

Effects of tillage on behavior of carbon dioxide in an Andisol

(耕起方法が黒ボク土中の二酸化炭素ガスの挙動に及ぼす影響)

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Abstract

Soil respiration contributes to the production of carbon dioxide (CO₂) that is a major greenhouse gas. Tillage practices are considered to have a potential to restrict or enhance CO₂ flux from the soil. Andisol is an important soil for agricultural production in many areas of Japan, but the studies on the CO₂ behavior in Andisols under different tillage systems are limited. Behavior of soil CO₂ in an Andisol under different tillage systems was studied and reported in the present paper.

The undisturbed soil column incubation experiments were performed for a period of 150 days to conduct the study. Soil physical properties of five layers in soil columns were measured under no-tillage and tillage treatments. Tillage reduced soil dry bulk density and increased saturated hydraulic conductivity at the chiseled layer. No significant difference in soil temperature was observed between no-tillage and tillage treatments. Tillage modified the soil structure, and thus the water retention characteristics and volumetric water content. Soil air-filled porosity and the gas diffusivity under no-tillage treatment were observed to be smaller than that under the tillage treatment during the incubation period. Four widely used soil gas diffusivity models were evaluated on prediction of soil gas diffusivities under no-tillage and tillage treatments. The Buckingham-Burdine-Campbell (BBC) model fit well with the measured values for both no-tillage and tillage treatments. Soil aggregates, especially macroaggregates (>1 mm) were destructed by tillage. The soil structure included pore structure and aggregation was distinctly influenced by the tillage.

Studies on effects of tillage on soil physical properties may provide necessary information for assessing the soil CO₂ flux under different tillage systems. After the first

day, difference in the CO₂ flux between the no-tillage and tillage treatments was not as clear as that of the first day. The cumulative soil CO₂ flux under the tillage treatment for the incubation period tended to be higher than that under the no-tillage treatment. However, no significant differences in soil carbon stock and soil carbon associated with soil aggregates were seen between them, since the carbon loss of the 150 days of the incubation period was small to the carbon storage in the soil column. Long-term experiments are expected to conduct to study soil organic carbon stocks.

Soil CO₂ concentration was evaluated with the column incubation experiment, which was also used to estimate the CO₂ flux. Soil CO₂ concentration increased with the soil depth. During the incubation period, soil CO₂ concentration under the no-tillage treatment was clearly higher than that under the tillage treatment, except at the depth of 2.5 cm. Soil gas diffusivity under the tillage treatment at depths of 0–15 cm that estimated by the BBC model was greater than that under the no-tillage treatment. The CO₂ flux through the soil profile, calculated from the CO₂ concentration and gas diffusivity, decreased with depth. Linear relationship was observed between the estimated and measured CO₂ surface flux. The CO₂ production at depths of 0–15 cm accounted for 70.5 % and 60.4 % of the whole CO₂ production of the 0–35 cm soil profile for no-tillage and tillage treatments. Soil CO₂ production was higher under the no-tillage treatment at depths of 0–5 cm in comparison to the tillage treatment, but contrary results were observed at depths of 5–35 cm. For the soil profile of 0–35 cm, the CO₂ production was increased by tillage.

The tillage depth and macropore in the soil were considered as important factors to affect the CO₂ behavior. Repacked soil column incubation experiments of 150 days were conducted to examine the contributions of the tillage depth and macropore on

soil CO₂ behavior. Soil physical properties (i.e., soil gas diffusivity, dry bulk density and saturated hydraulic conductivity) were significantly affected by the depth of tillage at the chiseled layers. The CO₂ cumulative flux from the soil tended to show as deep tillage > conventional tillage > no-tillage. At deeper layers (20 cm and 30 cm), soil CO₂ concentration was lower under the deep tillage treatment than that under the conventional tillage, and the highest CO₂ concentration was observed under the no-tillage treatment. Similarly, no difference in soil total carbon was observed among the treatments.

Soil CO₂ concentration under the no-tillage- with macropore treatment was lower than that under the no-tillage- without macropore treatment, but the lowest CO₂ concentration was observed under the tillage treatment. The CO₂ cumulative flux from soils tended to show as tillage treatment > no-tillage- with macropore > no-tillage- without macropore. Although tillage destroyed the macropore in the soil, soil cumulative CO₂ flux tended to be increased and the CO₂ concentration tended to be decreased by tillage.

The column incubation keeps the soil structure the same with that in the field. With column incubation experiments, the behavior of CO₂ in the Andisol was well studied.

Keywords: Tillage systems, Soil physical properties, Soil CO₂ behavior, Andisol, Tillage depth, Macropore

Chapter 1 Introduction

1.1 Background

1.1.1 Global warming

Global warming caused by an increase in the greenhouse gas (GHG) concentration in the atmosphere is one of the serious threats to sustainable development. Greenhouse gases mainly include CO₂, CH₄ and N₂O, which contribute 60%, 15% and 5%, respectively, on a global basis to the anthropogenic greenhouse effect (Rodhe, 1990). Global GHG emissions due to human activities (e.g., fossil fuel burning and deforestation) have grown since industrialization times, with an increase of 70% between 1970 and 2004. Rising atmospheric levels of the greenhouse gases have caused an increase in radiative forcing of the earth atmosphere, and thus a rise in the temperature of the globe. The earth's average surface temperature rose by 0.74 ± 0.18 °C over the period 1906–2005. The rate of warming over the last half of that period was almost double of that over the period as a whole (IPCC, 2007).

Changes in global climate have discernible impacts on the hydrological system, such as the increase in the global average air and ocean temperatures leads to the widespread melting of snow and ice and the rising in global average sea level. In addition, climate change may increase the frequency of extreme adverse climate events such as droughts, heat waves, heavy rainfalls, ocean acidification and hurricanes. Moreover, the further threatening to the stability of agricultural production by climate changes have also been reported recently (Tao et al., 2003). Future warming could result in changes of crop yields and increase in the risk of malnutrition. Therefore, most countries proposed policies aimed to prevent dangerous anthropogenic climate changes

(UNFCCC, 2010). These policies require the GHG concentrations are stabilized in the atmosphere at a level where ecosystems can adapt naturally to climate changes, food production is not threatened, and economic development can proceed in a sustainable fashion.

1.1.2 Carbon cycle

Carbon dioxide is the most important anthropogenic greenhouse gas, and is one of the main forms of carbon in the atmosphere. Growth rate of CO₂ equivalent (CO₂-eq) emission was much higher during the recent 10-year period of 1995-2004 (0.92 Pg CO₂-eq yr⁻¹) than that during the previous period of 1970-1994 (0.43 Pg CO₂-eq yr⁻¹) (IPCC, 2007).

As shown in Fig. 1, carbon stores in five major pools including oceanic pool (38400 Pg), biotic pool (550 Pg), atmospheric pool (800 Pg), pedologic pool (2300 Pg) and fossil fuel (10000 Pg) in the earth. Carbon transfers between these pools through physical, chemical and biological processes. Such as, carbon leaves the atmosphere through photosynthesis, and enters into the terrestrial and oceanic biospheres. Carbon in the atmosphere can also transport to the ocean or the soil as the form of CO₂ through directly dissolving into the water. Carbon in the pedologic pool is released into the atmosphere by soil respiration. Soil as a store of huge amount of carbon plays an important role in the carbon cycle.

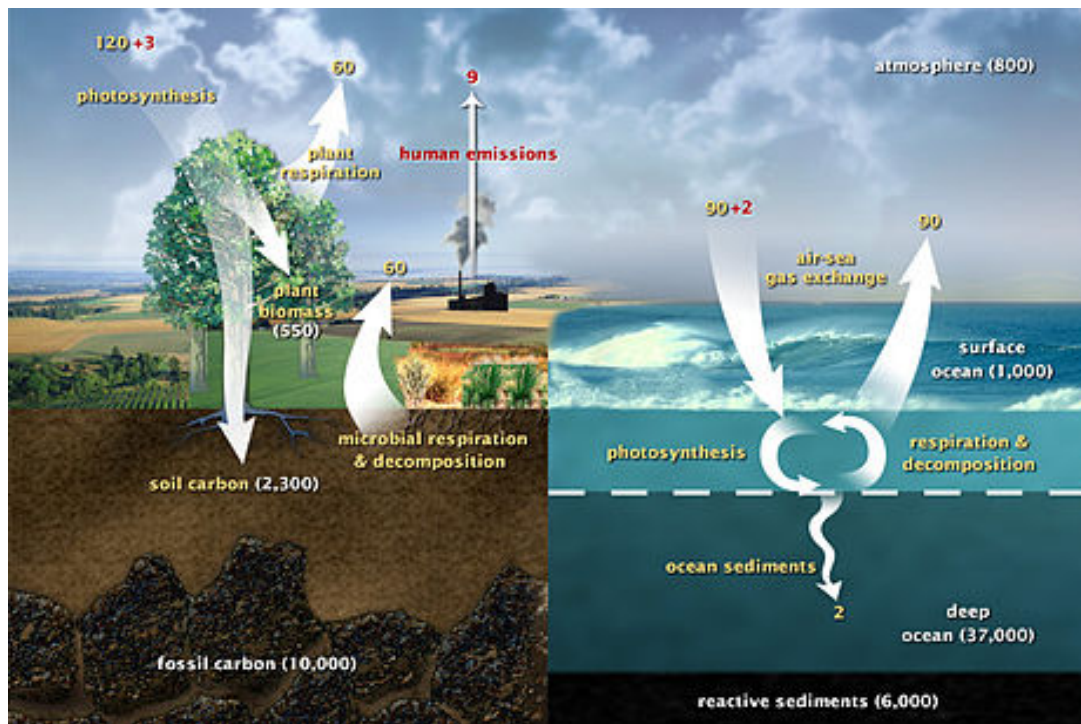


Fig. 1 Global carbon cycle. <http://earthobservatory.nasa.gov/Features/CarbonCycle>. The numbers mean the amount of carbon stored in the pools or transported between the pools. The unit of the number in this figure is Pg yr⁻¹ (10¹⁵g per year).

1.1.3 Carbon sink and source

The role of soil in the global carbon cycle is considered as a sink or a source of carbon. A carbon sink is a natural or artificial reservoir that accumulates and stores some carbon-containing chemical compounds for an indefinite period. The process by which carbon sinks remove CO₂ from the atmosphere is known as carbon sequestration. Plants take up CO₂ from the atmosphere in the process of photosynthesis and return to the soil. Plant litter and other biomass are accumulated as organic matter in soils, and are degraded by chemical weathering and biological degradation. Forms of carbon that are difficult to decompose become stabilized in the soil as humus (Fig. 2). Thus, organic matter tends to accumulate in soils.

On the other hand, soil is considered as a major source of CO₂. About 2500 Pg carbon stores in the pedologic pool, and this amount is distinctly greater than that in biotic pool and atmospheric pool (Fig. 1). Easily decomposable forms of carbon in the soil transfer to the atmosphere as CO₂ by soil respiration (Fig. 2). Soil respiration refers to the production of CO₂ when soil organisms respire, which includes respiration of microbes, plant roots, and fauna. Soil respiration rates can be largely affected by human activities. This is because humans have the ability to change the various controlling factors of soil respiration (Burney et al., 2010).

Higher soil organic carbon (SOC) results in a improved soil structure, lower bulk density, greater porosity, higher infiltration rates, greater sequestration of nutrient elements, reduced erosion, increased biodiversity and higher biomass productivity (Sparling et al., 2006; Lal, 2004). Recently, since the negative environmental impacts of global warming due to higher greenhouse gas concentration in the atmosphere were realized, estimations on carbon stocks in soils became hot topics. A stock of carbon in the soil is the quantity presented at a given time and determined by carbon inputs and outputs. Carbon stock is influenced by the climate (e.g. temperature, rainfall) and agricultural managements. Therefore, if environmental factors or management practices cause the SOC stock increasing over time, the soil can be described as a sink because carbon is moving into it. Otherwise, the soil is a source since the carbon stock is declining (Powlson et al., 2011).

Carbon sequestration of a variety of tropical soils was estimated by Lugo and Brown (1993). They reported that tropical soils with an area of 250 million hectares (in Hawaii and Caribbean) could accumulate 0.17–0.55 Pg C yr⁻¹. The greatest potential for carbon sequestration in tropical soils was due to the forest fallows.

Zhuang et al. (2010) used the terrestrial ecosystem model to examine the carbon dynamics in the Tibetan plateau in China. The result showed that the soil acted as a carbon sink of $0.036 \text{ Pg C yr}^{-1}$ during the 1990s. Tall grasslands with an area of 100 million hectares dominated the regional sink, and were responsible for 90% of the total carbon sink. During the 20th century, the soil in Tibetan Plateau exhibited a significant annual variability of carbon dynamics. Overall, the regional sink slightly increased.

A multi-compartment model was developed to summarize existing data and predict soil carbon sequestration beneath switch grass (*Panicum virgatum*) in the southeastern USA (Garten, 2012). Results reported that the rate of soil carbon sequestration varied from -28 to $114 \text{ g C m}^{-2} \text{ yr}^{-1}$. The soil could be a sink or source of carbon. Temperature, nitrogen fertilization, and initial soil carbon stocks were important externalities factors to affect soil carbon dynamics.

Murty et al. (2002) summarized the data of carbon stocks in cultivated soils (Canada, Australian, USA, Africa) and reported an average loss of approximately 30 % of soil carbon was found in these sites. A decrease in carbon was contributed by the conversion of forest to cultivated land.

Dunn and Freeman (2011) estimated the carbon in peat lands in UK. They reported peat lands were the most efficient carbon stores of all terrestrial ecosystems, containing approximately 455 Pg of carbon, which is twice the amount found in the world's forest biomass. Peat lands were sequestering carbon at a rate of $0.096 \text{ Pg C yr}^{-1}$. However, anthropogenic degradation of peat lands through draining, fires and exploitation could increase the production of GHGs and switch peat lands from net sinks to net sources of carbon.

Suitable agricultural managements may enhance carbon sequestration and

decreased the CO₂ emission from soils (Paustian et al., 1997; Gregorich et al., 1998; Burney et al., 2010). The agricultural managements including tillage, converting land use systems, applying manure, crop rotation, irrigation, and so on, are more widely used in recent farming. Tillage as an important agricultural management was discussed in the present study.

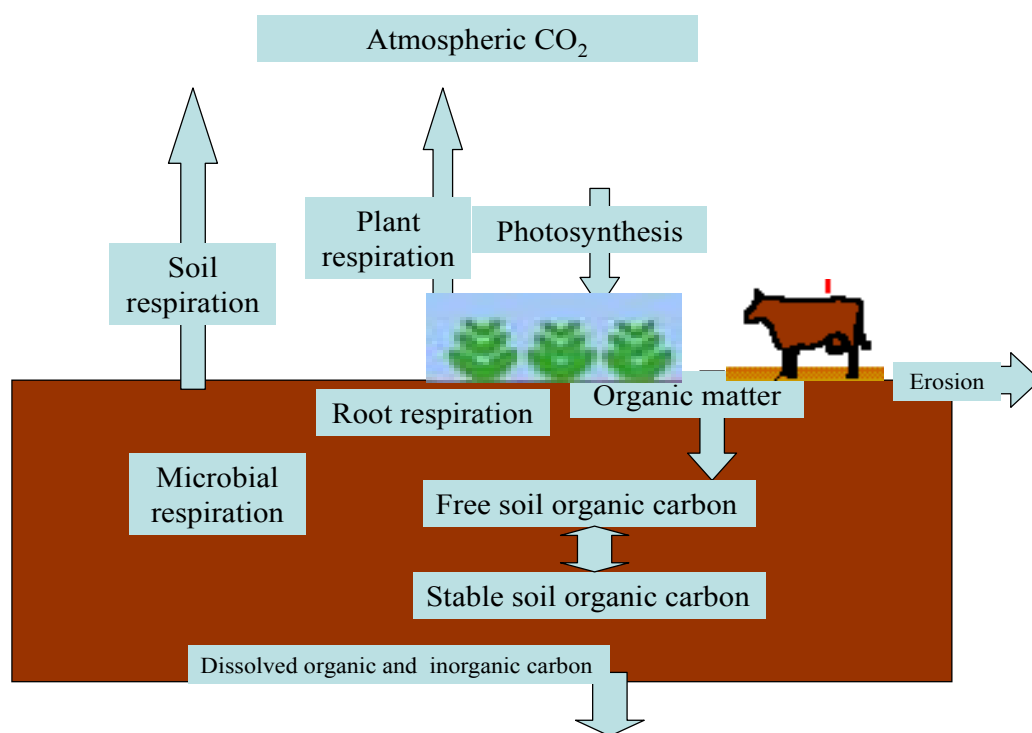


Fig. 2 Carbon dynamics in soils

1.2 No-tillage and tillage systems

Tillage is an agricultural preparation of the soil by mechanical agitation of various types, such as digging, stirring, and overturning. Due to different tilling tools, tillage methods include hoeing, raking, ploughing, rolling, cultivating and so on. Since ancient times, tillage has a number of important roles in farming activities, such as weed management, fertilizers and residue incorporation, compaction relief, topsoil aeration and seedbeds preparation (Philips et al., 1980). But negative impacts (i.e., soil erosion, degradation of soil structure, depletion of soil nutrients, soil drought, death or disruption of soil microbes and other organisms, and formation of hard pan) also have been reported in tillage systems (Warkentin, 2001; Xie et al., 2007).

Reduction of the use of tillage has been recommended in the modern agricultural science. No-tillage farming (also called zero tillage) is a way of growing crops from year to year without disturbing the soil through tillage. No-tillage systems avoid the harmful effects owing to tillage, and have been reported to have the advantages of reducing soil erosion, conserving moisture, improving soil structure, raising beneficial insects and annelids and increasing the crop yield (Crovetto, 1998; Gupta and Sayre, 2007). Less tillage conducted on the soil may also reduce the labor, fuel, irrigation and machinery costs (Lafond et al., 1993). However, the no-tillage method requires some different skills in order to do it successfully according to the local conditions. Such as, the no-tillage farming requires specialized seeding equipments designed to plant seeds into undisturbed soil. In addition, cover crops are used occasionally in the no-tillage system to help controlling weeds and increasing nutrients. No-tillage also requires rotating the crops on a multi-year cycle to decrease the pests and diseases.

No-tillage is known to improve the soil qualities and decrease the economic consumption (Fernandez et al., 2009; Lal, 2007). Recently, some studies focused on the effects of the no-tillage system on carbon sequestration in soils. The no-tillage system may have a potential to decrease soil CO₂ emission through the storage of soil organic carbon. Therefore, suitable tillage systems may lead to the environmental profit. However, there is a debate over whether the increased carbon sequestration is contributed by the no-tillage system or is due to flawed testing methods or other factors (Powlson et al., 2011; Johnson et al., 2005). This study aimed to evaluate the effects of tillage on soil CO₂ behavior.

1.3 Tillage and carbon dynamics in soils

Relationships between tillage practices and soil physical, chemical and biological properties have been reported by Logan et al. (1991) and Alvarez and Steinbach (2009). Carbon dynamics in the soil is strongly affected by soil environmental conditions. Thus, the no-tillage system may not only enhance the soil qualities but also affect carbon dynamics in soils.

1.3.1 Tillage and soil aggregates

Soil structure is one of the key physical properties that affect carbon dynamics in soils (Bronick and Lal, 2005; Conant et al., 2007). Aggregate stability and distribution are used as indicators of the soil structure. The aggregate model developed by Tisdall and Oades (1982) forms the basis for the aggregate hierarchy concept, which is the first model to link the mechanisms of aggregate formation and stabilization with spatial and temporal distributions of soil organic matter (SOM). It also helps to explain

how land management practices affect SOM stocks and dynamics through influencing the formation and stabilization of aggregates. The model describes that soil macroaggregates are bounded by microaggregates, primary particles and organic material agents. The bonds within microaggregates are stronger than that between microaggregates. It is suggested that the organic carbon is protected by the soil aggregates. Basis on the aggregate model, soil organic carbon (SOC) was observed to be higher in well aggregated soils (Elliott, 1986; Puget et al., 2000; Balesdent et al., 2000).

Agricultural managements involving tillage have often been reported to affect the soil structure. Increasing in the tillage intensity decreases soil aggregation, and especially destroys macroaggregates (Alvaro-Fuentes et al., 2008). Compared to conventional tillage, reduced tillage improves the stability of aggregates against the water content related forces of disintegration (Daraghmeh et al., 2009). Sundermeier et al. (2011) found the tillage significantly influenced the aggregate stability that the aggregate stability was 35 % and 45 % higher in 23-years no-tillage and 44-years no-tillage, respectively, than in conventional tillage.

After tillage, the organic matter once protected or combined by aggregates is exposed to microorganisms, microbial enzymes and their substrates, and hence is easily decomposed. Thus, the carbon associated with aggregates is affected by different tillage systems (Six et al., 1998; La Scala et al., 2009). Six et al. (1999, 2000) conducted the experiment on four kinds of soils to proposal a conceptual model for the soil organic matter dynamics in soil aggregates under no-tillage (NT) and conventional tillage (CT) systems. The model shows the rate of macroaggregate degradation is reduced under NT in comparison to CT. The NT system leads to a formation of stable microaggregates in

which carbon is stabilized and sequestered in the long term. Therefore the link between the aggregate formation and carbon stabilization within aggregates partly explains the observed increase in soil organic matter under NT. Soil organic matter is also protected by the structural pores formed by aggregates which are small enough to limit microbial accessibility and preclude microbial attack. Structural soil pores between the aggregates are very susceptible to the disturbance due to tillage. Therefore, the organic carbon protected by the structural pores would be bared to microbes after the tillage practice and the loss of soil carbon enhanced (Thomsen et al., 2003). Shi et al. (2010) reported that the organic carbon in soils was increased in the following order: 50 years cultivation < 12 years cultivation < native grassland. They explained that losses of SOC by cultivation would be largely related to the disruption of >1 mm size aggregates and exposure of intra-aggregate organic matter to the microbial attack.

