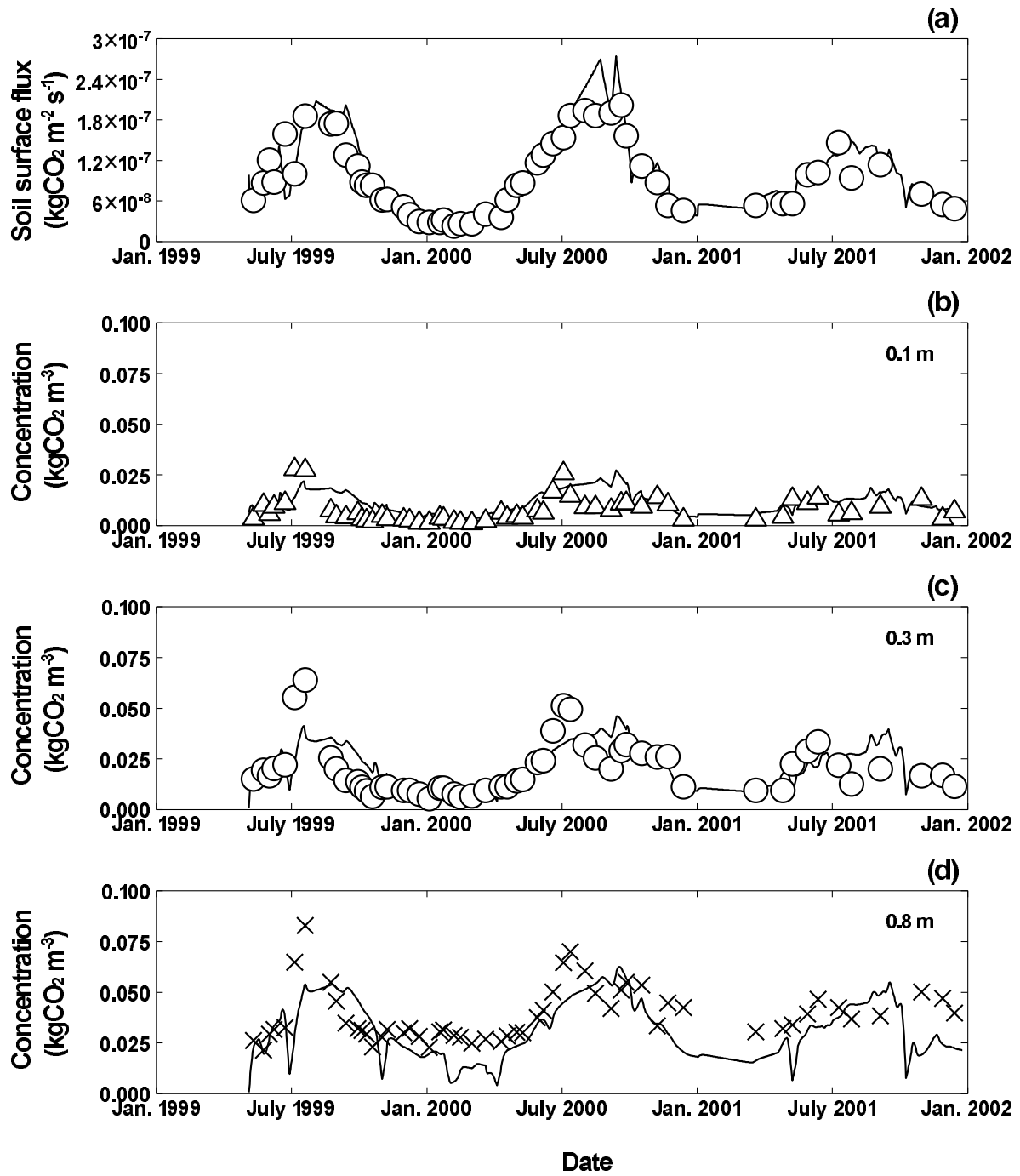


Figure 6.6: Simulated soil surface CO₂ flux, CO₂ concentration at each depth in Fukuroyamasawa watershed.

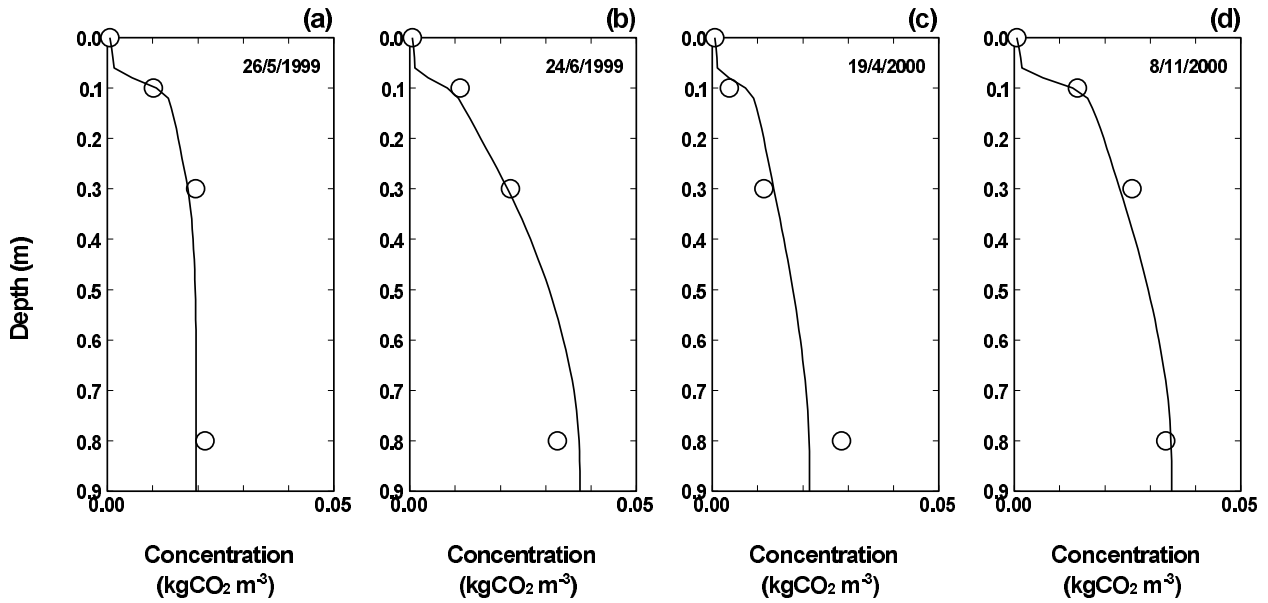


Figure 6.7: Vertical distributions of CO₂ gas concentration, measured (marks) and simulated (lines) in Fukuroyama watershed.

concentration agreed quite well with observation data. Figure 6.7 shows the vertical distribution of CO₂ concentration in soil. The simulated distributions showed good agreements with measured data. It is assumed in this simulation that soil above 0.07 m depth had fairly larger gas diffusivity, soil CO₂ concentrations above 0.07 m were accordingly small.

6.4.2 Tropical forest

Parameters Table 6.3 shows the parameters value assumed in Kog-Ma watershed.

Seasonality of soil respiration/CO₂ concentration profile The simulated soil surface CO₂ flux showed good agreement with observed data. Soil surface CO₂ flux were large in rainy season and small in dry season; however, the fluctuation among the years, in particular between first two years and last two years. Also, soil surface CO₂ flux measured in rainy season had large deviations. Although most of the simulated data model the measured soil surface flux, the simulated soil surface flux underestimated in the spring of 2000.

The simulated and measured concentrations of CO₂ for individual depths are presented in Fig. 6.8.

CO₂ concentrations were large in rainy season and small in dry season. There is a large fluctuation in CO₂ concentration in rainy season. The simulated CO₂ concentrations modeled well the increase and decrease in rainfall event observed in dry season in the spring season of 2001. Although the simulated and measured CO₂ concentrations were quite agreed, the simulated concentration showed slightly lower values in dry season.

Possible causes of discrepancy There were comparatively larger differences between the simulated and measured soil surface flux in March of 2000. In this simulation, I switched soil CO₂ production potential at shallowest layer (0-0.125m) on Jan first, 2000 (Table 6.3), because the degree of soil surface CO₂ flux were