Moreover, some researchers have observed that the SOC sink capacity of different-sized soil particles responded differently to tillage systems. The quantification of SOC stabilized in individual particle-size fractions, rather than the total SOC pool, may properly reflect the changes in SOC dynamics caused by the agricultural management. Compared to the tillage treatment, the SOC of macroaggregates under the no-tillage treatment was significantly high and showed 1.5–2.8 times higher than that of other aggregate-size classes (Jagadamma and Lal, 2010). Kushwaha et al. (2001) reported that SOC and microbial biomass carbon contents were strongly correlated with the amount of soil macroaggregates. Compared to the conventional tillage treatment, no-tillage showed the increase in the fraction of macroaggregates, and SOC was also observed to be higher. Since the SOC in different positions of the aggregates performs different functions and turnover processes, the studies on the SOC associated with

aggregates of different sizes are also challenged.

Disintegration of aggregates by tillage makes an important contribution to the soil carbon decomposition. Decrease in the storage of carbon for no-tillage or reduced tillage soils may contribute to an increase in the CO₂ emission from the soil to the atmosphere (Mishra et al., 2010; John et al., 2005; Ashagrie et al., 2007).

1.3.2 Tillage and soil microbial activities

Soil carbon is transferred to the atmosphere as CO₂ by microbial respiration. Tillage managements may create different soil physical conditions such as moisture, temperature and pore size distribution. As critical factors for microbial respiration, soil physical properties affect the process of carbon mineralization and CO₂ production.

The tillage operation leads to soil loosening or compacting, thus, soil bulk density, soil strength, infiltration capacity, water redistribution within the soil and the moisture retention are affected by the tillage operation (Alvarez and Steinbach, 2009). Low dry bulk density, low penetration resistance and high hydraulic conductivity were found under the conventional tillage treatment by soil loosening (Dolan et al., 2006; Rahman et al., 2003). But Benjamin (1993) and Green et al. (2003) reported that high macroporosity and hydraulic conductivity were observed in the no-tillage system since tillage destroyed macropores in soils. Shukla et al. (2003) reported the available water capacity, air filled porosity, volume of storage pores, equilibrium infiltration rate and pore size distribution index were greater for no-tillage fields than that for tillage fields at depths of 0–10 cm. No-tillage or conservation tillage also has been reported to decrease topsoil temperature and to increase soil water content (Licht and Al-Kaisi, 2005; Carter et al., 2005). Although some contradictions are seen in the previous reports, these

findings suggest that soil physical properties are affected by tillage practices.

Microbial activities in soils are sensitive to the physical environments (Balesdent et al., 2000). As an important variable of soil respiration, in an appropriate range, soil microbial respiration increases with the soil temperature (Borken et al., 2002; Wang et al., 2004). Cumulative microbial respiration rates at the lower water contents are always lower than that at the higher water contents for sand soils (Chowdhury et al., 2011). Increase in the O₂ concentration of soil air-phase up to that of the atmosphere can enhance the soil respiration rate (Sierra and Renault, 1995; 1998). Microbial respiration changes with the changes in physical environments caused by tillage managements.

Recently many researchers focused on the relationship between microbial activity and tillage managements. First, microbial biomass C and N has been found to be higher under no-tillage and reduced tillage treatments than that under the conventional tillage treatment. In addition, the microbial biomass C has been observed to be positively correlated with SOC (Babujia et al., 2010). Sundermeier et al. (2011) reported the microbial biomass was 13 %, 83 %, and 86 % higher in 2-years, 23-years, and 44-years no-tillage systems, respectively, than that in the conventional tillage system. In addition, no-tillage had significantly lower microbial respiration rates and microbial biomass losses in comparison to conventional tillage. Second, the microbial community structure is altered by tillage, and the changes in microbial community structure may affect the carbon decomposition. Jackson et al. (2003) indicated that tillage caused temporary stress on soil microbes and changed the soil microbial community structure. This might decrease the ability of microbes to retain soil C and N. Helgason et al. (2010) reported the microbial community structures associated with aggregates of different size classes were different between no-tillage and conventional

tillage treatments. Thus, carbon dynamics associated with aggregates of different size classes between the two treatments might be different. Moreover, high levels of microbial respiration and microbial metabolic quotient have also been found under the no-tillage system (Jiang et al., 2011). Melero et al. (2011) reported the dehydrogenase activities and glucosidase activities were higher under the no-tillage system than that under the traditional tillage system. Since these papers showed effects of tillage practices on microbial activities, amount and community structures, the soil CO₂ production governed by microbial respiration would be affected by tillage practices.

Tillage causes changes in soil physical conditions through modifying the soil structure, and consequently, the soil pore structure. Therefore, to better understand the soil CO₂ flux under different tillage systems, influence of tillage on soil physical properties has to be studied.

1.3.3 Soil carbon sequestration and carbon dioxide emission as affected by tillage systems

Some studies estimated effects of tillage practices on soil organic carbon (SOC) sequestration and CO₂ flux in different locations with different types of soils. Johnson et al. (2005) reported effects of tillage systems on potential SOC sequestration in the region of central USA, where the main soil taxonomies were typic hapludoll and paleudalf, and the main soil texture was silt. Conservation tillage, including no-tillage was more widespread in the region. Durations of tillage system in experimental sites were about 5–30 years, the tillage depths ranged among 7.5–30 cm. The SOC for conventional tillage was 53.3 Mg C ha⁻¹ (10⁶ g per hectare), for no-tillage was 59.1 Mg C ha⁻¹. The average rate of SOC storage under no-tillage was significantly higher in

comparison to conventional tillage, but for all the regions, the results were variable. In the Southeastern USA, data of the 147 comparisons across eight states showed that the SOC sequestration under conservation tillage was $0.45 \pm 0.04 \text{ Mg C ha}^{-1}$ higher than that under conventional tillage in the duration of $11 \pm 1 \text{ yr}$ (Franzluebbers, 2010). Ludwig et al. (2010) reported the carbon stocks in soils under different tillage systems on Alluvial soil in North China Plain. SOC tended to increase from 10 year onwards. Under conservation tillage, SOC content was on average 2.1 Mg ha^{-1} greater than that under conventional tillage and the tillage depth was about 20 cm. Yan et al. (2007) estimated the potential and sustainability for carbon sequestration with improved soil management in agricultural soils in China. The arable land in China covered about 124 million hectares, accounting for about 13% of the world's total. The results showed that practicing no-tillage and returning crop residue on the arable lands would lead to an annual soil carbon sequestration of $0.26 \text{ Mg C ha}^{-1}$. Practicing no-tillage caused higher rate and longer sustainability of soil carbon sequestration, but the potentials varied greatly among different regions due to the differences in climate, soil conditions and crop productivity.

These results confirmed the effects of tillage on soil carbon stocks, but some contradictions on soil carbon stocks in different tillage systems have also been found in previous studies. VandenBygaart et al. (2003) reported the results of long-term studies in Canada to assess the effects of agricultural management on SOC. No-tillage increased the storage of SOC in western Canada by $2.9 \pm 1.3 \text{ Mg ha}^{-1}$, but conversion to no-tillage from conventional tillage did not increase SOC storage in eastern Canada. Differences in crops and tillage systems were found between the two locations. In western Canada, the depth of tillage usually ranged between 15 and 30 cm, the common

crop was corn, and the cool moist soil was poorly drained. In eastern Canada, the depth of tillage was about 10 cm, and the predominant crop was wheat. Differences in crops and tillage systems between the west and east Canada might partly contributed to the uncertain results.

Six et al. (2004) compared the carbon storage under no-tillage and conventional tillage treatments in the experiment sites including US Corn Belt under humid climate and North American Great Plains under dry climates. Under humid climates, net soil organic carbon storage within the 0–30 cm soil layer averaged $0.22 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ over the 20 years following the adoption of the no-tillage practice. In contrast, no-tillage adoption in dry climates was estimated to result in soil carbon loss at the first 10 years, whereas the trend changed to net carbon sequestration during the second decade, being averaged only $0.097 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. The contrast results between the two regions might depend on the climates.

West and Post (2002) recorded the response of SOC to changes in the tillage systems from the long-term agricultural experiment sites (i.e. Norway, Argentina, USA, Canada and New Zealand). Comparisons between conventional tillage and no-tillage treatments indicated that, on average, a move from conventional tillage to no-tillage could sequester $0.48 \pm 0.13 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. But within these experiments, the changes in the tillage practice in wheat-fallow rotations system showed no significant increase in SOC sequestration.

Most of the researchers presented that no-tillage and reduced tillage could increase the carbon sequestration in soils. However some data showed little or no difference between no-tillage and tillage systems in the total amount of soil carbon. The differences in soil types, climates, tillage systems, and crops may partly contribute to

the contradictory results.

Changed in the carbon storage in the soil may control the CO₂ emission to the atmosphere. Since the negative environmental impacts of global warming owing to higher CO₂ concentration in the atmosphere are realized, the effects of tillage systems on CO₂ emission attract more attentions recently. Some published experiment results, which recorded the response of soil CO₂ flux to different tillage systems, are listed in Table 1.

As shown in Table 1, soil CO₂ flux affected by different tillage systems was estimated in varying types of soils such as Luvisol, Mollisol and Cambisol. The descriptions of soils, crops and tillage methods are also listed in this table since the differences in these factors may lead to the contradictory results. Although most studies reported the no-tillage system reduced the CO₂ flux from the soil, the results that no differences in soil CO₂ flux under no-tillage and tillage treatments have also been found (e.g. Ahmad et al., 2009; Ussiri and Lal, 2009). Variety of soil properties, climates and tillage systems increase the complexity of studies on the carbon dynamics, but the studies on these influencing factors are limited. Therefore, despite some studies evaluated the soil CO₂ flux affected by tillage systems, further studies on CO₂ flux from different types of soils and the influencing factors are required.

Table 1 Summaries of studies on soil CO₂ flux affected by different tillage systems

Citation	Year	Location	Soil description	Crop	Tillage depth(cm) /duration(yr)	Duration of sampling	CO ₂ flux (Kg CO ₂ -C ha ⁻¹ year ⁻¹)	
							T	NT
Oorts et al.	2007	Northern France	Luvisol	Maize-wheat	20/-	1 year	3160	4064
Nagata et al.	2009	Hokkaido, Japan	Peat	Wheat	25/-	7 months	6493	5713
Ahmad et al.	2009	Hubei, China	Paddy soil/ Silty clay loam	Rice	8-10/-	3 months	7640	7624
Al-Kaisi and Yin	2005	Iowa, USA	Calcaric Gleysols/ Fine loamy	Corn-soybean	25/-	20 days	9332	7234
Passianoto et al.	2003	Rondonia, Brazil	Ultisol/	Pasture	20/-	6 months	8690	6120
Drury et al.	2006	Minnesota, USA	Mollisol/ Clay loam	Wheat-corn -soybean	15/-	6 months	5750	5590
Omonode et al.	2007	Indiana, USA	Mollisol/Silty clay loam	Corn-soybean	20–25/-	2 years	5900	5700
Ussiri and Lal	2009	Ohio, USA	Alfisol/ Silt loam	Corn	20–30/ 43	1 year	5500	6200

Yan et al.	2011	Northwest China	Sierozem/ Sandy loam	Wheat	-/3	1 year	18240	14039
Boeckx et al.	2011	Maulde, Belgium	Luvisol/-	Wheat-maize	10/-	2 years	10100	9600
Nyakatawa et al.	2012	Alabama, USA	Paleudult/ Silt loam -	wheat	-/-	1 year	1788.5	1314
Feiziene et al.	2012	Lithuanian	Cambisol / Loam	wheat-oil seed rape-wheat- barley-peas	23-25/-	3 year	7735	7718
Sanchez et al.	2002	Spanish	Aridisols/-	barley	-/-	1 year	7682	6433
Fuss et al.	2011	Munich, German	Cambisol/ Loamy sandy	wheat-potato- winter wheat-maize	25-30/-	2 year	4581	4310

1.3.4 Studies on Andisols

Andisol, derived from volcanic ash, is an important soil for crop production in Japan. Andisol shows unique chemical and physical properties, such as high organic carbon contents, low dry bulk density and high porosity (Shoji et al., 1993; Rahman et al., 1998). Munoz et al. (2011) assessed seasonal variability of the CO₂ flux from an Andisol in southern Chile under a no-tillage system by using a closed chamber method. The CO₂ flux responded to seasonal patterns, and the higher CO₂ emission was observed mainly under the wet soil conditions.

Nouchi and Yonemura (2005) examined the CO₂ flux from double-cropping upland fields under no-tillage (1600–2400 g CO₂-C m⁻² yr⁻¹) and conventional tillage (2300–2900 g CO₂-C m⁻² yr⁻¹) systems, respectively, and suggested that the no-tillage cultivation was one of the most promising managements for mitigation of greenhouse gas emissions. Yonemura et al. (2009) reported the yearly estimated CO₂ production of the top 30 cm of the soil was 1854 g CO₂-C m⁻² yr⁻¹ in conventional plots and 1689 g CO₂-C m⁻² yr⁻¹ in no-tillage plots. Astier et al. (2006) studied the effects of tillage on soil carbon in Andisol fields in Mexico, and found the soil under zero tillage had higher organic carbon than that under conventional tillage. It also reported that the crop yield was higher in the conventional tillage system, but the soil under zero tillage showed higher quality. Rahman et al. (2008) compared the carbon content in the apple orchard with no-tillage to that in the dryland cropped wheat and soybean with conventional tillage, and reported the organic carbon contents for no-tillage and conventional tillage were 66.61 and 37.43 g kg⁻¹, respectively. Both the soils are Andisols.

However, Koga and Tsuji (2009) suggested the reduced tillage had no clear effect on the overall soil carbon sequestration, and explained that in comparison to the

effects of tillage, high air permeability of Andisols contributed a lot to the soil carbon evolution rate. Nakamoto et al. (2012) conducted the experiments on the Andisol in Japan, and reported the soil under the no-tillage system showed higher SOC content at depths of 0–15 cm than that under the tillage system, but no difference was found at 15–30 cm. The studies with regard to soil physical properties and soil CO₂ behavior in Andisols as affected by different tillage systems are limited. Additionally, the contradictories on soil carbon storage as affected by the tillage have been found in existing results. Therefore, further studies on soil carbon sequestration and CO₂ flux in Andisols under different tillage systems are required.

1.4 Problems in recent studies

Results in the CO₂ flux from soils found in previous studies are influenced by many factors, such as climates, soil properties, crops, tillage methods and measurement methods. Understanding of effects of tillage on the CO₂ behavior would be improved by considering these factors, within which the depth of tillage and macropores in soils were chosen to study in the present experiment.

1.4.1 Depth of tillage

Apart from tillage implements such as a mouldboard plow, cultivator, chisel plow and harrow, the deeper the soil is plowed the greater the soil displacement in the direction of tillage is observed. Conventional tillage usually disturbs the soil to about 12–18 cm in depth, but some tillage treatments deeply disturb the soil to 25 cm or deeper. As shown in Table 1, the tillage systems with different tillage depths were conducted by researchers to evaluate the soil CO₂ flux, and this may affect the results of

the CO₂ flux.

The influence of the tillage depth on soil properties is reported by previous papers. Soil erosion was serious with the deep tillage (St Gerontidis et al., 2001) . Sarkar and Singh (2007) reported that the reduction in the tillage depth from 150 to 90 mm was responsible for higher grain yield and water use efficiency, and the shallow tillage contributed to better soil structure. In addition, daily soil temperature changes were different if the tillage depth changed. The soil dry bulk density, compactness and penetration resistance were substantially increased below the depth of tillage (Etana et al., 1999). Since the effects of the tillage depth on soil properties have been intensified by previous literature, increase or decrease the tillage depth may lead to the changes in soil carbon stocks that controlled by soil physical properties.

Tillage depth affects the decomposition of organic carbon and the vertical distribution of SOC. Melero et al. (2011) reported the application of traditional tillage obviously reduced soil total organic carbon and microbial biomass carbon. High CO₂ flux was found more related to the depth of soil disturbance that resulted in a rougher surface and larger voids (Reicosky and Lindstrom 1993). They explained the soil CO₂ was lost to the atmosphere and presumably O₂ entered into the soil through large voids to enhance microbial activity. Lower CO₂ flux was caused by the tillage associated with low depth of soil disturbance. The near linear relationship between the cumulative CO₂ loss and the volume of soil disturbed by tillage was observed by Reicosky and Archer (2007). The result suggests that controlling of the tillage depth can optimize or minimize the soil CO₂ exchange. Deep tillage breaks up more soil clods and aggregates to expose fresh surfaces for enhanced gas exchange. These previous studies implies that differences in depth of tillage may be an reason to explain the variations in the soil

carbon stock and CO₂ flux, but the roles of tillage depth on soil carbon dynamics have received little attention.

However, Etana et al. (1999) reported that an increase in the depth of tillage reduced the content of SOC in the tillage layer, but did not affect the content of SOC of the whole profile. West and post (2002) cited nearly 100 plot studies of the SOC under different tillage systems in Canada. When the studies were segregated by the sampling depth, the results were striking. In 17 experiments where the sampling depth was relatively shallower than tillage depth, 82 % of the no-tillage treatments showed higher soil carbon content in comparison to the conventional tillage controls. In five experiments where the sampling depth was deeper (>30 cm), the soil carbon content under no-tillage treatments was not greater than that under conventional tillage. A comparison of soils in Brazil under conventional tillage and no-tillage treatments illustrated that the SOC concentration was greater under no-tillage in the 0–5 cm and 5–10 cm depth layers but below these layers it was slightly less. Overall, the total SOC presenting to a depth of 35 cm was similar in the two systems (Machado et al., 2003). Considering the fact that soil carbon is concentrated at the soil surface under the no-tillage treatment, sampled soil at the layer that are shallower than the tillage depth for analysis may overestimate the potential of no-tillage system on the carbon sequestration (Gregorich et al., 2005). Therefore, to avoid such overestimation, the sampling depth should be greater than the tillage depth.

Tillage depth is an important factor to affect the CO₂ flux from the soil. However, little work has been done to characterize the effects of the depth of tillage on the CO₂ behavior. Based on the effects of the tillage operation on soil CO₂ behavior, the present study also reported the influence of the tillage depth on soil CO₂ behavior.

1.4.2 Macropores in soils

The gas transport in soils is affected by the soil pore characteristics. Tillage increased the soil porosity to promote the gas diffusion and convection in the soil. Effects of tillage on the soil diffusion are reported as one contributor of raising CO₂ emission, since soil respiration is accelerated by higher soil aeration (Weltecke and Gaertig, 2012).

Macropores are the relatively large pores or channels that are formed in interaggregates and interpedals as well as channels that left by biological activities in soils. Pierret et al. (1999) reported the soil with more macropores contained more microbial biomass per unit mass in comparison to the soil with less macropores. The bacterial population in a macropore sheath was able to utilize a wider range of carbon substrates. Pankhurst et al. (2002) suggested, in comparison to the bulk soil, the soil with macropores had higher organic C, total N, bicarbonate-extractable P, Ca, Cu, Fe and Mn and supported higher populations of bacteria, fungi and other microbes. Previous studies indicated that soil macropores influenced the rate of water movement, chemical transport, aeration and penetration of rooting systems (Allaire-Leung et al., 2000; Jose de, 1992). Eguchi and Hasegawa (2008) detected the preferential water flow caused by macropores two to seven times per year and it accounted for 16 to 27% of the annual total drainage in an Andisol. Tokumoto et al. (2007) reported that the preferential water flow and solute transport caused by macropores were observed in an undisturbed Andisol, especially under high water content conditions. The macropores in the Andisol reported by Tokumoto et al. (2007) were mainly formed by plant roots.

Roseberg and Mccoy (1990) found a fine loamy soil core with macropores (>1 mm diameter) had a higher air permeability in comparison to that without macropores.

Bronswijk et al. (1993) simulated the O₂ diffusion in macropores in a wet and tight clay soil, and observed that the formation of pyrite was directly related to the macropore network, since the O₂ is an important factor of pyrite formation. Dziejowski et al. (1997) evaluated the O₂ concentration in a soil column with or without a artificial macropore. The result indicated that the O₂ concentration for the homogeneous soil and the soil with a macropore was almost the same at a depth of 10 cm, but the O₂ concentration was higher at the deeper layer for soil with a macropore. The greater O₂ concentration at deeper layer could not be explained by the diffusion process only. The existence of preferential flow of O₂ in the soil also contributed to the higher O₂ concentration at deeper depths. From these studies, it is concluded that macropores could affect the gas behavior in soils. Brito et al. (2009) reported the high macroporosity and low bulk density contributed to the highest CO₂ emission in an eutrustox soil, and this was due to the importance of the soil porous space for gaseous transport, and consequently, for microbial activities. However, the exiting studies on the effects of macropores on the CO₂ behavior in soils are insufficient.