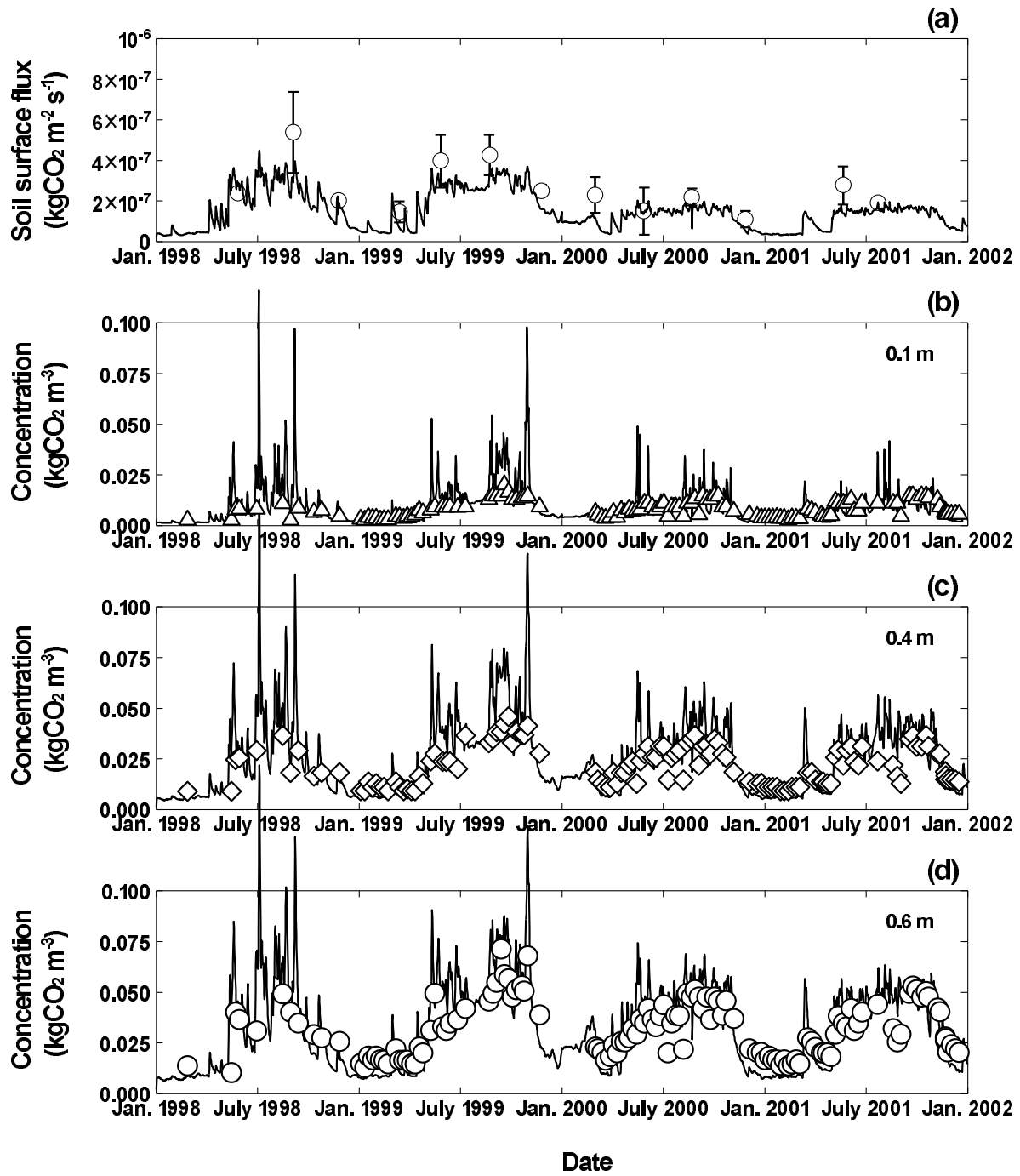


Figure 6.8: Simulated soil surface CO₂ flux, CO₂ concentration at each depth in Kog-Ma watershed.

different between 1998-1999 and 2000-2001. But the date on which the potential was switched was arbitrary. The date would be later actually.

There is a large fluctuation in CO_2 concentration in rainy season. These fluctuations were probably caused by the sudden decrease of pore space after rainfall, and cannot be seen in the simulation of Fukuroyamasawa watershed. There are some possible reasons. Firstly, Kog-Ma watershed experiences sudden and heavy rainfalls in rainy season many times because it locates in tropic regions. Secondly, it was caused by the difference of input data interval, that is to say, Fukuroyamasawa lacked data measured at short intervals. The soil water was measured at one week interval in Fukuroyamasawa and was measured at 15 minutes interval in Kog-Ma watershed. These high fluctuations in simulated results are reported in other studies (Suarez and Simunek, 1993; Moncrieff and Fang, 1999). Hirsch et al. (2002) measured soil CO_2 concentration using an automated system and showed high fluctuation of soil CO_2 concentration.

Vertical distributions of CO_2 concentrations, CO_2 production rates and gas diffusivity in high-soil respiration and low soil respiration season Compared to the simulation of Fukuroyamasawa watershed, the simulated CO_2 concentration in soil relatively showed good agreement with observation data. The vertical

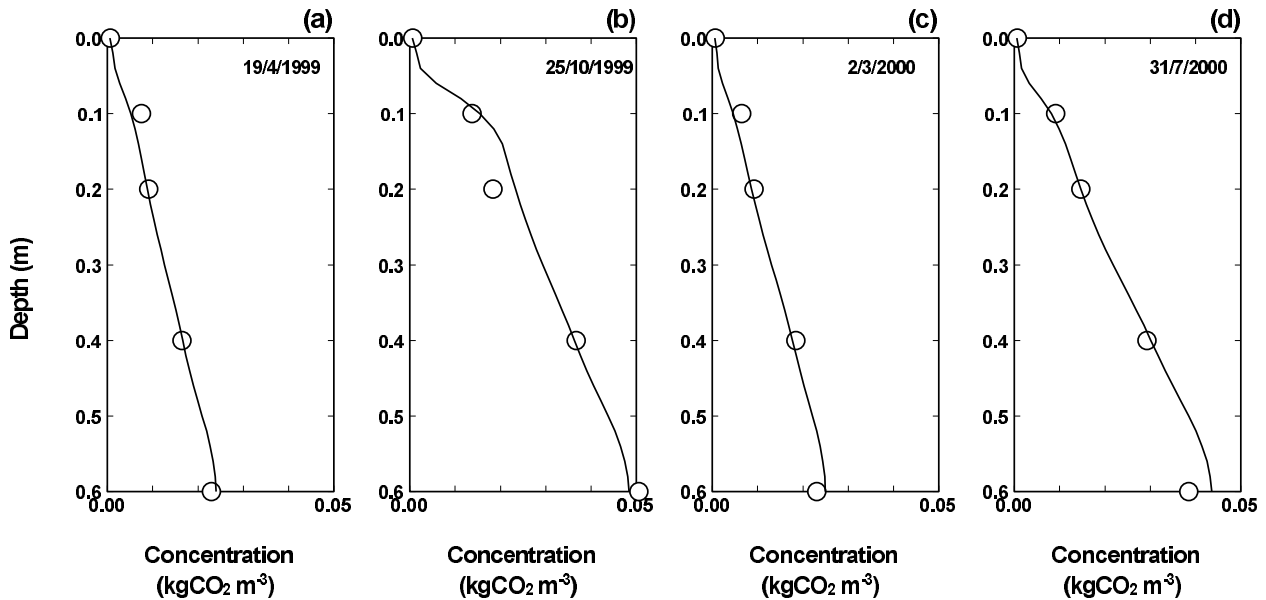


Figure 6.9: Vertical distributions of CO_2 gas concentration, measured (marks) and simulated (lines) in Kog-Ma watershed.

distributions of soil CO_2 concentration are presented in Fig. 6.9. These results model the observation data well. In the simulation of Kog-Ma watershed, I assumed that the gas diffusion coefficient above 0.05 m were constant and large. Then the CO_2 concentrations above 0.05 m were relatively low, but not so low as in the simulation of Fukuroyamasawa watershed.

6.4.3 Interannual changes

There were interannual variation in soil surface CO_2 flux in both Chiba and Thai data. These variations cannot be explained only by environmental factors, that is to say, soil temperature and soil moisture. I described

interannual changes with switching CO₂ production properties at shallowest layer, without altering soil physical properties and CO₂ production properties at deeper depth. CO₂ production property was changed between 1998-1999 and 2000-20001 in Thai simulation, and was changed yearly in Chiba simulation. This is realistically possible and, to some extent, reasonable. Because soil surface layer accepts litter fall from above ground biomass, and also organic matter from roots. The roots distribute most at shallowest layer (Jackson et al. 1996). Fresh organic matters contain labile C, and are easier to be decomposed than aged organic matter. They affect significantly soil surface flux after their inputs. These inputs of organic matter, then, would differ among years, even in a forest in equilibrium. Moreover, assuming constant root respiration potential (property) is difficult. Root respiration would also vary among year. These switching allowed to simulate interannual variation well. As an sensitivity analysis of case 3, changes of CO₂ production rate at shallowest layer do not affect soil CO₂ concentration profile significantly (Fig. 6.2). On the other hand, soil surface CO₂ flux was controlled directly by the change of CO₂ production rate.