Macropores in soils are sensitive to the agricultural practices, especially the tillage. Weisskopf et al. (2010) reported that tillage increased the volume of soil macropores (porosity at pF=2) and air permeability especially for the topsoil. And changes in the topsoil structure also led to unintended changes in the subsoil environment. Roseberg and Mccoy (1992) reported that the conventional tillage decreased the stability, the number, and continuity of macropores (>1 mm diameter) in comparison to the no-tillage. Imhoff et al. (2010) reported that effective pores, the mean pore radius and the effective macroporosity (>0.5 mm diameter) were observed to be greater in the no-tillage system. Pores had better continuity in the no-tillage system,

which increased the water and gases transports in soils.

Tillage impacts the number and continuity of soil macropores, and thus, the gas behavior. All these add the uncertainty of CO₂ flux from soils. Therefore, the effects of tillage practices on the CO₂ behavior in the soil with macropores may be different from those without macropores, but the studies on this subject are limited. More detailed studies on the effects of macropores on soil CO₂ behavior and the effects of tillage on the CO₂ behavior in the soil with macropores are required.

1.4.3 Soil carbon dioxide concentration

The existing studies focused on soil CO₂ flux, but neglected the other CO₂ behavior in soils such as production and transport of CO₂ under different tillage systems. The CO₂ transport in soils or from the soil to the atmosphere is governed by the CO₂ concentration gradient, since the main mechanism of gas transport in the vadose zone is gas diffusion (Yoshikawa and Hasegawa, 2000). The measurement of CO₂ concentration in the soil contributes to the evaluation of the soil CO₂ flux. Moreover, soil CO₂ production can be estimated by the CO₂ concentration in the soil profile with the models (Pumpanen et al., 2003; Fierer et al., 2005).

Several studies have been conducted to evaluate soil CO₂ flux by using the data of the concentration gradients in soil profiles (Pihlatie et al., 2007). Nakadai et al. (2002) reported seasonally representative soil CO₂ flux from an Andisol which was calculated by the CO₂ concentration in the soil profile in a bare field. The results indicated that diurnal changes of the calculated CO₂ flux were similar to that of the measured ones. Tang et al. (2003) assessed the CO₂ concentration in the forest soil and suggested that the mean CO₂ concentration remained steady at a depth of 2 cm during summer, but

obviously fluctuated at deeper layers. The estimated CO₂ efflux was very close to chamber measurements.

CO₂ concentration has also been used in some studies to estimate the CO₂ production in soils at different soil horizons. Davidson and Trumbore (1995) calculated the CO₂ production in the forest soil by the profiles of the CO₂ concentration and revealed that 70–80 % of the measured CO₂ flux from the soil surface was produced in the top 1 m of the soil (including litter in the forest). Fierer et al. (2005) used the data of soil CO₂ concentration and soil gas diffusion coefficients to estimate CO₂ production rates in soil profiles. Calculated net soil CO₂ production was similar with the measured CO₂ flux. Pumpanen et al. (2003) used the installed CO₂ probes to determine the CO₂ concentration, and then calculated the respiration rates of different soil horizons by using data of CO₂ concentration. He also estimated the contribution of each soil layer to the total CO₂ production, and the result showed that humus layer and A horizon, B horizon and C horizon contributed 69.9 %, 19.8 %, and 10.4 % to the total CO₂ production, respectively.

These studies showed that the soil CO₂ concentration could be used to estimate the CO₂ flux and production. Precise measurements of the CO₂ flux from soil by using the chamber method is difficult, since measurements are affected by many factors, such as rain events. Thus, measurements of the CO₂ concentration could help to evaluate the CO₂ emission, and the calculation of CO₂ production by using CO₂ concentration could also help to study the mechanisms of the CO₂ flux. However, a relatively small number of studies focused on the CO₂ concentration in the soil profile and attempted to estimate the effects of tillage systems on soil CO₂ concentration.

1.5 Incubation experiments

Incubation experiments are widely used in recent studies on soil CO₂ flux. In comparison to the field experiments, the experimental conditions such as temperature and water content are easily controlled by incubation experiments. Therefore, some researchers conducted the studies of greenhouse gas behavior in soils by using the incubation experiments.

Dumale (2009) studied the dynamics of turnover of active-biological and stable-mineralogical soil organic carbon by a 110-d incubation experiment. In this study, the 500 ml bottle with 20 g soil was used to conduct the incubation experiment, and the soil CO₂ emission rates under different treatments were in the range of 7.87 to 46.81 mg kg⁻¹ d⁻¹ (mg CO₂-C per kg soil per day). Ou et al. (2005) studied the influence of soil acidification on greenhouse gases emission by a 42 months incubation experiment. Nakadai et al. (2002) measured soil CO₂ production rates in the laboratory using undisturbed soil core samples. He reported the CO₂ production rates ranged between 19 and 57 mg kg⁻¹ d⁻¹ in August. Briones et al. (2004) studied the influence of warming and enchytraeid activities on soil CO₂ flux with a 116-d incubation experiment. In the study the 100 cm³ bottles were used as the incubators, and the soil CO₂ flux ranged between 20 and 50 mg kg⁻¹ d⁻¹. Plante and McGill (2002) incubated 80 g moist soil in 125 ml bottles to study the soil aggregate dynamics and the retention of organic matter with differing tillage frequencies. The 56 days of incubation showed that the CO₂ emission ranged between 7.9 and 24.3 mg kg⁻¹ d⁻¹ under different tillage frequencies.

However, most of these experiments incubate small amount of soils in an incubator. Therefore, structure of the incubated soil is altered and different from that in the field. In addition, for greenhouse gas emission analysis, bottle incubation

experiments neglect gas transport in the soil profile. In comparison to the bottle experiments, conditions of column incubation experiments are similar with field conditions, and column incubation experiments have been used by some researchers to study the CO₂ behavior in soil profiles.

Rottmann and Joergensen (2011) measured the CO₂ production with the maize-straw-amended soil stored in the PVC cylinders (the diameter of 15 cm and the height of 20 cm) and the mean CO₂ flux of 0.6 g CO₂-C m⁻² d⁻¹ was observed. Bouma and Bryla (2000) used the column incubation (the inner diameter of 7.6 cm and the height of 30 cm) to estimate root and soil respiration in soils with different textures, especially to determine the interaction between the soil water content and soil CO₂ concentration, considering it was difficult to measure the soil CO₂ concentration by the bottle incubation method. Camarda et al. (2009) studied the effects of soil gas permeability and recirculation flux on soil CO₂ flux, which was performed with the soil column (the diameter of 0.58 m and the height of 1 m) incubation experiment. It insisted that the experiment system was available commercially under diverse conditions and essential to check the accuracy of all measurements. These column incubations can be used for the studies on gas behavior in the soil such as diffusion and permeation. But the sampling for soil columns is more difficult and laborious than the bottle incubation, and hence, fewer studies were conducted by using the soil column incubation experiments.

A 150 days of incubation experiment with undisturbed soil columns (height of 40 cm) taken from the field was conducted in this study. The conditions of the present soil column incubation experiment were similar with that in the field. Gas samples, especially the gas samples in soils were also easy to be collected by using the soil column incubation experiments.

1.6 Objectives of the study

(1) To study the effects of the tillage practice on soil CO₂ flux, transport and production in an Andisol. For this purpose, a 150-d soil column incubation experiment was conducted.

(2) To evaluate the influence of the tillage practice on soil physical properties, and study how the changes in soil physical properties induced by tillage affect the soil CO₂ behavior in the Andisol. Since the gas diffusivity is an important factor to affect the soil CO₂ flux and can be used to estimate the CO₂ production, the performances of models on the prediction of gas diffusion coefficients of soils under different tillage systems were evaluated.

(3) To evaluate the effects of the tillage depth and the soil macropore on the CO₂ behavior in soils.

1.7 Structure of the dissertation

This dissertation includes Introduction (Chapter 1), Materials and Methods (Chapter 2), Results and Discussion (Chapter 3, 4, 5, 6) and Summaries and Conclusions (Chapter 7). Column incubation experiments were conducted in this study to examine the soil CO₂ behavior. Column incubation experiments included undisturbed soil column and repacked soil column incubation experiments. The results and discussions of Chapter 3 and Chapter 4 were based on the undisturbed soil column experiments, and those of Chapter 5 and Chapter 6 were based on the repacked soil column experiments. The structure of the study is as follows:

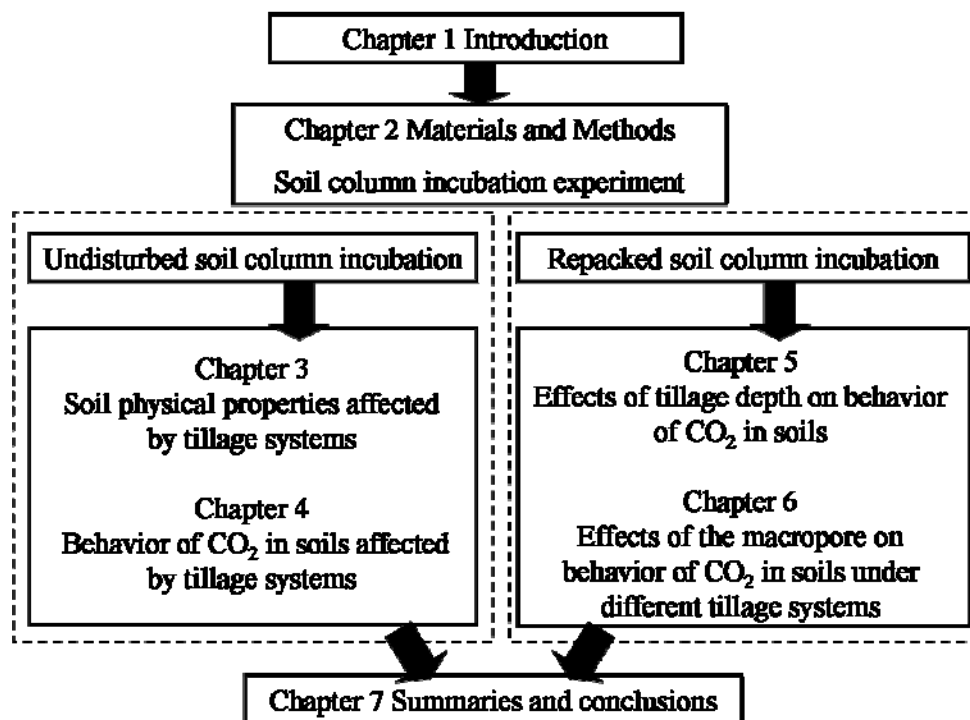


Fig. 3 The structure of the study

Chapter 2 Materials and methods

2.1 Soil description

Soil was sampled in April 2011 at the experimental farm of the University of Tokyo located in Nishitokyo, Tokyo, Japan (139°54'E, 35°73'N). The sampling site was fallowed and covered by 10-cm-tall weeds that were removed before sampling. The soil profile is shown in Fig. 4. The soil used in this experiment was sampled from 0–40 cm in depth. Soil at depth of 0–40 cm is an Andisol derived from volcanic ash, which is called “kuroboku” soil in local dialect. The characteristics of the soil are listed in Table 2.



Fig.4 Soil profile of the sampling site

Table 2 Soil characteristics of the sampling site

Depth (cm)	Hardness (kgf cm ⁻²)	Bulk density (g cm ⁻³)	Saturated hydraulic conductivity (cm s ⁻¹)	Particle size distribution [†] (%)	Particle density [‡] (g cm ⁻³)	Total carbon (g kg ⁻¹)
0–5	16.0	0.90	3.5E-05	sand 40.52	2.58	55.9
5–10	18.3	0.86	1.0E-04	silt 37.86		54.5
10–15	24.5	0.90	2.0E-04	clay 21.62		55.7
15–20	16.8	0.85	1.6E-04	sand 44.92	2.55	55.5
20–25	21.5	0.80	2.0E-03	silt 39.41		
25–30	19.8	0.85	1.2E-03	clay 15.67		55.6
30–35	23.8	0.76	1.2E-03			
35–40	11.3	0.69	9.9E-04		2.58	

[†], soil particle size was measured at depths of 2.5 cm and 17.5 cm

[‡], soil particle density was measured at depths of 2.5 cm, 17.5 cm and 37.5 cm

2.2 Soil sampling

Undisturbed soil columns (diameter of 15 cm and height of 40 cm) were taken by driving 50-cm-height PVC cylinders (inner diameter of 15 cm and sidewall thickness of 3 mm) into the soil and carefully digging up the cylinders (Fig. 5). A thin metal ring with cutting edge was attached to the bottom of the PVC cylinders, so that the soil columns were not damaged during insertion. Since the 40-cm-height soil column was sampled, about 10 cm of head space was left in the PVC cylinder. To avoid water loss from the soil surface, the soil columns were covered by plastic films after the sampling. These soil columns were brought to the laboratory for the incubation experiments. In addition, disturbed soil samples were also collected from soil profile (0–40 cm) and stored in plastic bags for soil analyses.

About 100 kg disturbed soil at depth of 0–40 cm was taken at the sampling site and stored in plastic boxes for repacked soil column experiments.



Fig. 5 Undisturbed soil columns sampling

2.3 Undisturbed soil column experiment

- Effects of tillage on soil physical properties and carbon dioxide behavior

2.3.1 Treatments and incubation experiment

The experiment included two treatments: 1) no-tillage (NT) and 2) tillage (T). For the no-tillage treatment, did not apply any tillage operation to the soil. 736 g m⁻² of leaf compost (with a total carbon content of 340.3 g kg⁻¹) was applied to the surface of the soil and the leaf compost was crushed before applying (Fig. 6a).

For the tillage treatment, the tillage operation was simulated in the laboratory. Surface soil was chiseled to a depth of 15 cm by a garden helper (Fig. 6b), and then gently compacted. Before tillage, leaf compost was applied to the surface of the soil.

(a)



(b)



Fig. 6 Leaf compost (after crushed) applied to the soil (a); Garden helper used to simulate tillage operation in the laboratory (b)

The soil columns were incubated in a glass greenhouse on the top floor of the Life Science Research Building in the University of Tokyo. Sunshine was the major source of light, and lamps were set in the greenhouse for supplementary lighting to control the radiation in the greenhouse. Temperature in the room was set to 30°C for daytime (06:00–18:00) and 25°C for nighttime (18:00–06:00). Humidity ranged from 55% to 65% throughout the day. The incubation duration was 150 days and from August in 2011 to February in 2012. Every 5 days of the incubation, 13.8 mm of water was irrigated on the soil surface to maintain soil moisture. This was equal to the amount of water evaporation in the greenhouse determined by weighing the loss of water over a period of 5 days. The temperature and irrigation conditions are shown in Fig. 7.

The soil temperature and water pressure were monitored by sensors that installed to the columns before the incubation. Soil CO₂ flux and concentration were measured during the incubation. After the incubation, the soil columns were split into 5 layers (0–5, 5–10, 10–15, 15–25, and 25–35 cm), and the soil properties of each layer were measured separately. The column incubation experiment in the greenhouse is shown in Fig. 8.

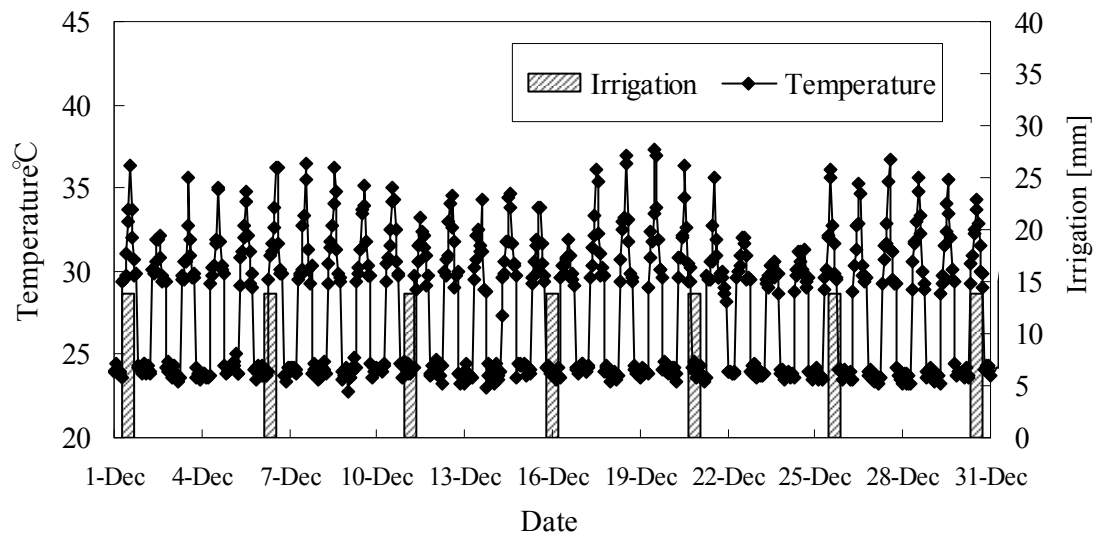


Fig. 7 Irrigation and temperature in the glass greenhouse during the incubation period.

Data of December are shown in this figure



Fig. 8 Incubation experiment in the glass greenhouse

2.3.2 Experimental setup

The schematic of the experimental setup is shown in Fig. 9a. The PVC cylinder (A) was assembled by using seven rings, four of which were 5-cm-height and the rest were 10-cm-height. The assembling of cylinders was convenient to soil columns sampling and splitting. Small holes were made on the PVC cylinders for setting up the sensors. Gas sampling ports (C), thermocouples (D) and porous cups (E) were installed horizontally at depths of 2.5, 7.5, 12.5, 20, and 30 cm. The gas sampling port was a 7-cm-long porous resin tube that was permeable for gas but not for soil and water. One end of the tube inserted into the soil was closed, and the other end was fitted with a septum to sample the soil gas. The copper-constantan thermocouples were inserted into the soil about 3 cm from the sidewall to measure the soil temperatures. The temperature in the greenhouse was also measured with the copper-constantan thermocouple. Porous cups connected with pressure transducers were used to measure the soil water pressures in the soil profile. The thermocouples and the pressure transducers were connected with a data logger (CR10X, Campbell Scientific Inc. Co.) to store the data at 10-min intervals. At the bottom of the column, an outlet (B) was fixed to collect the drainage. During the incubation, the soil was open to the atmosphere. The soil columns were covered by the chamber (F) only when measured the CO₂ flux. The gas sampling port, the thermocouples, the porous cup and the chamber are shown in the Fig. 9b.

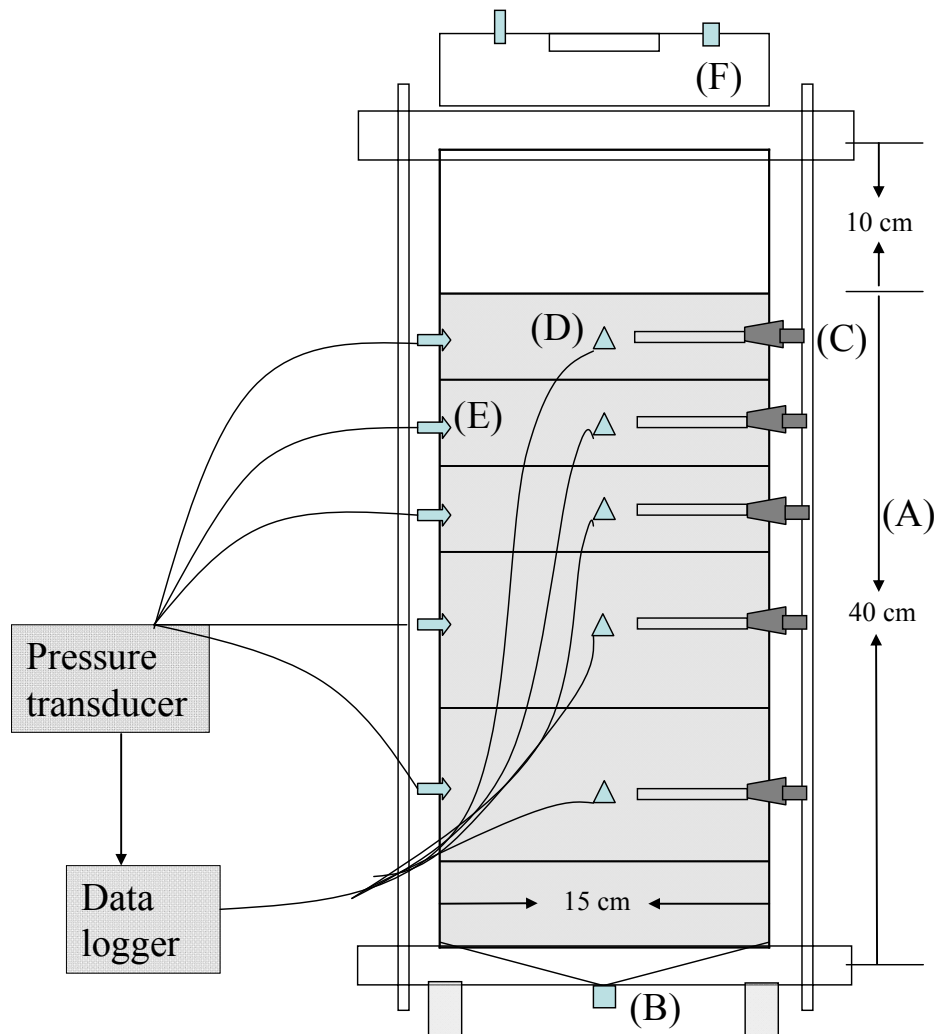


Fig. 9a Schematic of incubation experimental setup. (A) is the PVC tube, (B) is the outlet for draining, (C) are the gas sampling ports, (D) are the thermocouples, (E) are the porous cups and (F) is the chamber

Gas sampling port



Porous cup



Thermocouple



Chamber for CO₂ flux measurement



Fig. 9b The gas sampling port, the thermocouples, the porous cup and the chamber used in the incubation experiment

2.3.3 Measurements

Soil carbon dioxide flux and concentration

CO₂ flux was measured using a closed chamber method (Kessavalou et al., 1998; Nagata et al., 2009). Measurement interval was 7 days. The cylindrical chamber (the inner diameter of 16.3 cm and the height of 5.5 cm) was made by acrylic plastic [(F) part in Fig. 9]. A circulating fan fixed in the chamber top was used to mix the headspace air homogeneously during the measurement. The chamber had two ports, one was an acrylic tube with a septum, which was used for gas sampling, and the other one with a stopcock, which was used for exchanging gas in the chamber with outer air. A plastic bag connected with the air was used to compensate the pressure inside the chamber through expanding the volume when sampling the gas. During the gas flux measurement, the chamber was fixed to a groove on top of the soil column, and then, the perimeter of the chamber was sealed with water to prevent gas leakage. The gas inside the chamber was sampled by a 5 ml plastic syringe 0, 10, 20 and 30 min after the chamber was closed. To ensure that the irrigation did not affect the surface CO₂ flux measurement, if the irrigation and the CO₂ flux measurement were arranged on the same day, the irrigation was done only after the gas flux measurement. Gas samples were stored in 5-ml vacuum glass vials, and then quantified back in the laboratory using a gas chromatograph (GC 2014, Shimadzu Inc.). The CO₂ flux was calculated using the following equation:

$$Flux = \rho \left(\frac{273}{T} \right) \left(\frac{V}{A} \right) \left(\frac{\Delta C}{\Delta t} \right) \quad (1)$$

where *Flux* is the CO₂ flux (g CO₂-C m⁻² d⁻¹); ρ is the gas density (g m⁻³); *T* is the

temperature (K); V is the volume of the chamber (m^3); A is the area of the soil column surface (m^2); ΔC is the concentration increment ($\text{m}^3 \text{ m}^{-3}$) and Δt is the gas-sampling interval (day).

Gas sampling for CO_2 concentration in the soil profile was conducted with the same interval as that for the CO_2 flux measurement. After the CO_2 flux measurement, soil gas samples were collected from each depth through the gas sampling ports by a 5 ml plastic syringe. The CO_2 concentration in the atmosphere was determined by sampling the CO_2 in the air near the soil surface using the syringe. Gas samples were stored in 5 ml vacuum glass vials, and then brought back to the laboratory for quantification using a gas chromatograph.

Soil characteristics

After the incubation, the soil columns were split to 5 layers (0–5, 5–10, 10–15, 15–25 and 25–35 cm). 100 cm^3 and 50 cm^3 soil cores were taken from each layer of soil columns, and the rest soils were stored in plastic bags for future soil analyses.

Mass water content of soil samples for the respective layers was determined gravimetrically by drying them at 105°C . Dry bulk density was determined by the core method, and soil particle density was determined by the pycnometer method. Soil total porosity was computed from the data of dry bulk density and particle density. Water retention curves were determined by the hanging water method ($10 \text{ cmH}_2\text{O} < \text{soil water pressure} < 100 \text{ cmH}_2\text{O}$) and the pressure plate method ($100 \text{ cmH}_2\text{O} < \text{soil water pressure} < 1000 \text{ cmH}_2\text{O}$) using 50 cm^3 soil cores. Soil water pressures monitored during the incubation could be converted to the soil volumetric water content by using the water retention curves. The difference between the total porosity and the volumetric

water content was assumed to be the air-filled porosity.

Soil aggregation was measured by the wet sieving method (Miyazaki and Nishimura, 2011). The apparatus was constituted by four identical cylindrical water containers, and each with a set of five sieves that can be moved vertically by a motor driven system. Aggregate size distribution was measured using a nest of sieves (1, 0.5, 0.25, 0.1, 0.053 mm) with the soil aggregates evenly spread over the top sieve. Before sieving, the soil samples of each treatment were grinded slightly by hands to make the size of soil aggregates smaller than 4 mm. Then the soil was immersed slowly into water for one night. The frequency was fixed and duration of oscillations was 40 minutes. After sieving, aggregates of each fraction were dried and weighed. The percent of aggregates in each class was calculated, and then the mean weight diameter (MWD) was also calculated as the following equation:

$$MWD = \sum_{i=1}^n \overline{X_i} W_i \quad (2)$$

where X_i is the mean diameter of class i (mm); W_i is the percentage weight of class i to all the soil aggregates.

Soil total carbon content of each layer and total carbon associated with aggregates of different size classes were measured using a CN Analyzer (90A, Shimadzu Inc.).

Respiration rate of aggregates was determined by the bottle incubation method (Fig. 10). The volume of the incubated bottles was 500 ml. Three ports were fixed to the bottle lid. One was an acrylic tube with a septum served for gas sampling and the other two were with stopcocks used for air refreshing. The air dried aggregates (15 g) of each size class were weighed and adjusted the mass water content to the 55% of field water

holding capacity. After the 2 weeks pre-incubation, the bottles were sealed and the incubation started. 5 ml gas samples were taken at 3, 6, 9, 12, 15 days during the incubation with a plastic syringe and the gas samples were stored in vacuum glass vials. CO₂ concentration of gas samples was measured by using a gas chromatograph (GC 2014, Shimadzu Inc.). After sampling, the gas in the bottle was refreshed by air. Then the bottles were sealed till the next sampling day. The respiration rate of aggregates was calculated by the following equation:

$$R = \frac{(C_t - C_0)V}{tw} \quad (3)$$

where R is the respiration rate (g-C kg⁻¹-soil h⁻¹), C_t is the CO₂ concentration of air in the bottle (g m⁻³), V is the volume of the bottle (m³), C_0 is the CO₂ in the fresh air (g m⁻³), t is the incubation time (hour) and w is the weight of aggregates (kg).



Fig. 10 Incubation bottles used for the measurement of the respiration rate associated with aggregates

Soil gas diffusivity (GD) was measured by using the 100 cm³ soil cores under 5 water potentials [pF=1.3, 1.8, 2.3, 2.8 and 3, where $pF = \log_{10}(-\Psi)$, the matric potential in cmH₂O)]. Before measurement, the water potentials of soil cores were adjusted to the certain value by using the pressure plate chamber. The diffusion chamber with O₂ as the tracer gas was used for the measurement of soil gas diffusivity (Hamamoto et al., 2011) (Fig. 11). The diffusion chamber was flushed with the pure N₂ gas before measurement. The upper end of the soil core was exposed to the atmosphere and the bottom end was connected with the diffusion chamber. Since the O₂ in the atmosphere was diffused through the soil, and the O₂ concentration in the chamber was increased, the O₂ inside the diffusion chamber was measured using a galvanic electrode (OXYGEN SENSOR KE12, GS YUASA Co.) connected to a CR10X data logger. The soil gas diffusivity was calculated by the changes of the O₂ concentration in the chamber with the follow

equation (Currie, 1960):

$$\frac{C(L_s, t) - C_i}{C_0 - C_i} = \frac{2h \cdot \exp(-D_p a_1^2 t / \varepsilon)}{L_s (a_1^2 + h^2) + h} \quad (4)$$

where D_p is the gas diffusion coefficient in soil ($\text{m}^2 \text{s}^{-1}$), $C(L_s, t)$ is the O_2 concentration in the diffusion chamber (g m^{-3}), C_i is the O_2 concentration in the atmosphere (g m^{-3}), C_0 is the O_2 concentration at $t=0$ (g m^{-3}), ε is the air-filled porosity ($\text{m}^3 \text{m}^{-3}$), L_s is the height of soil core (m), a_1 is the first positive square root of $hL_s = aL_s \tan(aL_s)$ and $h = \varepsilon/L_a$ (L_a is the height of diffusion chamber, m).

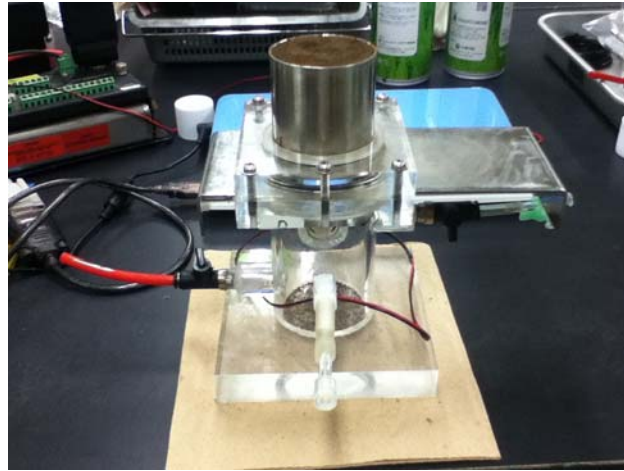


Fig. 11 Setup of soil gas diffusivity measurement

2.4 Repacked soil column experiment

- Effects of tillage depth and macropore on soil carbon dioxide behavior

2.4.1 Soil preparation and treatments

Before repacking, the soil sampled from the experimental site was sieved through 2 mm mesh screen. The soil was packed into the 50-cm-height PVC cylinders homogeneously till 40-cm-height, and about 10 cm of head space was left. Soil dry bulk density was 0.7 g cm^{-3} , the mass water content was 55.9 %, and soil total carbon content was 53.1 g kg^{-1} . The aggregates distributions were: >1mm 17.8%, 1–0.5mm 20.3%, 0.5–0.25mm 24.5%, 0.25–0.1mm 21.0%, <0.1mm 17.5%. The leaf compost was mixed with the top 5-cm-depth soil. After packing, the soil columns were incubated in the greenhouse.

The repacked column experiment included 5 treatments:

- (1) No-tillage (RNT): did not apply any tillage practice to the soil after packing.
- (2) Conventional tillage (RCT): chiseled the soil to a depth of 15 cm and then gently compacted.
- (3) Deep tillage (RDT): chiseled the soil to a depth of 25 cm and then gently compacted.
- (4) No-tillage- with macropore (RNT-M): A plastic stick (diameter of 3 mm) was inserted into the PVC cylinder before packed the soil, and then packed the soil into to the cylinder. After packing, the stick was taken out that a macropore (diameter of 3 mm) was left in the soil column. The soil column under RNT-M treatment is shown in Fig. 12.
- (5) Conventional tillage- with macropore (RCT-M): The preparing of the soil

column was as the same as the RNT-M treatment, and thus, the 40-cm-height soil column with a macropore was obtained. Then chiseled the soil to a depth of 15 cm and gently compacted.

The packed soil columns were pre-incubated in greenhouse about one month and then the measurements of CO₂ flux and concentration started.



Fig. 12 Soil column under no-tillage-with macropore (RNT-M) treatment. A macropore (diameter of 3 mm) was left in the soil column

2.4.2 Incubation experiment conditions and measurements

The experimental setups and the environmental conditions in the greenhouse were the same with that of the undisturbed soil columns experiments. The 150 days of incubation was from February in 2012 to August in 2012. During the incubation period, the CO₂ flux and concentration were measured. After the incubation period, the soil physical properties (the dry bulk density, saturated hydraulic conductivity and water retention curves), and the total carbon content of each layer of the soil column (0–5, 5–10, 10–15, 15–25 and 25–35 cm) were measured. The analysis methods of soil CO₂ flux, CO₂ concentration and soil properties were the same with that described in

undisturbed soil experiments.

2.5 Models and estimations

2.5.1 Soil gas diffusivity models

Four models widely used for gas diffusion coefficient prediction were chosen to predict the gas diffusion coefficients.

The most frequently used gas diffusivity model is the classical equation suggested by Penman (Penman, 1940), and the equation predicts gas diffusivity with soil air-filled porosity is as follows.

$$\frac{D_p}{D_0} = 0.66\varepsilon \quad (5)$$

where D_p is the gas diffusion coefficient of the soil ($\text{m}^2 \text{s}^{-1}$), D_0 is the gas diffusion coefficient in free air ($\text{m}^2 \text{s}^{-1}$), ε is the air-filled porosity ($\text{m}^3 \text{m}^{-3}$).

Millington-Quirk (MQ) model (Millington and Quirk, 1961) predicts the gas diffusion coefficients with both soil air-filled porosity and total porosity.

$$\frac{D_p}{D_0} = \frac{\varepsilon^2}{\Phi^{2/3}} \quad (6)$$

where D_p is the gas diffusion coefficient of the soil ($\text{m}^2 \text{s}^{-1}$), D_0 is the gas diffusion coefficient in free air ($\text{m}^2 \text{s}^{-1}$), ε is the air-filled porosity ($\text{m}^3 \text{m}^{-3}$), Φ is the total porosity ($\text{m}^3 \text{m}^{-3}$).

The Buckingham-Burdine-Campbell (BBC) model (Moldrup et al., 1999) was developed based on soil air-filled porosity, total porosity and water retention characteristics. The $2+3/c$ is an analogue to the tortuosity model.

$$\frac{D_p}{D_0} = \Phi^2 (\varepsilon/\Phi)^{2+3/c} \quad (7)$$

where D_p is the gas diffusion coefficient of the soil ($\text{m}^2 \text{s}^{-1}$), D_0 is the gas diffusion coefficient in free air ($\text{m}^2 \text{s}^{-1}$), ε is the air-filled porosity ($\text{m}^3 \text{m}^{-3}$), Φ is the total porosity ($\text{m}^3 \text{m}^{-3}$), and c is the parameter determined by soil water retention curves, corresponding to the slope of the soil water characteristic curve in the $\text{Log}(\theta)$ - $\text{Log}(\Psi)$ coordinate system [θ is the water content ($\text{m}^3 \text{m}^{-3}$) and Ψ is the matric potential (cm)].

Generalized macroporosity-based (GMP) model (Deepagoda et al., 2011) predicts the gas diffusivity based on the correlation between the air-filled porosity and the measured gas diffusivity.

$$\frac{D_p}{D_0} = 2\varepsilon^3 + 0.04\varepsilon \quad (8)$$

where D_p is the gas diffusion coefficient of the soil ($\text{m}^2 \text{s}^{-1}$), D_0 is the gas diffusion coefficient in free air ($\text{m}^2 \text{s}^{-1}$), ε is the air-filled porosity ($\text{m}^3 \text{m}^{-3}$).

2.5.2 Estimations of carbon dioxide flux and production

The CO_2 flux through the soil profile can be calculated by Fick's law:

$$F_i = -D_i \frac{C_{i1} - C_{i2}}{l_i} \quad (9)$$

where F_i is the flux in the i^{th} layer ($\text{g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$), D_i is the soil gas diffusivity in the i^{th} layer ($\text{m}^2 \text{ d}^{-1}$), C_{i1} is the soil CO_2 concentration at the top of the i^{th} layer (g m^{-3}), C_{i2} is the soil CO_2 concentration at the bottom of the i^{th} layer (g m^{-3}) and l_i is the thickness of the i^{th} layer (m).

The CO_2 production in a soil layer (P_{ij}) was estimated as the cumulative difference between the inflow and the outflow CO_2 flux at each layer (Fierer et al., 2005; Kusa et al., 2010). From the calculation, the followings are assumed: 1) there is no downward flux of CO_2 at the deepest depth, 2) gaseous diffusion is the only mechanism of CO_2 transport, and 3) the flux of CO_2 is independent of the concentration of other soil gases.

$$P_{ij} = \sum_{j=1}^n (F_{i(1)j} - F_{i(2)j}) \times t \quad (10)$$

where P_{ij} is the soil CO_2 production in the i^{th} layer during the 150-d incubation ($\text{g CO}_2\text{-C m}^{-2}$), $F_{i(1)j}$ is the soil CO_2 flux through the top of the i^{th} layer at the j^{th} sampling day ($\text{g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$), $F_{i(2)j}$ is the soil CO_2 flux through the bottom of the i^{th} layer at the j^{th} sampling day ($\text{g CO}_2\text{-C m}^{-2} \text{ d}^{-1}$), and t is the gas sampling interval (day), chosen as 7 days in this experiment.

2.6 Statistical analysis

Collected data were subjected to statistical analysis to compare and determine any significant differences between and among treatments. The analysis of variance (ANOVA) was conducted using the SPSS software (IBM SPSS statistics 20.0). Data of soil physical properties and soil carbon under different treatments were analyzed by the least significant difference method (LSD).

The relationship between measured and predicted values of soil CO₂ flux, soil CO₂ concentration and soil properties were analyzed by the linear regression method (IBM SPSS statistics 20.0).

To compare gas diffusivity models, the root mean square error (RMSE) was used to estimate gas diffusivity model performances. In addition, bias was used to evaluate overestimation or underestimation of the models (Lerou and Booij, 2002; Moldrup et al., 2003). The RMSE and bias were calculated by using the following equations:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad (11)$$

$$bias = \frac{1}{n} \sum_{i=1}^n d_i \quad (12)$$

where d_i is the difference between the predicted and the measured value of D_p/D_0 at a given air-filled porosity, and n is the number of measurements.

Chapter 3 Soil physical properties affected by tillage systems

Since carbon dynamics are affected by the soil environmental conditions, changes in physical properties of the Andisol caused by the tillage operation were studied in this chapter.

3.1 Soil dry bulk density

Soil dry bulk density under the tillage treatment was obviously lower than that under the no-tillage treatment at depths of 0–10 cm (Fig. 13). Soil dry bulk density at 10–15 cm under the tillage treatment was higher than that under the no-tillage treatment, but the difference was not significant. Tillage loosened the soil at the chiseled layer, and this led to a reduction of soil dry bulk density. This result is in good agreement with that of Rahman et al. (2003) who reported that the soil dry bulk density under conventional tillage was obviously lower than that under the no-tillage treatment in Andisols. Osunbitan et al. (2005), Czyz and Dexter (2009) similarly observed higher dry bulk density under the no-tillage system. The effects of tillage on soil dry bulk density could be different among soil types. Gathala et al. (2011) found that the soil bulk density under tillage was higher than that under the no-tillage treatment in a moist soil, and this could be due to the clogging of macropores with finer soil particles.

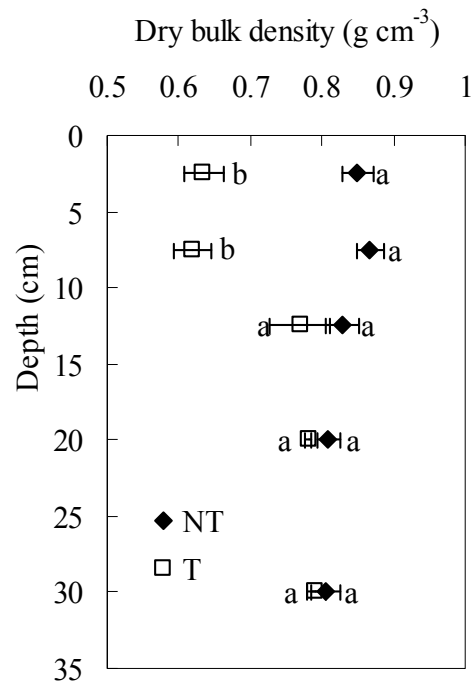


Fig. 13 Soil dry bulk density under NT and T treatments. Significant differences between treatments are indicated with different letters ($P < 0.05$, $n=4$)

3.2 Soil temperature

During the incubation experiment, the room temperature was set at 30°C for daytime (06:00~18:00) and 25°C for nighttime (18:00~06:00) in the greenhouse. As shown in Fig. 14, the soil temperatures of each layer changed with the greenhouse temperature. The temperature of the tillage soil was slightly higher than that of the no-tillage soil during night. The changes in the temperature are affected by the thermal characteristics such as the heat capacity and thermal conductivity. Soil disturbance caused by tillage leads to a greater air phase. Since a greater air phase depresses soil thermal conductivity and soil heat capacity, surface soil temperature under the tillage treatment slightly increased (Licht and Al-Kaisi, 2005). However, the difference between the two treatments was minimal. Similar results were obtained by other researchers (Ekeberg and Riley, 1997; Drury et al., 1999), who reported that no significant difference in soil temperature was observed between the two treatments.

The respiration rate was positively correlated with the soil temperature, within the optimal range (Kaur et al., 2010; Bradford et al., 2008). However, differences in soil temperatures between the no-tillage and tillage treatments were minimal in the present study. Therefore, the effect of the slight increase in temperature due to tillage on the CO₂ flux may also be minimal.