6.4.4 Future developments

I developed a simpler model which simulates soil surface CO₂ flux and soil CO₂ concentration. I did not include various processes or influences which were not clearly understood yet. Even though the model is a simple, the model can provide good predictions. However, this model should be improved to include such processes and influences when these processes and influences are clear.

Separation of root respiration and heterotrophic respiration Firstly, I did not separate the sources of CO₂ productions into root respiration and heterotrophic respiration (organic matter decomposition). The ratio between root respiration and heterotrophic respiration differ among ecosystems and is difficult to evaluate (Nakane et al. 1983; Bowden et al. 1993; Lytle and Cronan, 1998; Striegl and Wickland, 1998; Kutsch et al. 2000; Hanson et al. 2000). Moreover it is difficult to evaluate the dependences of root respiration to environmental factors like temperature and water content (Boone et al. 1998), even in experimental conditions. Because roots exist in soil, and dividing roots from soil should change root respiration. Also, roots respiration may be affected by above ground biomass, above ground environment factors, or plant phenology. Some studies tried to describe CO₂ production with root respiration and heterotrophic respiration; however, they used the same dependency of root respiration to environmental factors as heterotrophic respiration (Fang and Moncrieff, 1999). In this way, in contrast to soil, root respirations are less understood. More studies on roots respiration are needed.

CO₂ concentration Secondly, I did not include the dependence of CO₂ production in soil to CO₂ concentration or O₂ concentration. In some modeling, the dependence of CO₂ production rate to oxygen concentration in the soil air was described with Michaelis-Menten equation (Fang and Moncrieff, 1999).

$$q = \frac{q_{max}}{1 + (K_M/[CO_2])} \quad (6.12)$$

where q is the oxygen uptake rate, q_{max} is the maximum oxygen uptake rate, K_M is the the Michaelis constant, and $[CO_2]$ is the CO₂ concentration. But studies on the dependencies to CO₂ or O₂ concentration are very few, and the dependences are not yet clear (Luxmoore et al. 1970; Armstrong and Gaynard, 1976).

Constant potential of CO₂ production rate and constant soil properties Thirdly, I assumed constant CO₂ production potential and soil properties, although the CO₂ production rate at shallowest layer was changed on purpose due to interannual variations. Strictly and realistically say, these values are never constant under natural conditions. It is reasonable to assume these values to be constant when I simulate for one year or less; however, in several years or longer simulation, CO₂ production potential and soil properties probably cannot be constant. In my three- or four-years calculation, only changing the CO₂ production potential at shallowest layer allowed good estimations.

Compartment model vs. process based model and the future vision In contrast to process-based model, compartment model can evaluate carbon cycle in soil under unsteadily. Compartment model is one of two major models which simulate carbon cycle in soil, and describes C and N cycling of plant growth and organic decomposition using many compartments. Century is a widely used model and can simulate carbon cycle for decades and centuries unsteadily (Parton et al. 1987, 1988; Townsend et al. 1995; Krishna et al. 2001; Kirschbaum and Paul, 2002). Compartment model is better suited for evaluating unsteady carbon cycle for decades and centuries at monthly or yearly intervals; on the other hand, it cannot simulate realistic CO₂ movements in soil at hourly or daily intervals. They have both advantages and disadvantages; one's advantages are other's disadvantages. I consider that compartment model will not be able to simulate at such a short interval and evaluate CO₂ gas movements in soil, and does not have to, and I consider that process based model will include unsteady CO₂ production rate and soil properties and prolong the period which can simulate, but does not have to be so long as compartment model.

6.5 Conclusions

I developed a simple process-based model for predicting soil CO₂ flux from soil surface, and CO₂ concentration in soil. The model was validated with field data collected in temperate artificial forest and tropical evergreen forest, and then it successfully predicted soil surface CO₂ flux and CO₂ concentration in soil. The sensitivity analysis illustrated the more complex performance of soil CO₂ concentration than soil surface flux. This model will help my understanding the mechanisms of CO₂ production and its transport in soil, what happens in soil in reality.

On the other hand, I can find some subjects to overcome. Firstly, the contributions of root respiration and heterotrophic respiration are not yet clear and neither is the response of root respiration to environmental factors.

Secondly, the concern is the interannual differences. In this model, the parameters of shallowest layer were changed for the interannual fluctuation. An ecosystem usually, to a greater or lesser extent, changes annually. A process-based model should include the interannual change.

Thirdly, evaluation of soil surface is difficult. The gas diffusion is the main process of CO₂ transport in soil except when soil water rapidly moves. However, at soil surface, the gas diffusion is not always the main process because of wind. Also, the accurate evaluation of soil properties of soil surface is difficult, and soil surface conditions probably change often due to litter fall.

In future, these will be improved, which will allow us to model soil CO₂ more accurately and in detail.

6.6 List of symbols

Each symbol means as follows:

z depth in soil, m

D_{std} gas diffusion coefficient in air at standard condition, m²s⁻¹

C CO₂ concentration, kgCO₂m⁻³

F CO₂ flux,

D CO₂ gas diffusion coefficient in soil, m²s⁻¹

Y CO₂ production rate, kgCO₂m⁻³s⁻¹

n_1, n_2 parameters of the relationships between gas diffusion coefficient and temperature, and pressure

ϵ porosity, m³m⁻³

θ soil water content, m^3m^{-3}

θ_{max} maximum soil water content or saturated soil water content, m^3m^{-3}

$f(T)$ temperature dependence of soil CO_2 production

T_0 reference temperature, $^{\circ}\text{C}$

k parameter of the temperature sensitivity of soil CO_2 production

$g(\theta)$ dependence of soil CO_2 production on soil water content

Parameter	Symbol	Value	Unit
Maximum depth		0.9	m
The relative gas diffusion coefficient at soil surface		0.3	
The depth of soil surface layer		0.07	m
Reference temperature		20.0	°C
<i>0-0.125 m</i>			
CO ₂ production potential (1999)	<i>A</i>	1.14E-06	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity (1999)	<i>k</i>	0.099	
CO ₂ production potential (2000)	<i>A</i>	1.56E-06	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity (2000)	<i>k</i>	0.119	
CO ₂ production potential (2001)	<i>A</i>	9.79E-07	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity (2001)	<i>k</i>	0.0555	
Parameter <i>a</i> of water dependency	<i>a</i>	-4.0	
Parameter <i>b</i> of water dependency	<i>b</i>	4.0	
Parameter <i>c</i> of water dependency	<i>c</i>	0.0	
<i>0.125-0.375 m</i>			
CO ₂ production potential	<i>A</i>	3.08E-08	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.139	
Parameter <i>a</i> of water dependency	<i>a</i>	-4.0	
Parameter <i>b</i> of water dependency	<i>b</i>	4.0	
Parameter <i>c</i> of water dependency	<i>c</i>	0.0	
<i>0.375-0.675 m</i>			
CO ₂ production potential	<i>A</i>	1.05E-08	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.072	
Parameter <i>a</i> of water dependency	<i>a</i>	-4.0	
Parameter <i>b</i> of water dependency	<i>b</i>	4.0	
Parameter <i>c</i> of water dependency	<i>c</i>	0.0	
<i>0.675 m -</i>			
CO ₂ production potential	<i>A</i>	3.33E-08	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.072	
Parameter <i>a</i> of water dependency	<i>a</i>	-4.0	
Parameter <i>b</i> of water dependency	<i>b</i>	4.0	
Parameter <i>c</i> of water dependency	<i>c</i>	0.0	

Table 6.2: Parameters in the simulation of Fukuroyamaswa watershed.