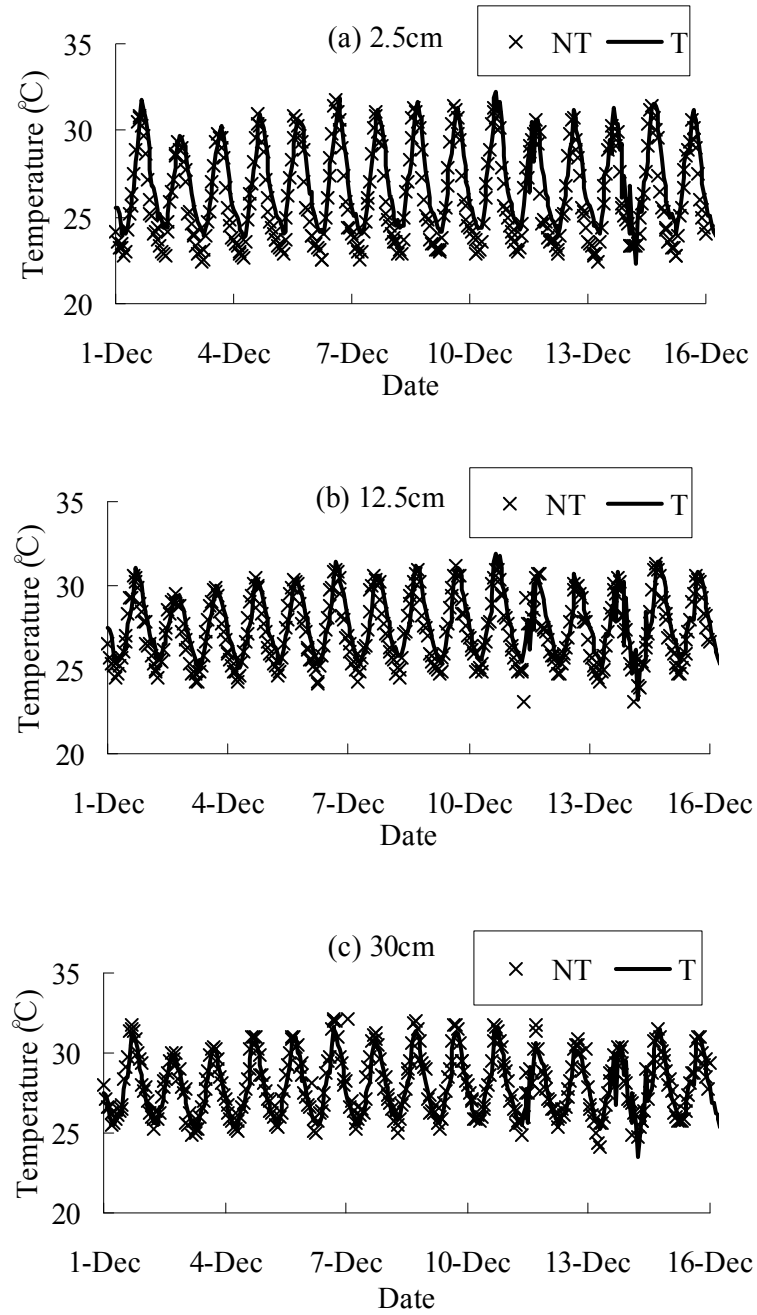


Fig. 14 Soil temperatures at depths of 2.5, 12.5 and 30 cm under NT and T treatments.

Data of 15 days are (December) shown in this figure

Difference in the soil temperature was observed in soil profile between the field experiment and column experiment. The diurnal variations of soil temperatures in the soil profile (Andisol) in field were monitored by Yonemura et al. (2009) as shown in Fig. 15. For the shallow layer, the changes in soil temperatures observed with the column experiment were similar with that with the field experiment. For the deeper layers (20 and 50 cm), the soil temperatures in field did not change with the temperature of atmosphere, but the soil temperatures in soil columns fluctuated with the atmosphere temperature. This is because, in the field, the soil in the deeper layer could not directly absorb radiation from the sunshine and release heat to the atmosphere neither. For the column incubation experiment, since the wall of cylinders could not prevent the sunshine radiation absolutely, the fluctuations of the soil temperatures in the deeper layer were observed in the present study..

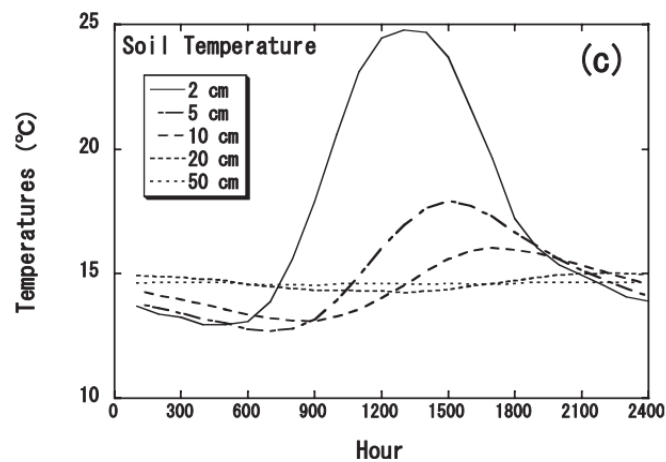


Fig. 15 Diurnal changes in soil temperatures of the experiment site (Yonemura et al., 2009)

The CO₂ production and transport in soils are affected by the fluctuation of the soil temperature. Such as, based on the equation of $V=nRT/P$ (13), the volume of the gas may expand or shrink with the changes of the temperature, and this may affect the gas transport in the soil. In present study, the soil temperature at the deeper layer fluctuated in the range of 25 °C to 32 °C. The fluctuation of the temperature was about $\pm 3.5^{\circ}\text{C}$, and the changes in the volume of the gas could be calculated by the Eq. (13).

$$V=nRT/P \quad (13)$$

$$(V+\Delta V)/V=(T+\Delta T)/T=(301.5\pm 3.5)/301.5=0.988-1.012$$

The result shows the changes in the volume of the gas caused by the temperature is small. And thus, the fluctuation of the temperature would not obviously influence the gas transport.

On the other hand, the soil respiration rate is affected by the temperature. However, Uvarov et al. (2006) reported that the cumulative CO₂-C production did not differ between two treatments (i.e., the diurnal fluctuations of soil temperature and no fluctuation). Although differences in the variations of soil temperature in deeper layer were observed between the column incubation and field experiment, the small difference could not obviously affect the gas transport and soil respiration, implying the column incubation experiment can be used to study the soil CO₂ flux.

3.3 Soil aggregation

The percentages of the aggregates of different size classes at depths of 0–15 cm and 15–35 cm under no-tillage and tillage treatments were measured (Fig. 16). The fractions of aggregates in the 4–1 mm size class for no-tillage and tillage treatments were 30.45% and 24.24%, respectively, showing the greatest fraction of the soil aggregates.

Size distributions were different between the two treatments at depths of 0–15 cm. The fractions of aggregates in 4–1 mm and 1–0.5 mm size classes under the no-tillage treatment were greater than that under the tillage treatment. In contrast, the fractions of aggregates in 0.5–0.25 mm and 0.25–0.1 mm size classes were smaller under the no-tillage treatment than that under the tillage treatment. The no-tillage practice kept binding of the aggregates and protected the macroaggregates against destruction. In comparison to the other size classes, the fractions of aggregates in 0.1–0.053 mm and <0.053 mm size classes were small, and no obvious difference was observed between the two treatments. The MWD of the aggregates under the no-tillage treatment at depths of 0–15 cm was 0.884 mm, which was greater than the MWD for the tillage treatment (i.e., 0.765 mm). At 15–35 cm depth layers, no significant difference in size distribution of soil aggregates was observed between the two treatments. A similar result for Andisol in Japan that tillage decreased the MWD near the surface soil was reported by Nakamoto et al. (2012). The results presents the advantage of the no-tillage system over the tillage system in improving soil structure in the Andisol.

The aggregate hierarchy model proposed by Tisdall and Oades (1982) describes that the macroaggregates are formed by the microaggregates, finer individual

soil particles and organic binding agents, and thus, the organic carbon is protected by the soil macroaggregates. Kushwaha et al. (2001) reported that the soil organic carbon was strongly correlated with the amount of soil macroaggregates. However, results of this experiment showed that tillage destructed the soil macroaggregates. After tillage, soil organic carbon protected by the soil aggregates was bared to microorganisms and microbial enzymes (Six et al., 2000). The decreased physical protection induced by disruption of soil aggregates enhanced the mineralization of soil organic carbon, and this could contribute to the increase in the carbon loss from soil (Hevia et al., 2007; Shi et al., 2010).

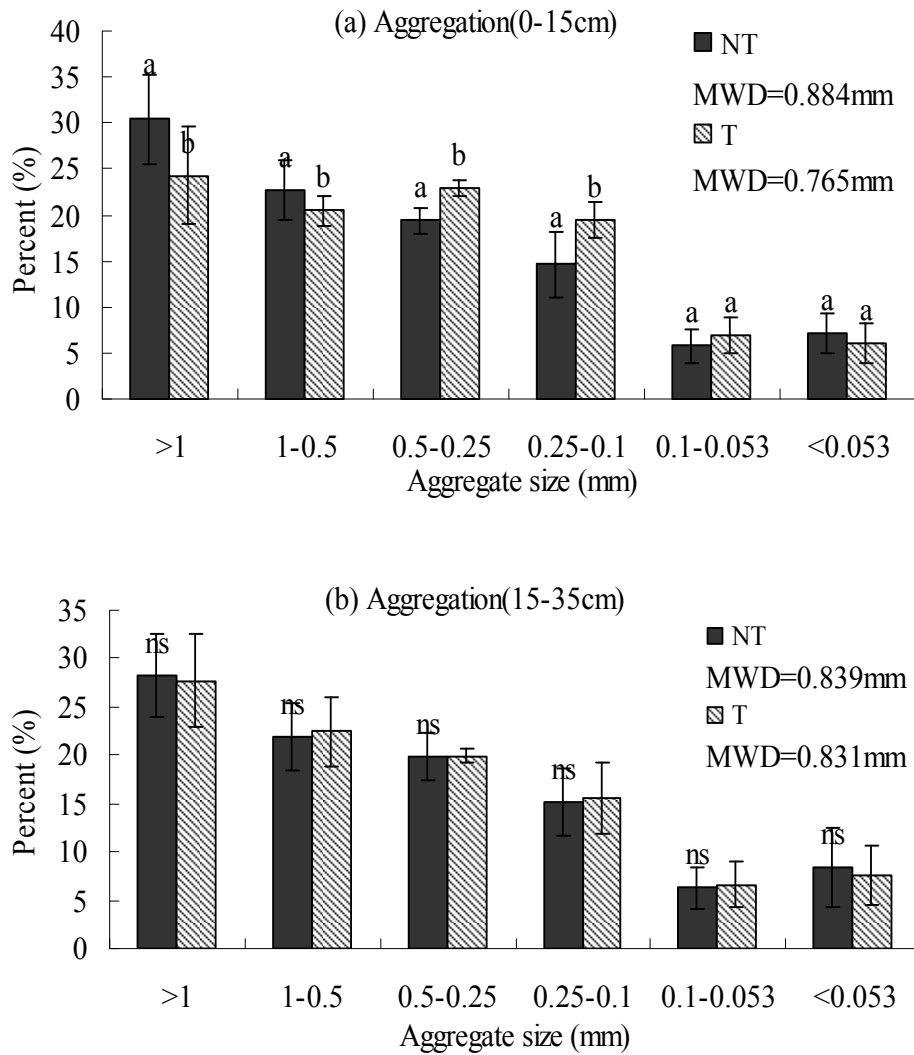


Fig. 16 Soil aggregation under NT and T treatments at depths of 0–15 cm (a) and 15–35 cm (b). Significant differences between treatments are indicated with different letters ($P < 0.05$, $n=4$). ns, no significant difference

3.4 Soil saturated hydraulic conductivity

Many researchers have reported that the soil saturated hydraulic conductivity was higher under the no-tillage treatment, since tillage decreased the volume of greater pores and pore continuity in loamy sand soil (Benjamin, 1993; Osunbitan et al., 2005). In contrast, soil saturated hydraulic conductivity under the tillage treatment at depths of 0–15 cm was significantly higher than that under the no-tillage treatment in present study (Fig. 17). At depths of 15–35 cm, no significant difference in the saturated hydraulic conductivity was observed between the two treatments. Consistent results for Andisols with our study were also observed by Rahman et al. (2008). The effect of tillage on soil saturated hydraulic conductivity could differ among soil types. The Andisol is well-aggregated and without many macropores. It is considered that tillage produced lower soil dry bulk density and higher soil porosity, which allowed the soil easily draining excess water. Moreover, that no rain or other force could destroy the aggregates and form the surface seal in this experiment may be another reason to explain the water could quickly drain in the tillage soil.

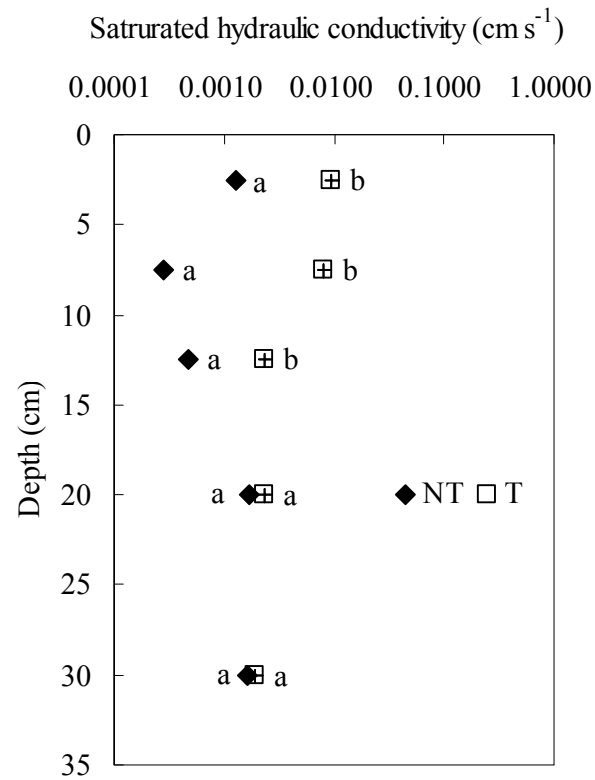


Fig. 17 Soil saturated hydraulic conductivity under NT and T treatments. Significant differences between treatments are indicated with different letters ($P < 0.05$, $n=4$)

3.5 Soil moisture

Since the soil structure was obviously changed by tillage, the water retention curves of the tillage soil at depths of 0–15 cm were different from that of the no-tillage soil (Fig. 18), suggesting the pore size distribution was changed by tillage. Tillage increased the volume of the larger pores of the soil. When the water potentials changed in the range of $pF=1.3$ to $pF=3$ (drying process), soil volumetric water content under the no-tillage treatment ranged from $0.55 \text{ m}^3 \text{ m}^{-3}$ to $0.40 \text{ m}^3 \text{ m}^{-3}$, but under the tillage treatment it ranged from $0.49 \text{ m}^3 \text{ m}^{-3}$ to $0.31 \text{ m}^3 \text{ m}^{-3}$ at depths of 0–15 cm. Lower soil volumetric water content at depths of 0–15 cm under the tillage treatment has been observed in comparison to that under the no-tillage treatment at the same soil water pressure. No clear difference in the soil retention characteristic was observed between the two treatments at depths of 15–35 cm.

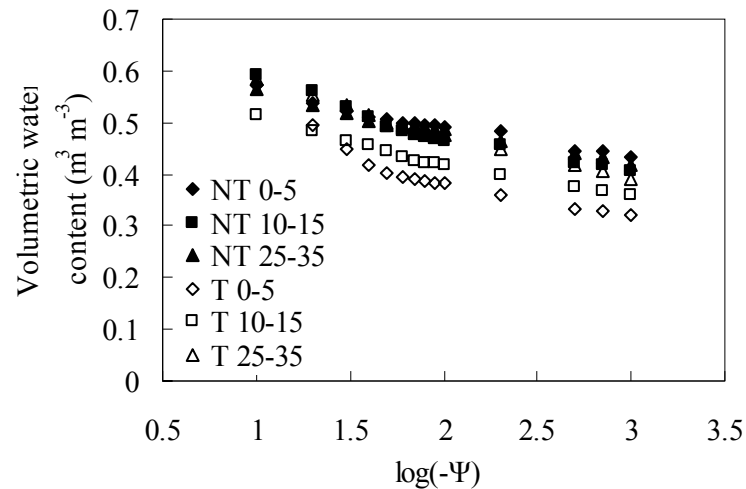


Fig. 18 Soil water retention curves at depths of 0–5, 10–15 and 25–35 cm under NT and T treatments. Ψ , matric potential (cmH₂O)

The RETC program (van Genuchten et al. 1991) was used to fit the measured data by using a water retention curve equation. The water retention curve equation [Eq. (14)] developed by van Genuchten (1980) was used in the present study. The fitting curves of water retention characteristics under no-tillage and tillage treatments are shown in Fig. 19. The parameters of θ_r , θ_s , α , n , m and R^2 at depths of 0–5, 10–15 and 25–35 cm under the two treatments are listed in Table 3.

$$\theta(h) = \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m} + \theta_r \quad (14)$$

Where $\theta(h)$ is the volumetric water content at the water pressure h ($\text{m}^3 \text{m}^{-3}$), h is the water pressure (cmH_2O), θ_r is the residual volumetric water content ($\text{m}^3 \text{m}^{-3}$), θ_s is the saturated volumetric water content ($\text{m}^3 \text{m}^{-3}$) and α , m and n are fitting parameters.

Table 3 Parameters of water retention curve equation for NT and T treatments

Depth (cm)	NT			T		
	0-5	10-15	25-35	0-5	10-15	25-35
θ_r	0.304	0.391	0.276	0.308	0.309	0.253
θ_s	0.859	0.651	0.847	0.830	0.567	0.658
α	16.12	0.086	9.141	0.281	0.147	0.221
n	1.148	1.581	1.150	1.618	1.322	1.195
m	0.129	0.368	0.131	0.382	0.244	0.163
R^2	0.984	0.993	0.992	0.994	0.998	0.998

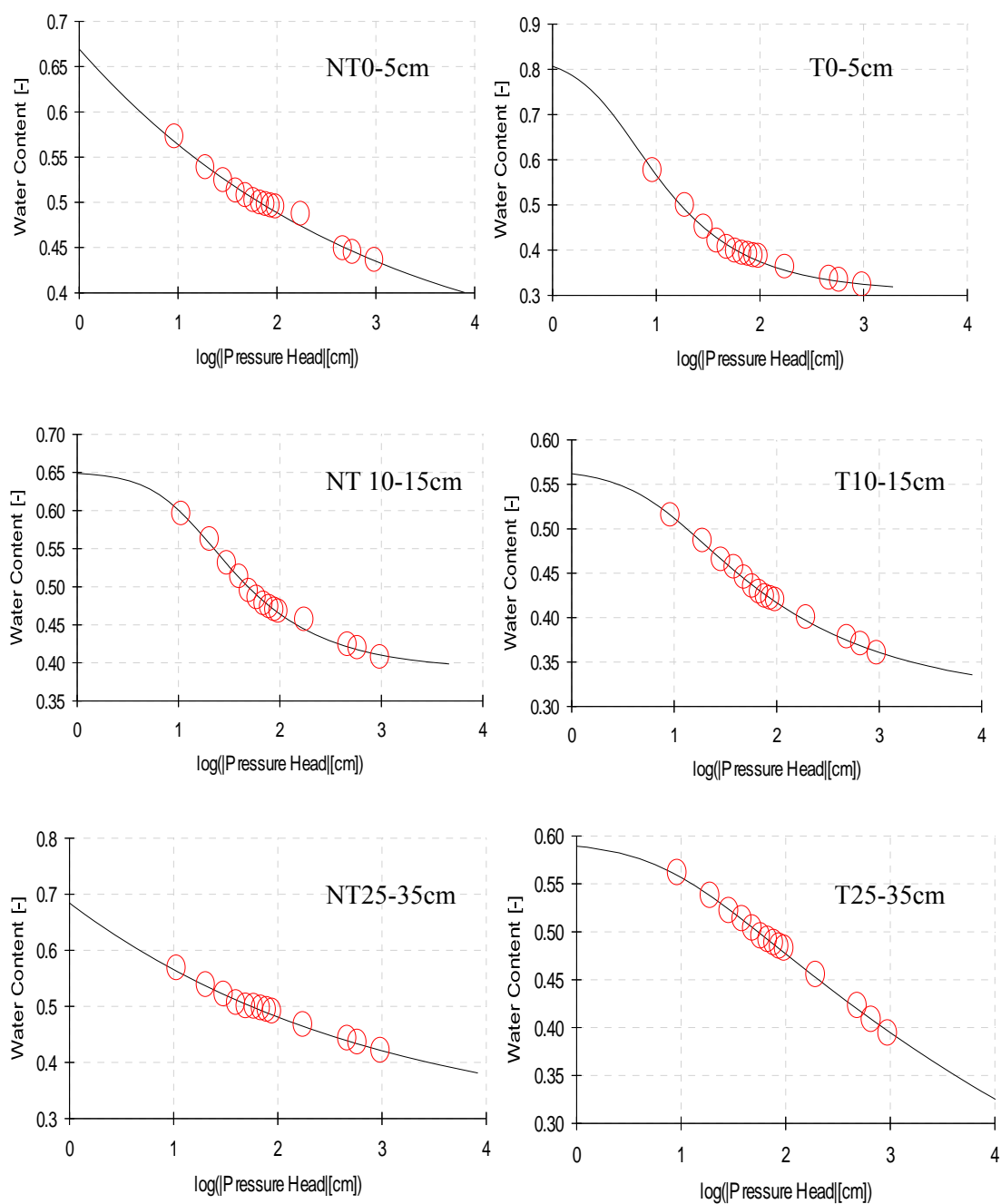


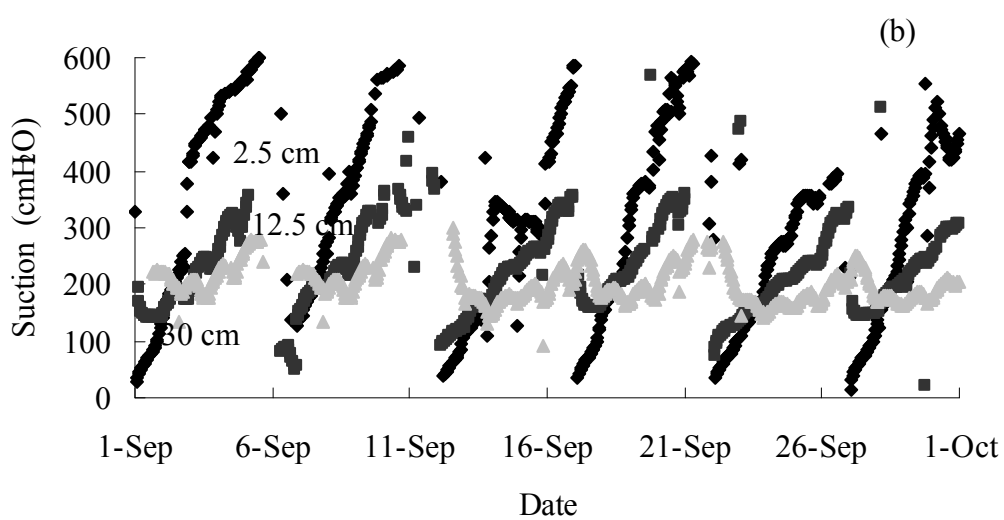
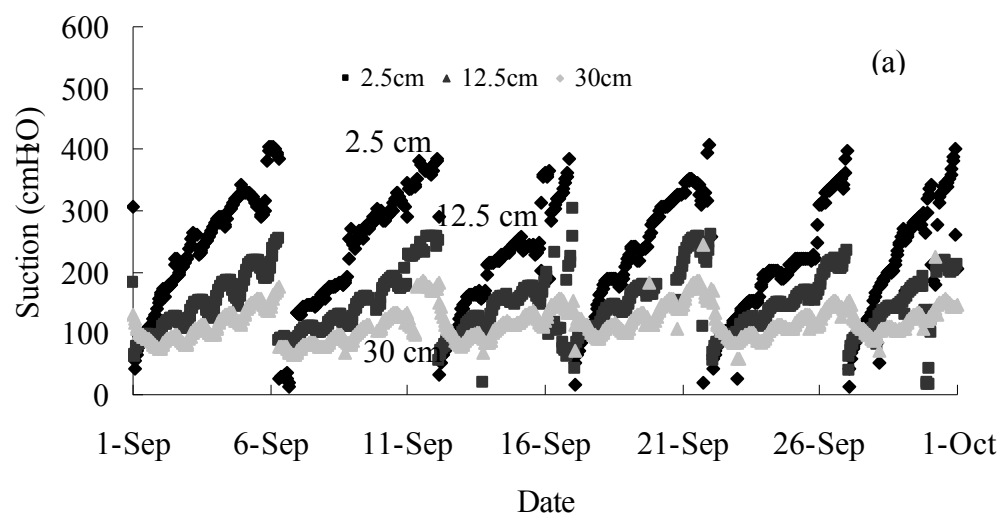
Fig. 19 Fitting curves of soil water retention characteristics at depths of 0–5, 10–15, 25–35 cm under NT and T treatments (lines are the fitting curves, circles are the measured data)

During the incubation, the soil water pressures were monitored by tensiometers (porous cups and pressure transducer), and the data in September and December are shown in Fig. 20. The water pressures affected by the irrigation and evaporation fluctuated in the range of -30 cmH₂O (pF 1.5) to -600 cmH₂O (pF 2.7) during the incubation period. Monitored soil water pressure was converted into the soil volumetric water content by using the water retention curve equation [Eq. (14) and Table 3].

Soil volumetric water contents at depths of 2.5, 12.5 and 30 cm under no-tillage and tillage treatments in September and December are shown in Fig. 21. Since the irrigation and temperature were controlled during the incubation period, the fluctuation ranges of the water content in September and December were the same for both no-tillage and tillage treatments. After irrigation, the water content of the surface soil rapidly increased and then decreased gradually due to evaporation and redistribution. Upon irrigation, water contents at depths of 12.5 and 30 cm also increased but less extent, and then decreased. Soil water contents fluctuated within a certain range due to supplemental irrigation, and similar soil water contents between the two treatments were observed at the depth of 30 cm. However, the tillage treatment tended to show smaller volumetric water contents at depths of 2.5 and 12.5 cm than that of the no-tillage treatment. Tillage loosened the soil of the plow layer, and this led to a reduction in soil dry bulk density and a rise in the total porosity (Fig. 13). Tillage caused changes in soil pore structure, and thus soil water retention characteristics (Fig. 18). Under the same matric potential, the volumetric water contents at depths of 2.5 and 12.5 cm were lower than that under the no-tillage treatment. Additionally, the volumetric water contents at depths of 2.5 and 12.5 cm decreased quickly with a decrease in soil matric potential ($-\psi < 100$ cm) in comparison to the no-tillage treatment, which implies

tillage increased the volume of the larger pores in the soil. Therefore, the volumetric water contents at the depths of 2.5 and 12.5 cm under the tillage treatment were lower than that under the no-tillage treatment during the incubation, and relatively large extent of fluctuations under the tillage treatment were observed.

Soil water content is another important variable of soil respiration. However, there is little change of the respiration rate within a relatively wide range of water content, and the respiration decreases obviously when soil is dried to exceed a certain range (Smith et al., 2003; Rey et al., 2002). In the present study, the lower volumetric water content under the tillage treatment was due to the decreased bulk density and changed water retention characteristic. No obvious difference in the mean mass water content between the two treatments was observed after the incubation. Tillage did not clearly change the soil moisture, and no extreme drought condition was observed for both the treatments owing to the supplementary irrigation. However, the soil air-filled porosity and gas diffusivity were affected by the fluctuations of the soil water content.



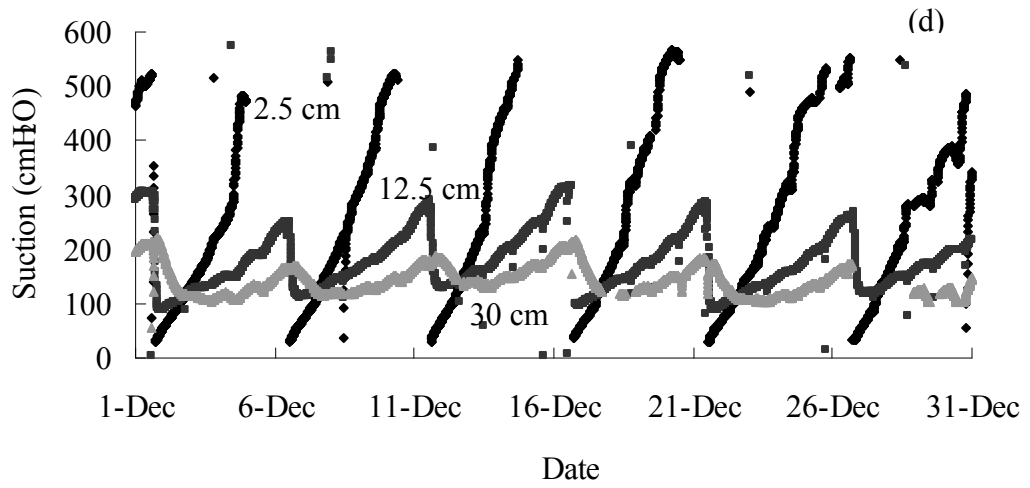
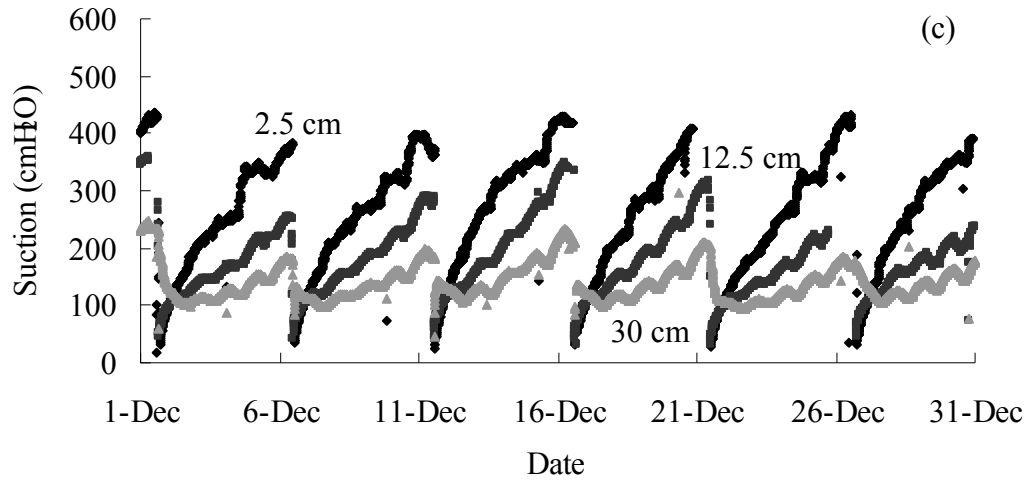
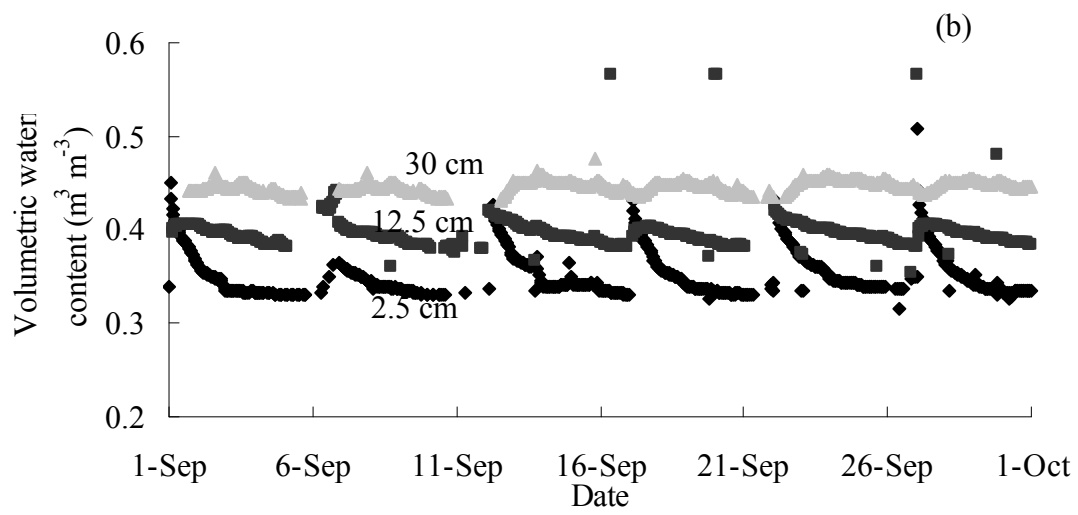
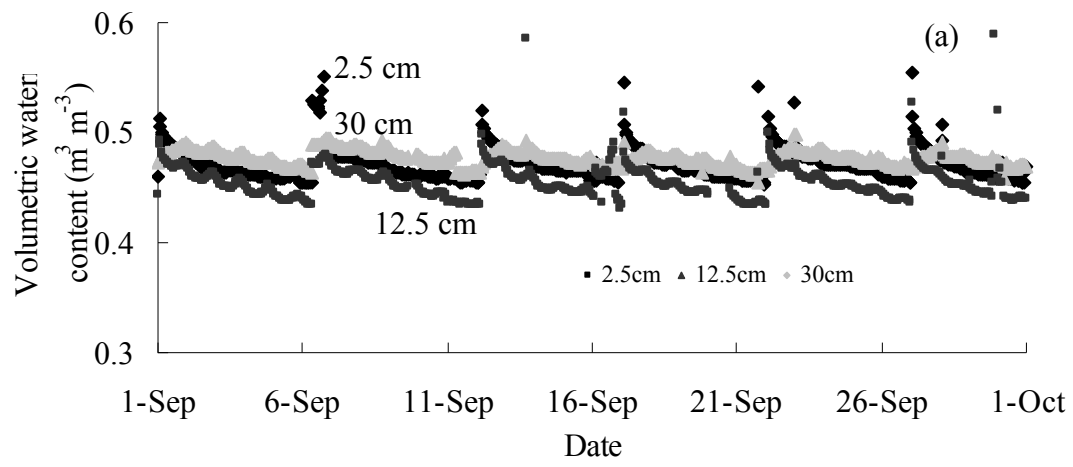


Fig. 20 Soil water suctions at depths of 2.5, 12.5 and 30 cm. (a) Data of September under NT, (b) Data of September under T, (c) Data of December under NT, and (d) Data of December under T



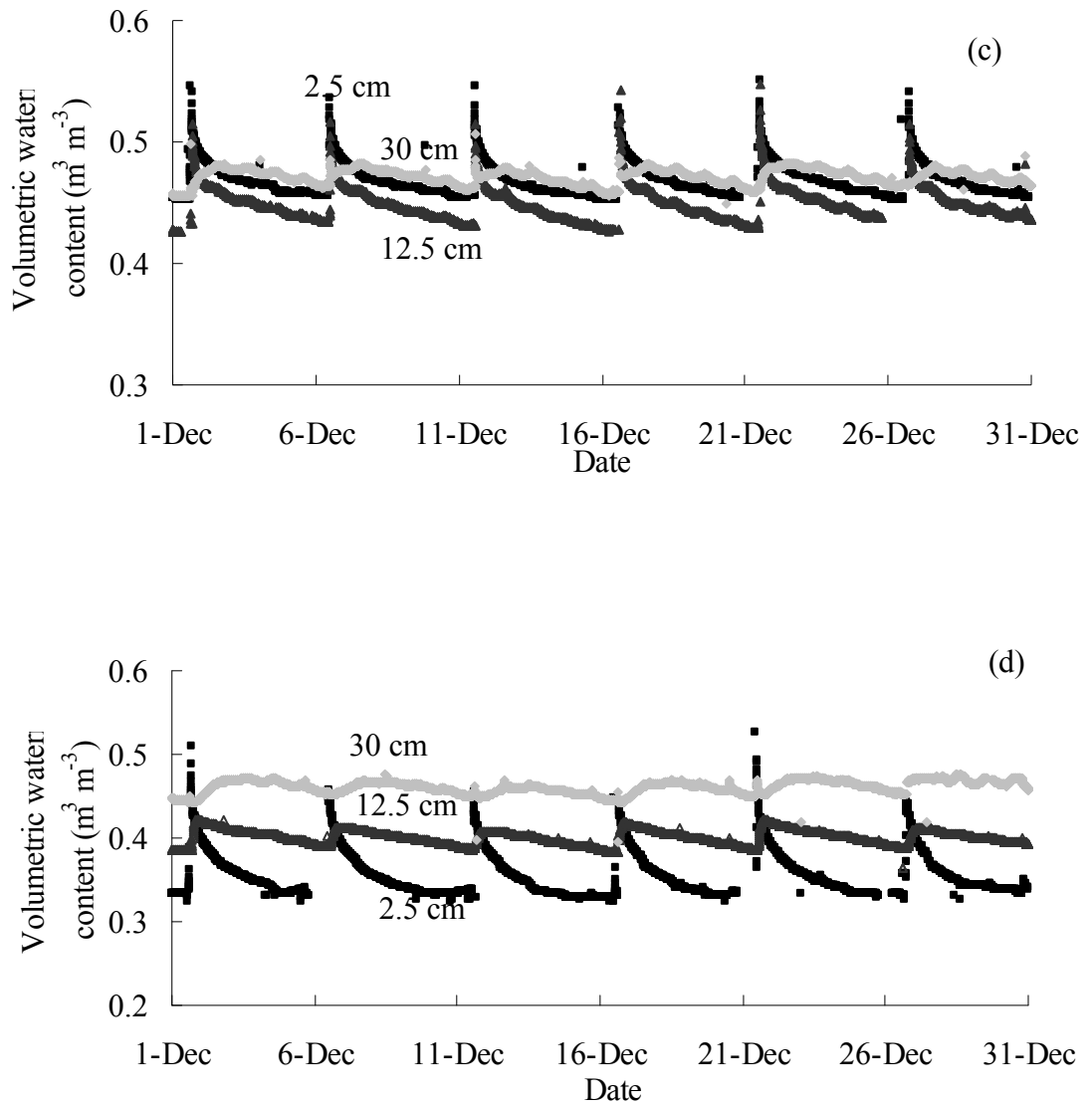


Fig. 21 Soil volumetric water contents at depths of 2.5, 12.5 and 30 cm. (a) Data of September under NT, (b) Data of September under T, (c) Data of December under NT, and (d) Data of December under T

3.6 Soil air-filled porosity

During the incubation period, soil air-filled porosity fluctuated due to irrigation (Fig. 22). Soil air-filled porosity decreased after irrigation, since the water content increased quickly. Then soil air-filled porosity increased gradually owing to water evaporation and redistribution. Tillage loosened the soil and increased the soil air-filled porosity at depths of 0–15 cm during the incubation period. At depths of 15–35 cm, there was no clear difference in the air-filled porosity between the two treatments.

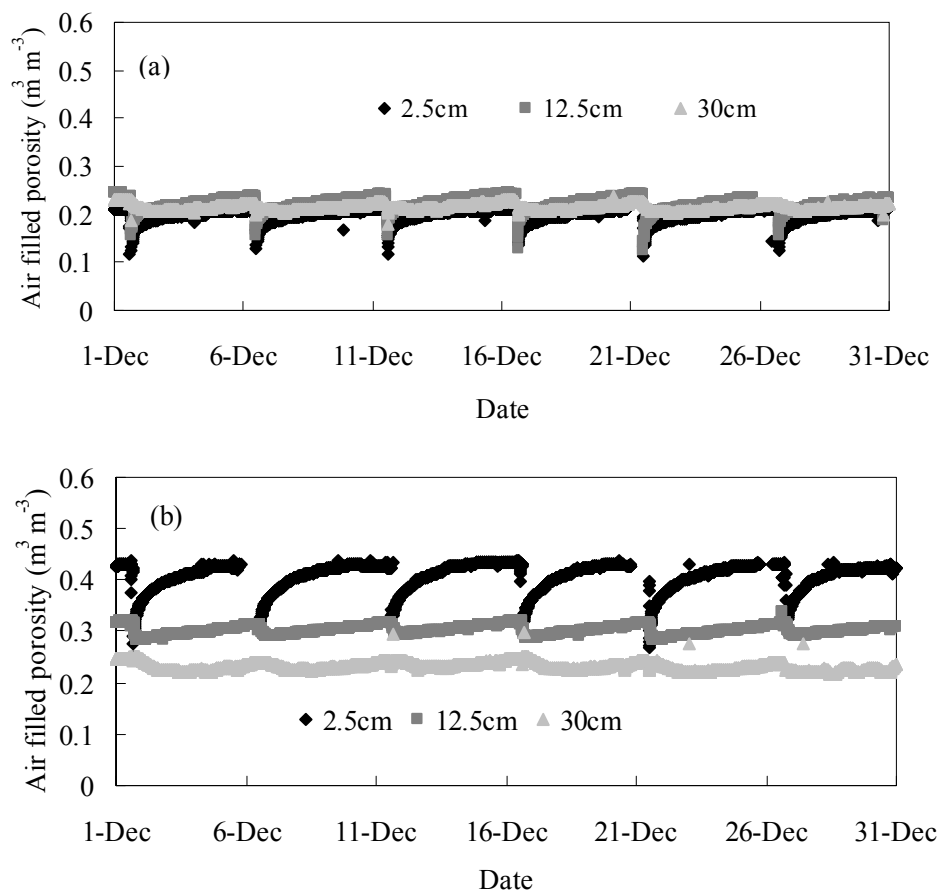


Fig. 22 Soil air-filled porosity under NT (a) and T (b) treatments at depths of 2.5, 12.5 and 30 cm

3.7 Soil gas diffusivity and gas diffusivity models

Soil water potentials fluctuated in the range from pF 1.5 to pF 2.7 ($pF = \log -\Psi$; Ψ , soil matric potential) during the incubation period (Fig. 20). Referring to the range of the water potential, soil gas diffusivities for the two treatments at 5 soil water potentials ($pF=1.3, 1.8, 2.3, 2.8, 3$) were measured. These potentials cover a range of soil water potential fluctuations during the incubation period.

The relationships between the soil water potential and air-filled porosity at depths of 0–5, 5–10, 10–15, 15–25 and 25–35 cm under the two treatments are shown in Fig. 23. At depths of 0–15 cm, soil air-filled porosity ranged from 0.10 to 0.27 $m^3 m^{-3}$ with the change of soil water potential from $pF=1.3$ to 3 under the no-tillage treatment, and no clear difference was found among each layer. The similar air-filled porosity was found between depths of 0–5 cm and 5–10 cm under the tillage treatment, and this was higher than that of depths of 10–15 cm. Since the soil was chiseled to a depth of 15 cm, the soil at 10–15 cm depth layer was partly chiseled. At depths of 15–25 cm and 25–35 cm, no clear difference in the air-filled porosity between the two treatments was observed at the same water potential.