Parameter	Symbol	Value	Unit
Maximum depth		0.6	m
The relative gas diffusion coefficient at soil surface		0.3	
The depth of soil surface layer		0.05	m
Reference temperature		20.0	°C
<i>0-0.15 m (1998-1999)</i>			
CO ₂ production potential (1998-1999)	<i>A</i>	2.9E-06	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.081	
Parameter <i>a</i> of water dependency	<i>a</i>	0	
Parameter <i>b</i> of water dependency	<i>b</i>	1.9017	
Parameter <i>c</i> of water dependency	<i>c</i>	-0.52136	
<i>0-0.15 m (2000-2001)</i>			
CO ₂ production potential	<i>A</i>	1.47E-06	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.081	
Parameter <i>a</i> of water dependency	<i>a</i>	0	
Parameter <i>b</i> of water dependency	<i>b</i>	1.960874	
Parameter <i>c</i> of water dependency	<i>c</i>	-0.5687	
<i>0.15-0.375 m</i>			
CO ₂ production potential	<i>A</i>	7.52E-08	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.081	
Parameter <i>a</i> of water dependency	<i>a</i>	-4.37323	
Parameter <i>b</i> of water dependency	<i>b</i>	3.350843	
Parameter <i>c</i> of water dependency	<i>c</i>	0.358132	
<i>0.375-0.55 m</i>			
CO ₂ production potential	<i>A</i>	9.18E-08	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.081	
Parameter <i>a</i> of water dependency	<i>a</i>	-4.64766	
Parameter <i>b</i> of water dependency	<i>b</i>	4.311688	
Parameter <i>c</i> of water dependency	<i>c</i>	0	
<i>0.55 m -</i>			
CO ₂ production potential	<i>A</i>	1.49E-07	kgCO ₂ m ⁻³ s ⁻¹
Temperature sensitivity	<i>k</i>	0.081	
Parameter <i>a</i> of water dependency	<i>a</i>	-5.18232	
Parameter <i>b</i> of water dependency	<i>b</i>	4.552941	
Parameter <i>c</i> of water dependency	<i>c</i>	0	

Table 6.3: Parameters used in the simulation of Kog-Ma watershed.

Chapter 7

Summary and Conclusions

Climate change is recognized as the most urgent concern of mankind, as well as the concern of the earth itself, and soil carbon cycle is considered to be one of keys to control the climate change.

Many researchers have been tackling the understanding of soil carbon cycle, especially soil respiration (CO_2 flux from soil surface). Nevertheless, most researchers do not consider the complex processes below the ground and only a few researchers take them into consideration.

In this study, I approached subsurface processes of soil respiration in three ways: experiments, analyzing field observation data, and modeling.

In Chapter 2, I proposed a new apparatus for measuring gas diffusion coefficients in sandy soil which did not emit CO_2 . This apparatus established a steady gas condition, adopted Fick's first law and allowed us to measure the vertical distribution of soil gas diffusion coefficient of sandy soil. I successfully obtained the relationship between soil gas diffusion coefficient and soil matric potential of Toyora standard sand. I also innovated a new method of measuring a small volume of the soil CO_2 gas using IRGA, which method could be used both in a field and in a laboratory.

Chapter 3 developed a new system for measuring vertical distributions of both CO_2 gas diffusion coefficients and CO_2 production rate in forest soil. The basic theory of the apparatus of Chapter 2 was applied to the system. This system could handle large, undisturbed soil sample and could control soil temperature and soil water. I measured the properties of soil respiration in temperate artificial forest using this system.

Chapter 4 showed the soil respiration properties of tropical evergreen forest in Thailand, which was measured using the new system. There are few studies on soil respiration in tropic regions, especially under experimentally environment-controlled conditions. I found the strong relationship between soil respiration and soil temperature ($Q_{10}=2.2$), which had been unclear because of the less seasonality of soil temperature in tropic regions. I also revealed the vertical distributions of soil CO_2 production rate and gas diffusion coefficient.

Chapter 5 presented the analysis of field observation data of CO_2 concentration and soil surface flux, which revealed CO_2 production rate at each depth and its seasonality. There are many studies on soil surface CO_2 flux; on the other hand, there are fewer studies which measured and analyzed both the soil surface CO_2 flux and soil CO_2 concentration, although the soil CO_2 concentration indicates a lot about what happens in soil. I analyzed soil surface CO_2 flux and soil CO_2 concentration in temperate artificial forest and tropical evergreen forest, and demonstrated the contributions and seasonality of CO_2 production rate at each depth. I found the high contributions of the shallowest layer in both two forests; however, in tropic forest the contributions of the shallowest layer dropped in dry season because of the severe dryness, in contrast to the constant contributions through the year in a temperate artificial forest. I also discovered the temperature sensitivities of deeper soil in temperate artificial forest, and the soil water sensitivities in tropical forest.