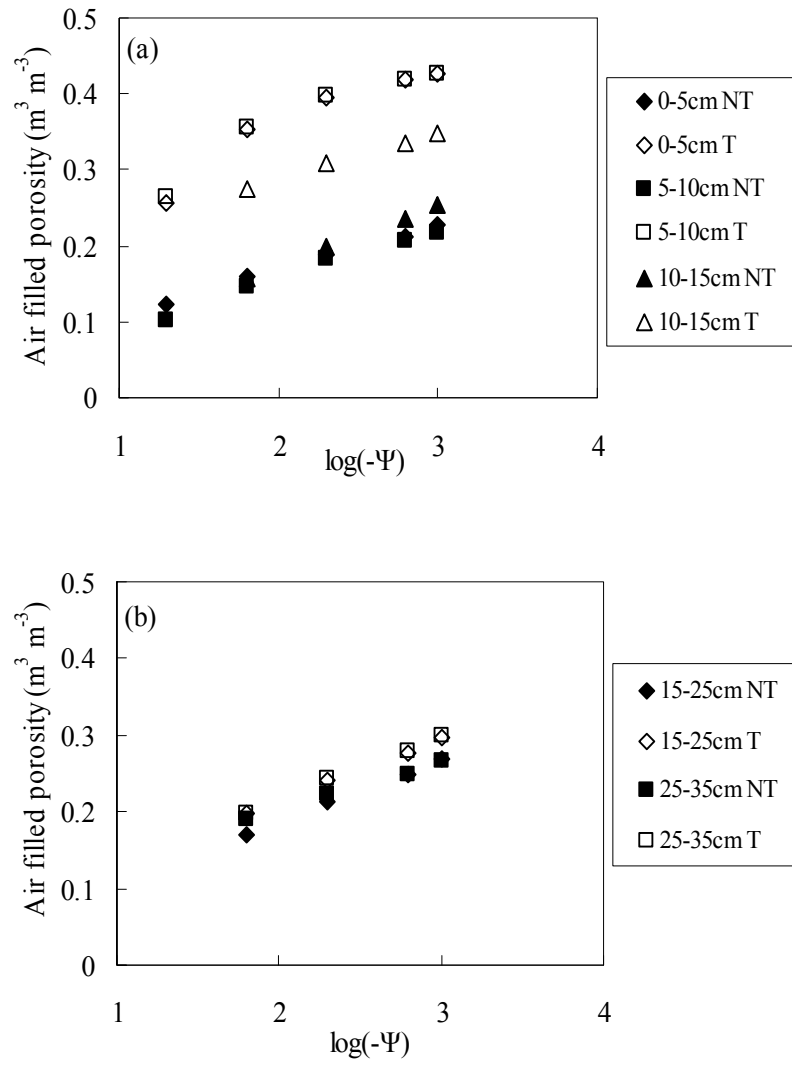


Fig. 23 Relationship between air-filled porosity and water suction at depths of 0–15 cm (a) and 15–35 cm (b) under NT and T treatments. Ψ , Soil matric potential (cm)

Relationships between soil gas diffusivity and air-filled porosity at depths of 0–15 cm and 15–35 cm under the two treatments are shown in Fig. 24. The soil gas diffusivity increased with the air-filled porosity for both the treatments. This result agrees with the previous literatures (Hamamoto et al., 2011; Resurreccion et al., 2010). When water potentials ranged from pF 1.3 to pF 3, soil gas diffusivities at depths of 0–15 cm ranged from 0.001 to 0.05 under no-tillage and from 0.025 to 0.16 under tillage treatments, respectively. Under the same water potential, the gas diffusivities under tillage treatment were higher than that under no-tillage treatment. At depths of 15–35 cm, no distinct difference in soil gas diffusivities was observed between the two treatments. It is interesting that at an air-filled porosity of about $0.25 \text{ m}^3 \text{ m}^{-3}$, where the water potential for the no-tillage treatment was the lowest (pF=3) and that for the tillage treatment was the highest (pF=1.3) among the measurements, there was a discrepancy in gas diffusivity between no-tillage and tillage treatments. This could be due to the differing extents of tortuosity caused by differences in water saturation at the similar air-filled porosity.

High soil gas diffusivity leads to quick soil air exchange with atmosphere. This may lead to more O_2 entry into the soil (Reicosky et al., 2008). Appropriately high level of O_2 concentration increased microbial respiration in the soil (Sierra and Renault, 1995; 1998). Weltecke and Gaertig (2012) examined higher soil respiration rates in soils with higher gas diffusivities. Thus, the soil CO_2 production caused by microbial respiration may be affected by tillage practices through the changes in soil porosity and gas diffusivity.

Soil aeration is one of the most important factors for soil respiration. Gas molecular diffusion is a major mechanism of gas transport within soils and between the

soil and the atmosphere. Thus, the evaluation of soil gas diffusivity is important to discuss soil aeration and CO₂ flux. However, continuous measurements of gas diffusivity are complex and laborious, and thus, predictive models have been proposed for accurate estimation of soil gas diffusivity.

Since soil gas diffusivity is governed by soil air-filled porosity, some gas diffusivity models employ the air-filled porosity as the primary parameter. In previous studies, most of the gas diffusivity models were reported to predict well for various types and textures of undisturbed soils (Resurreccion et al., 2010; Jay et al., 2012). However, compared to other types of soils, the Andisol exhibits the unique properties such as higher total porosity and broader pore size distribution. Thus, the Andisol shows highly valuable in testing the validity of predictive models (Moldrup et al., 2000). The present study tested the applicability of the gas diffusivity models for the Andisol. Due to tillage, soil structure was significantly changed, but few studies tried to predict gas diffusion coefficients of soils with varying structures by models. Therefore, studies on the prediction of soil gas diffusivity under the tillage treatment by using the models are required.

Four models widely used in previous literatures to predict gas diffusion coefficients were chosen in the present study to calculate soil gas diffusivities under no tillage and tillage treatments. The four models are Penman model [Eq. (5)], Millington-Quirk (MQ) model [Eq. (6)], Buckingham-Burdine-Campbell (BBC) model [Eq. (7)] and Generalized macroporosity-based (GMP) model [Eq. (8)]. Measured and modeled values of relative soil gas diffusion coefficients at depths of 0–15 cm and 15–35 cm are shown in Fig. 24. The c-parameters derived from soil water retention curves and total porosity (Φ) used to predict the soil gas diffusivity are listed in Table 4.

Table 4 Soil total porosity and c-parameters under NT and T treatments[†]

Depth (cm)	NT		T	
	$\Phi(\text{m}^3 \text{ m}^{-3})$	c	$\Phi(\text{m}^3 \text{ m}^{-3})$	c
0-5	0.67	17.7	0.75	7.9
5-10	0.66	16.3	0.76	7.5
10-15	0.68	12.0	0.71	12.9
15-25	0.68	14.3	0.70	12.9
25-35	0.69	16.2	0.69	11.5

[†], The parameters in this figure were used for predicting soil gas diffusivity with the MQ and BBC models.

Penman (1940) proposed a linear relationship between the soil gas diffusivity and the air-filled porosity, but this model overestimated the measured gas diffusivities for both the no-tillage and tillage treatments. The MQ model, predicting soil gas diffusivity based on soil total porosity and air-filled porosity, is a soil-type-dependant model. However, this model could not fit the measured gas diffusivities well for the Andisol used in the present study.

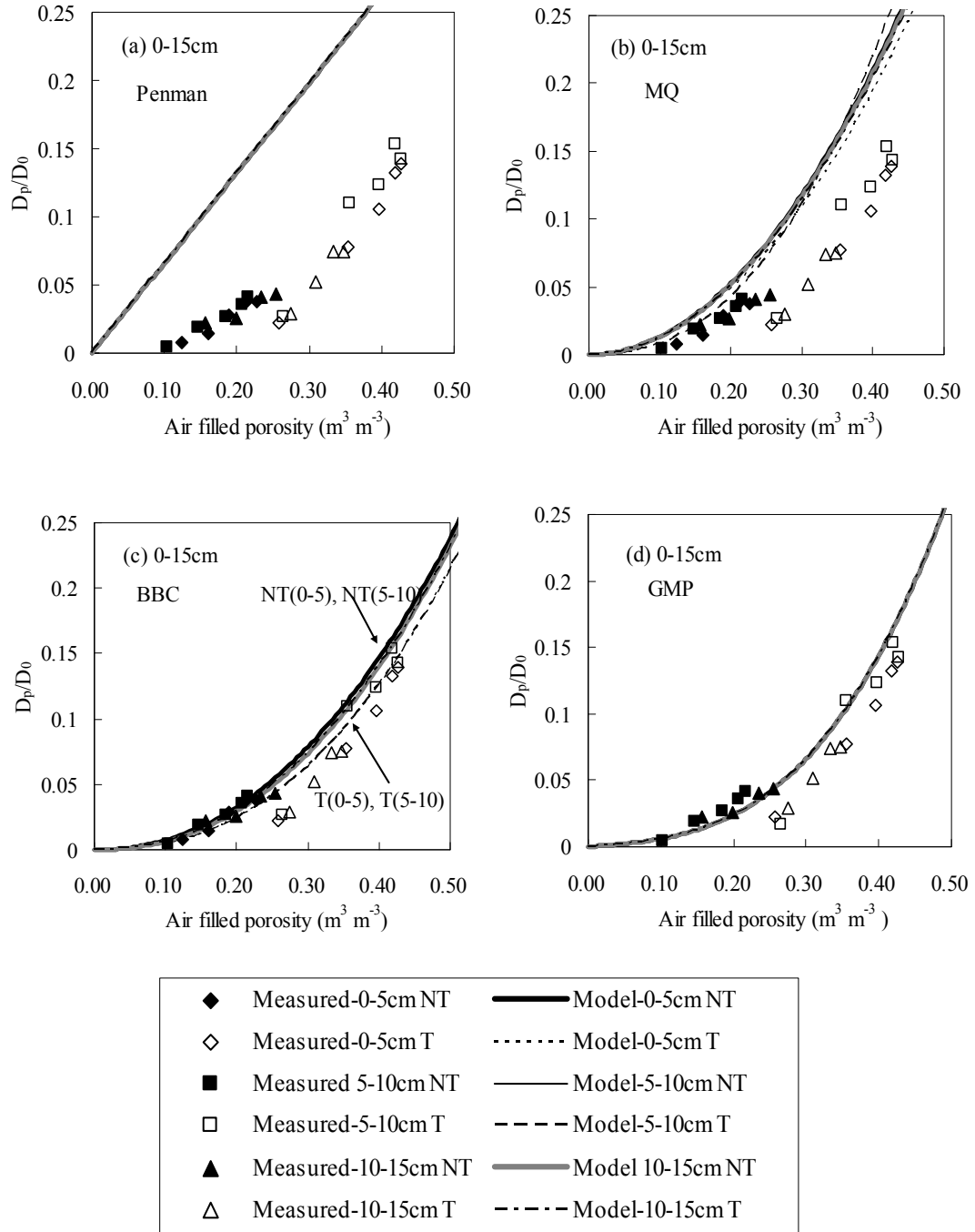
The GMP model predicts the gas diffusivity based on the correlation between the air-filled porosity and the measured gas diffusivity. The GMP model shows a tendency to underestimate the gas diffusivities for the no-tillage treatment and overestimate the gas diffusivities for the tillage treatment, although this model performs well in comparison to the Penman model and the MQ model.

Taking into account the effects of the pore volume and the pore size distribution, the BBC model predicts the gas diffusivity based on soil air-filled porosity, total

porosity and the c-parameter derived from the water retention curves. The BBC model agreed well with the measured gas diffusivities for both the no-tillage treatment with small air-filled porosity and the tillage treatment with a relatively greater air-filled porosity. However the gas diffusivities at an air-filled porosity of 0.25–0.32 m³ m⁻³ were slightly overestimated. Tillage changed not only the soil porosity but also the pore size distribution of the soil, and thus the water retention characteristics. Both the air-filled porosity and pore size distribution were important properties for gas diffusion in soils. Thus, among the four models, the BBC model predicted the gas diffusivities well.

In addition, the RMSE and bias were used for evaluating performances of the models (Fig. 25). Compared to the other three models, lower RMSE was obtained by using the BBC model for both the two treatments, and the lower RMSE indicated this model performed well for the prediction on the gas diffusivities. Bias was used to evaluate the model overestimation (positive bias) or underestimation (negative bias) of the measured data. The BBC model slightly overestimated the gas diffusivities for both the no-tillage and tillage treatments.

The BBC model, however, could not adequately predict the soil gas diffusivities at low air-filled porosity under the tillage treatment. It appears that more considerations of changes in tortuosity dependent on air-filled porosity and water saturation are required. However, in the present study, the air-filled porosity of topsoil was lower than 0.32 m³ m⁻³ only for several hours after irrigation, so the model could be used for gas diffusivities prediction under the tillage treatment. With measured data of the air-filled porosity and water retention characteristic, gas diffusivities of soils with various structures can be predicted.



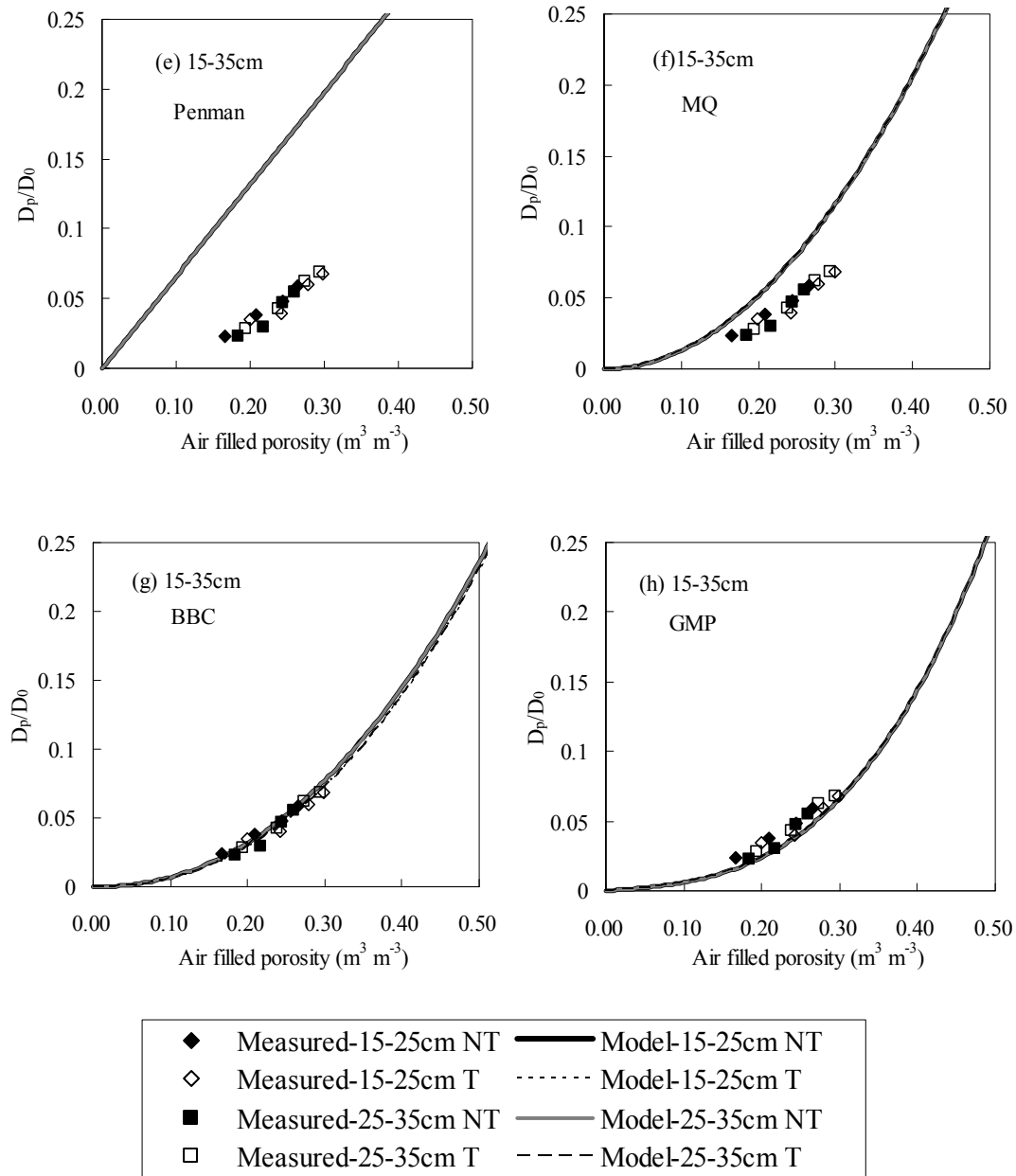
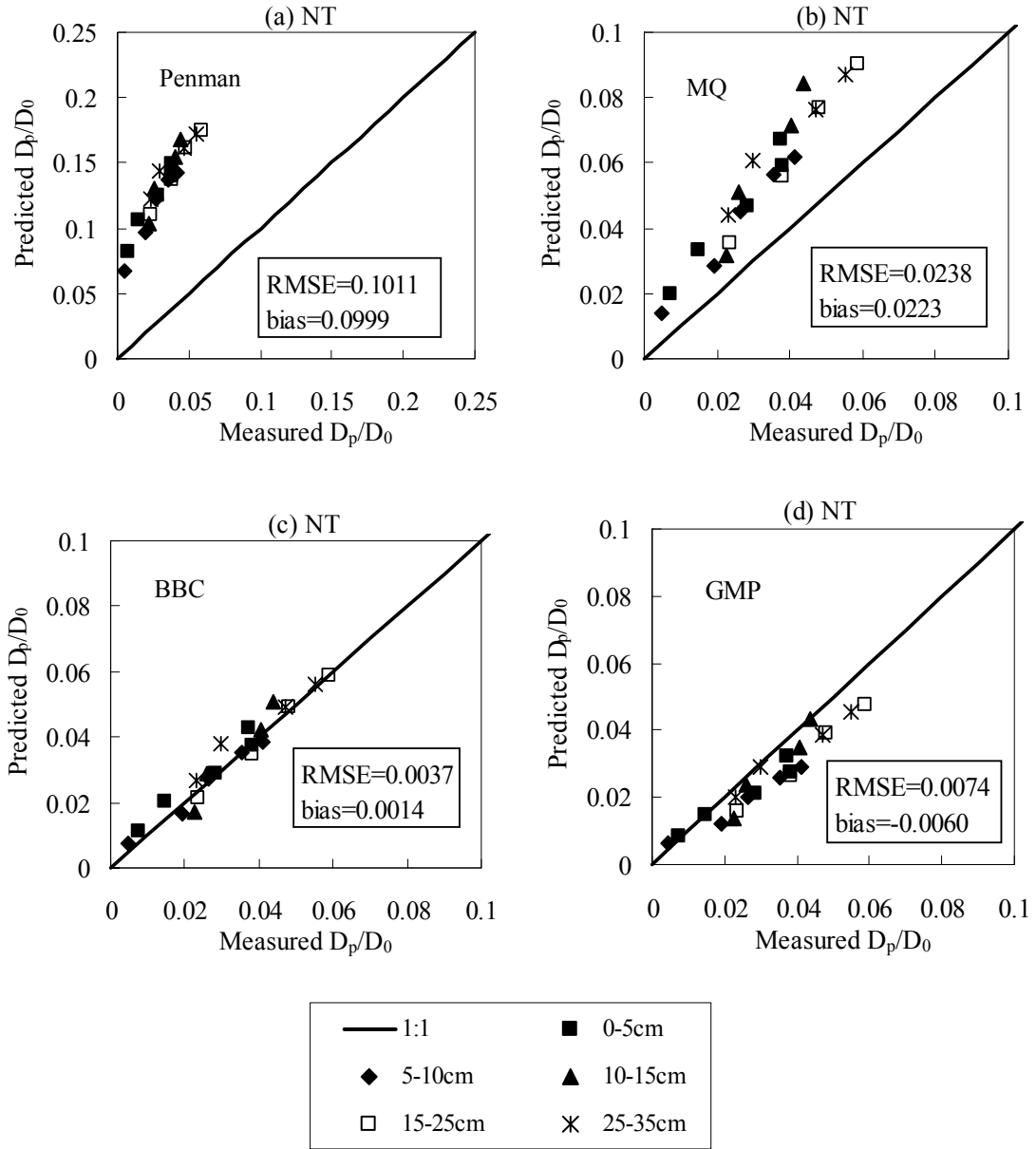


Fig. 24 Relationship between soil air-filled porosity and gas diffusivity. (a) Penman model at depths of 0–15 cm; (b) MQ model at depths of 0–15 cm; (c) BBC model at depths of 0–15 cm; (d) GMP model at depths of 0–15 cm; (e) Penman model at depths of 15–35 cm; (f) MQ model at depths of 15–35 cm; (g) BBC model at depths of 15–35 cm; (h) GMP model at depths of 15–35 cm