Chapter 6 developed a model which simulates CO_2 concentration in soil and soil surface CO_2 flux. The model included CO_2 production process and its transport process in soil. Sensitivity analysis was conducted, which presented the performances of this model, indicated the important parameters, and demonstrated the

complex relationships among CO_2 production in soil, CO_2 concentration profile and soil surface CO_2 flux. The model was validated to the data measured in temperate artificial and tropical evergreen forest, which were the forest sites in Chapter 3-5. Parameters were determined using the analysis in Chapter 3-5. The model successfully predicted soil surface CO_2 flux and CO_2 concentration in soil. There are no studies which simulate soil surface CO_2 flux and CO_2 concentration over years. This is the first study. Through the modeling soil surface CO_2 flux and CO_2 concentration in two different forests over years, I realized some difficulties which are my future subjects: separation of root respiration and heterotrophic respiration, their own sensitivities to various environments, and changes in the potential of CO_2 production and soil properties with time. Improving these subjects will help our full and clear understanding soil carbon cycle and its interaction with climate change, and make it possible to predict them more accurately and in detail.

Without the deep understanding of subsurface processes, it's impossible to evaluate carbon cycle in soil and to predict the accurate interaction between soil carbon cycle and climate change. Nevertheless, there are few studies; and more studies are needed. One of the reasons is the difficulty in approaching subsurface. I hope my study contributes to developing the understanding of the subsurface processes of soil CO_2 : CO_2 production and its transport.

Chapter 8

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Chapter 9

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Appendix A

The Crank-Nicholson implicit method

The mass balance and gas diffusion equation can be written as follows:

$$\frac{\partial aC}{\partial t} = -\frac{\partial q}{\partial z} + Y \quad (\text{A.1})$$

$$q = -D \frac{\partial C}{\partial z}. \quad (\text{A.2})$$

Then, the above two equations yields

$$\frac{\partial aC}{\partial t} = -\frac{\partial}{\partial z}(-D \frac{\partial C}{\partial z}) + Y \quad (\text{A.3})$$

$$= \frac{\partial}{\partial z}(D \frac{\partial C}{\partial z}) + Y. \quad (\text{A.4})$$

Adopting the Crank-Nicholson scheme on the assumption that air porosity is time-invariant, the above equation yields

$$a_i \frac{C_i^{n+1} - C_i^n}{\Delta t} \quad (\text{A.5})$$

$$= \frac{D_i \frac{\frac{C_{i+1}^{n+1} + C_{i+1}^n}{2} - \frac{C_i^{n+1} + C_i^n}{2}}{\Delta z} - D_{i-1} \frac{\frac{C_i^{n+1} + C_i^n}{2} - \frac{C_{i-1}^{n+1} + C_{i-1}^n}{2}}{\Delta z}}{\Delta z} + Y \quad (\text{A.6})$$

$$= \frac{D_i((C_{i+1}^{n+1} + C_{i+1}^n) - (C_i^{n+1} + C_i^n)) - D_{i-1}((C_i^{n+1} + C_i^n) - (C_{i-1}^{n+1} + C_{i-1}^n))}{2(\Delta z)^2} + Y \quad (\text{A.7})$$

where i means the step of space and n means the step of time, where Δt is the time step and Δz is the space step. Defining $\alpha = \frac{\Delta t}{2(\Delta z)^2}$, then

$$a_i(C_i^{n+1} - C_i^n) = \alpha \left(D_i((C_{i+1}^{n+1} + C_{i+1}^n) - (C_i^{n+1} + C_i^n)) - D_{i-1}((C_i^{n+1} + C_i^n) - (C_{i-1}^{n+1} + C_{i-1}^n)) \right) + Y \Delta t - \alpha D_{i-1} C_{i-1}^{n+1} + (a_i + \alpha D_i + \alpha D_{i-1}) C_i^{n+1} - \alpha D_i C_{i+1}^{n+1} \quad (\text{A.8})$$

and, the above equation yields

$$a_i(C_i^{n+1} - C_i^n) = \alpha D_{i-1} C_{i-1}^n + (a_i - \alpha D_i - \alpha D_{i-1}) C_i^n + \alpha D_i C_{i+1}^n + \Delta t Y. \quad (\text{A.9})$$

Appendix B

Homepages

Not only in books and journals, but also in home pages, there is so much information. Here I present some home pages about Climate Changes.

IPCC

<http://www.ipcc.ch/>

NASA, earth observatory

http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=7257

WWF

<http://www.wwf.or.jp/index.htm>

GHG (GreenHouse Gas Online) All about greenhouse gas science

<http://www.ghgonline.org/>

Japanese Forest Agency

<http://www.rinya.maff.go.jp/>

United Nations, Framework convention on climate change

<http://unfccc.int/>

International Energy Agency, Experience Curves for Energy Technology Policy

<http://www.iea.org/public/studies/curves.htm>