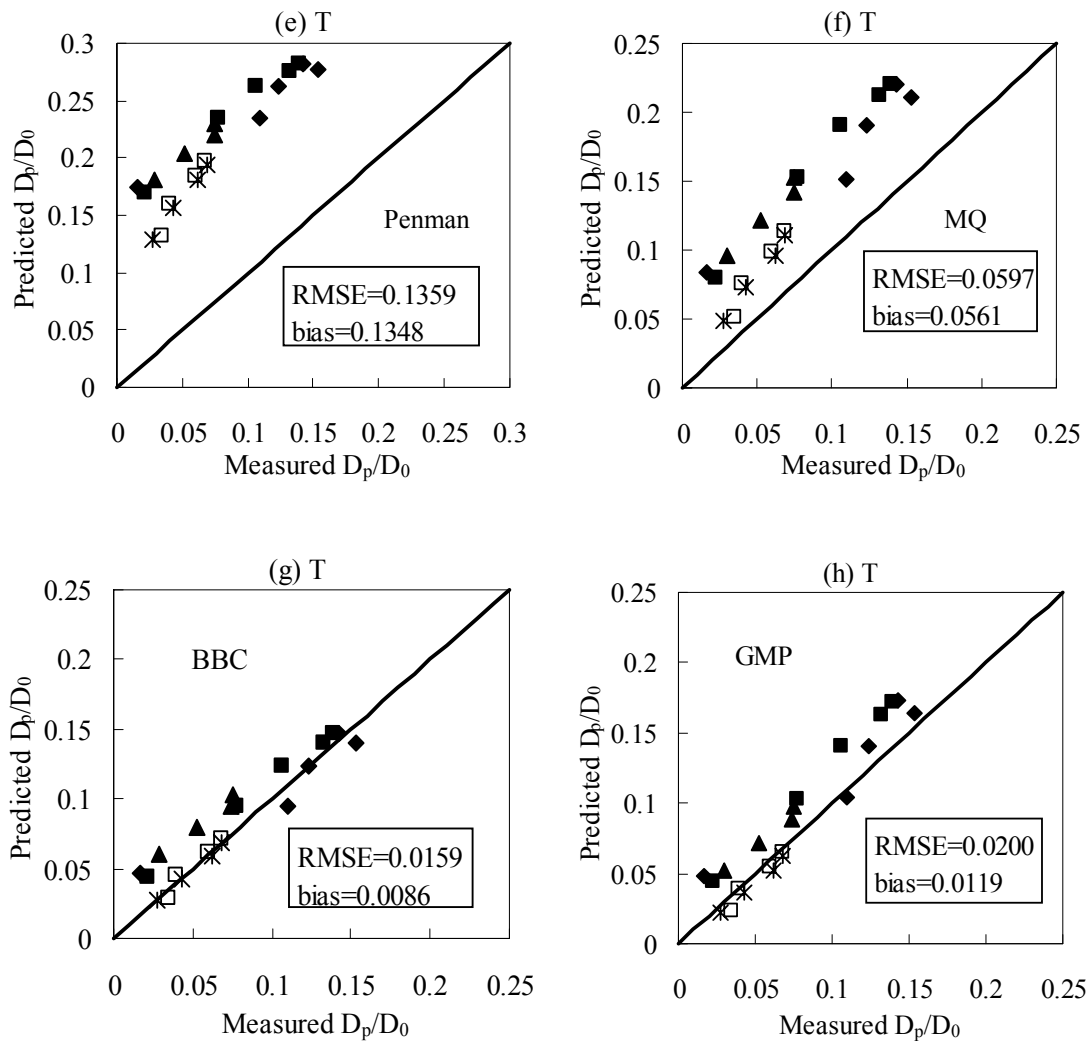


Fig. 25 Comparison of predicted and measured soil gas diffusivity. (a) Penman model under NT; (b) MQ model under NT; (c) BBC model under NT; (d) GMP model under NT; (e) Penman model under T; (f) MQ model under T; (g) BBC model under T (h) GMP model under T

In the present study, the BBC model was employed to predict soil gas diffusivities during the incubation (Fig. 26). The predicted gas diffusivities would be used to estimate the CO₂ flux from soil surface and through the soil profile in the next chapter. Predicted result showed that the soil gas diffusivity under the tillage treatment at depth of 0–10 cm was clearly higher than that under the no-tillage treatment. There was no significant difference in dry bulk density between the two treatments at depths of 10–15 cm (Fig. 13). Thus, the difference in soil gas diffusivity at depths of 10–15 cm between the two treatments was not as clear as that at depths of 0–10 cm. At deeper layer (15–35 cm), no distinct difference in gas diffusivity was found between the two treatments. Temporal changes in the soil diffusion coefficient were due to the changes in the soil volumetric water content.

Given the results that the soil physical properties (dry bulk density, aggregation, saturated hydraulic conductivity, air-filled porosity and gas diffusivity) were significantly affected by tillage practice, the changes in the physical environments may influence the soil respiration.

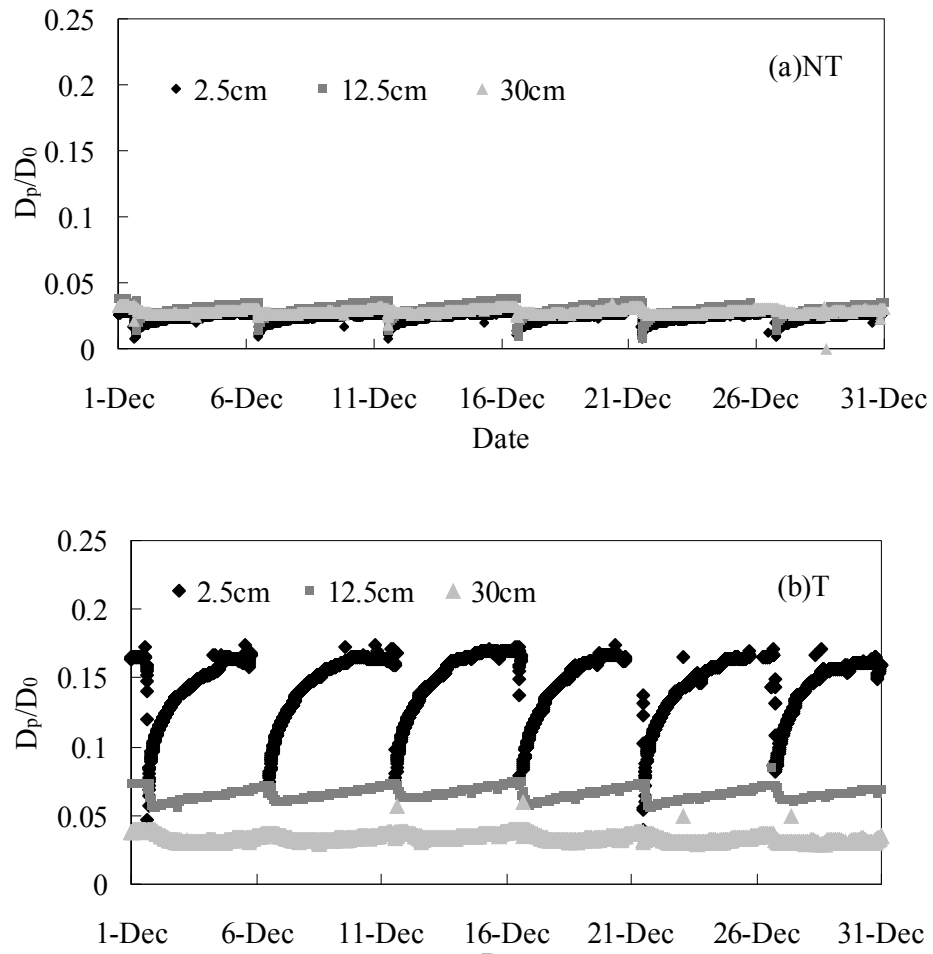


Fig. 26 Soil gas diffusivity at depths of 2.5, 12.5 and 30 cm under NT (a) and T (b) treatments

Chapter 4 Behavior of carbon dioxide in soils affected by tillage systems

4.1 Soil carbon dioxide flux

Results of the soil CO₂ flux under no-tillage and tillage treatments are shown in Fig. 27a. Difference in soil CO₂ flux between the two treatments at the first day was obvious. Soil CO₂ flux under the no-tillage was 2.38 g CO₂-C m⁻² d⁻¹, whereas that under the tillage treatment was 5.13 g CO₂-C m⁻² d⁻¹ for the first day. Similar results were also found in the literature: Gesch et al. (2007) observed that there was an increased CO₂ emission immediately after tillage and then the emission rate decreased within a day. Reicosky and Archer (2007) estimated that within 5 hour after tillage, there was a reduction in the CO₂ flux. Owing to the disturbance of the soil caused by tillage, CO₂ stored in soil pores is released to the atmosphere quickly and lead to an increase in the CO₂ flux. Tillage accelerates the air exchange between the soil and the atmosphere. The O₂ concentration of the air phase is higher in the atmosphere than that in the soil. This may lead to a temporal increase in the soil O₂ concentration. Higher O₂ concentration in the soil enhances the microbial activities and this may be another contributor to the increase in the soil CO₂ emission.

After the first day, soil CO₂ flux under the tillage treatment decreased, and fluctuated in the range of 0.2 to 1.1 g CO₂-C m⁻² d⁻¹, which was similar to that of the no-tillage (i.e., 0.0–1.0 g CO₂-C m⁻² d⁻¹). No noticeable increase or decrease in soil CO₂ flux was observed after the first day of the incubation period. An average CO₂ flux of 0.557 and 0.616 g CO₂-C m⁻² d⁻¹ was measured for no-tillage and tillage treatments, respectively.

Soil cumulative CO₂ flux under no-tillage and tillage treatments was 86.97 and 98.17 g CO₂-C m⁻², respectively, for the 150 days of incubation (Fig. 27b). The no-tillage treatment tended to show smaller cumulative CO₂ flux from the soil than the tillage treatment.

Chu et al. (2007) reported a value of 0.427–0.524 g CO₂-C m⁻² d⁻¹ CO₂ flux from an Andisol upland field in Japan under different fertilizer managements. A closed chamber method was used to determine the gas flux by Chu et al. (2007), which is the same as that used in the present study. Nakadai et al. (2002) conducted a field experiment to observe the soil CO₂ flux from an Andisol by using a chamber and an open-flow infra-red gas analyzer. It reported that the average soil CO₂ flux under the tillage treatment was 0.73–1.39 g CO₂-C m⁻² d⁻¹ for different seasons. Nakadai et al. (2002) also performed a laboratory incubation experiment to measure the CO₂ emission rate with small soil cores, and the CO₂ emission rate was observed to be 46.65 mg CO₂-C kg⁻¹ d⁻¹. Dumale (2009) determined the CO₂ emission rate of an Andisol by using the bottle incubation method in the laboratory. It reported the CO₂ emission rates of Andisol under different treatments were in the range of 7.87 to 46.81 mg CO₂-C kg⁻¹ d⁻¹. In the present study, if the unit was converted from g CO₂-C m⁻² d⁻¹ to mg CO₂-C kg⁻¹ d⁻¹, the soil CO₂ flux under no-tillage and tillage treatments was 1.65 and 1.83 mg CO₂-C kg⁻¹ d⁻¹. Results of our study are similar with that of the CO₂ flux from Andisol upland soils estimated by Chu et al. (2007) and Nakadai et al. (2002). However, the value of the CO₂ flux reported by using the bottle incubation experiments are obviously higher than that reported by using the column incubation experiment in the present study. This may because the O₂ supply is not a limit factor in the bottle incubation experiment, which accelerates the soil respiration. In comparison to the bottle

incubation experiment, results of soil CO₂ flux obtained by the soil column incubation experiment were more similar with results obtained by the field experiments.

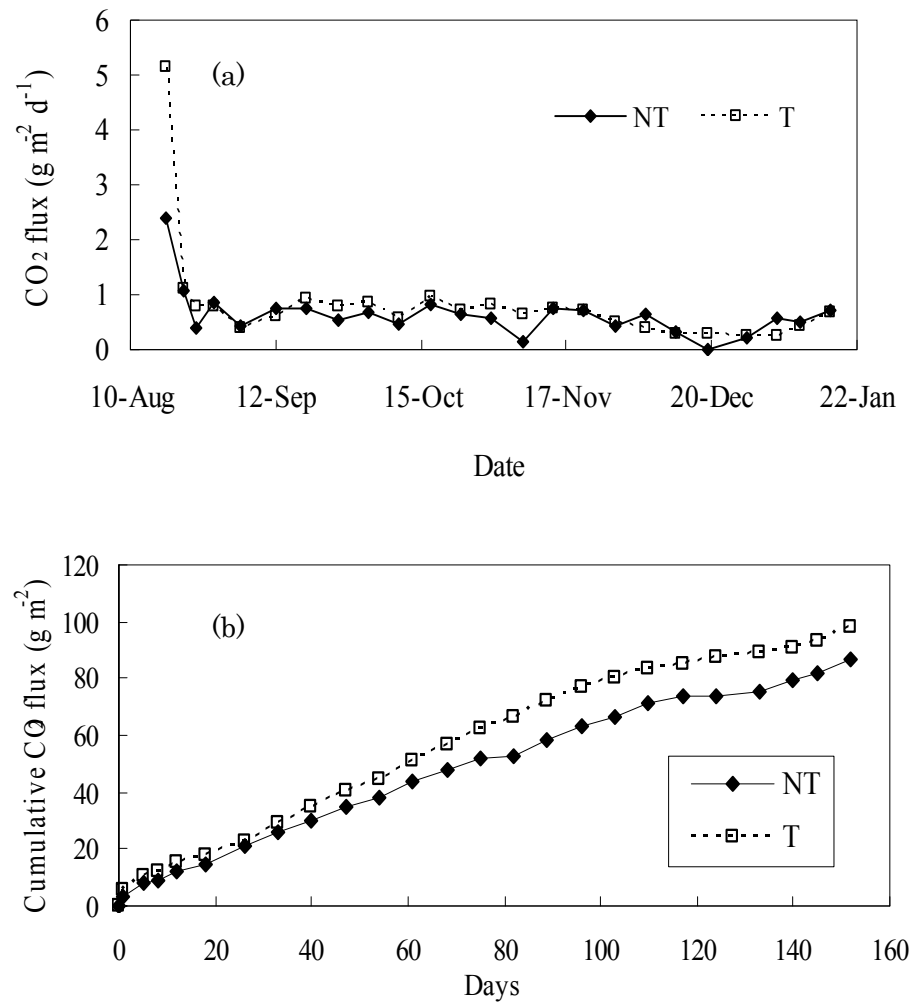


Fig. 27 Soil CO₂ flux (a) and cumulative CO₂ flux (b) under NT and T treatments during 150 days of incubation experiment

4.2 Soil organic carbon

4.2.1 Distribution of carbon in the soil profile

Andisol, derived from volcanic ash, shows high organic carbon and almost no inorganic carbon. Therefore, the total carbon considered as soil organic carbon was measured in the present study. As shown in Fig. 28, since leaf compost was applied to the surface of the soil before the incubation experiment, the total carbon of the topsoil (0–5 cm) under the no-tillage treatment was 58.74 g kg^{-1} after 150 days of incubation, and this was greater than that of the deep soils. Tillage redistributed the leaf compost throughout the entire chiseled layer (0–15 cm), which resulted in the changes in soil carbon in the chiseled layer. Since the soil of depths of 0–15 cm was chiseled but not fully overturned, the carbon content was not homogeneous in the chiseled layer. These results are consistent with previous studies (Poirier et al., 2009; Powlson et al., 2011), which indicated the distribution of soil carbon was changed by the tillage operation at the tilled layers. Result of the present study also suggests that the depth of soil sampling is a considerable factor for the determination of soil carbon. Using the surface soil as a representative soil for the determination of soil carbon may overestimate the effect of no-tillage on the soil carbon stock.

The Soil carbon stock is determined by the carbon input and the carbon decomposition rate. Since the carbon input for the two treatments was the same, the carbon stock much depended on the carbon decomposition rate. But the results of carbon stocks in the present study were not in agreement with that of the cumulative CO_2 emission. As shown in Fig. 29, the carbon stocks for no-tillage and tillage treatments were 16.43 kg m^{-2} and 16.39 kg m^{-2} , respectively, showing no clear difference between the two treatments.

Conant et al. (2007) reported that the influence of the tillage practice on soil carbon is more significant in the long-term experiments. Angers and Eriksen (2008) noted a net accumulation of additional organic carbon under the no-tillage system when the system was continued for at least 10–15 years. In the present short-term experiment (150 d), the cumulative effects of tillage practice on soil carbon decomposition were small. As shown in this study, soil carbon stocks under the no-tillage and tillage treatments were 16.43 kg m^{-2} and 16.39 kg m^{-2} , respectively, but the cumulative CO_2 flux was 86.97 g C m^{-2} and 98.17 g C m^{-2} , respectively. The loss of the soil carbon by the soil respiration during the 150-d incubation period was extremely small to the carbon stock in the soil column. This may be the main reason of the result that no clear difference in the carbon stock between the two treatments was observed. Another possible reason might be that, while the tillage system incorporated the applied leaf compost in the tillage layer, the compost for the no-tillage system was left on the soil surface. Similar to our study, the difference in the distribution of soil carbon content between the NT and T treatments has been found by previous studies (Poirier et al., 2009; Powlson et al., 2011). The organic carbon upon the surface soil could easily contact with the O_2 in the atmosphere, and thus, sufficient available O_2 might sustain high carbon decomposition under the no-tillage treatment.

In this study, 0.25 kg m^{-2} of carbon was supplied into the soil by the leaf compost applying. The carbon stock was about 16.3 kg m^{-2} . About 0.086 and 0.098 kg m^{-2} of carbon were lost by the CO_2 emission during the incubation period for no-tillage and tillage treatments. No drain was observed, and hence, the only carbon loss was through the soil respiration. Since the compost was applied to the top of the soil, the organic carbon in the top layer was contributed by the compost and the soil. The soluble

carbon could be removed to the deeper layer with the irrigated water, however less water was removed to the deeper layer since the water was tended to evaporate before removed into the deeper layer. The decomposed carbon in the deeper layer was mainly contributed by the carbon in the soil. The experiment was a short-term experiment, thus the undecomposed carbon was accumulated in the soil. For a long-term experiment, the no-tillage system has a potential to sink more carbon in comparison to the tillage system.

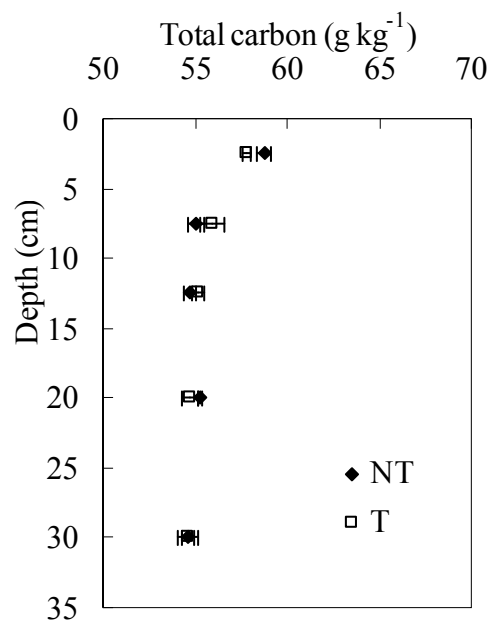


Fig. 28 Distributions of the total carbon in soil profiles under NT and T treatments

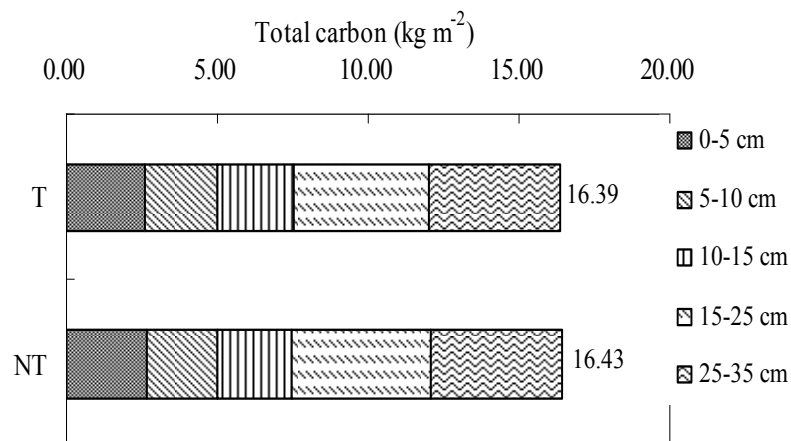


Fig. 29 Soil carbon stocks under NT and T treatments

4.2.2 Soil total carbon associated with aggregates

That the soil organic carbon is closely related to the soil aggregation has been reported by many researchers (e.g., Elliott, 1986; Puget et al., 2000; Balesdent et al., 2000). Soil environments (e.g., water, O₂ level and microbes) around the aggregates of various sizes are different (Sextstone et al., 1985; Guber et al., 2003). Since the carbon dynamics are affected by the soil environments, dynamics of carbon associated with different size classes of aggregates may be different. Since tillage significantly affects the size distributions of soil aggregates, the carbon dynamic may be affected by tillage, and thus the CO₂ production.

The organic carbon associated with soil aggregates of different size classes under no-tillage and tillage treatments are shown in Fig. 30. Distributions of total carbon in different sizes of soil aggregates were consistent for the no-tillage and tillage treatments. Aggregates in <0.053 mm size class showed the highest total carbon content for both the no-tillage (i.e., 64.17 g kg⁻¹) and tillage (i.e., 65.13g kg⁻¹) treatments. Aggregates in 0.5–0.25 mm size class showed the lowest total carbon content for the two treatments. Carbon associated with micro-aggregates of 0.1–0.053 mm and 0.25–0.1 mm size classes was slightly higher than that of macroaggregates (>0.25 mm). The aggregates in <0.053 mm size class are mainly formed by clay particles, fine silts and organic agents. Since fine silts and clays have the ability to adsorb more organic carbon (Hassink, 1997; Zhao et al., 2006), higher organic carbon associated with <0.053 mm size aggregates has been observed. Aggregates in 0.25–0.5 mm size class are mainly formed by macroaggregates and sand particles. That sand particles with low ability to preserve the organic carbon lead to the lowest carbon content in this size fraction.

Contradictions in the distributions of carbon associated with soil aggregates have been found in previous literature. Some studies reported that compared to the microaggregate, the macroaggregate (>0.25 mm) were more enriched in organic carbon (Jagadamma and Lal, 2010). But Huygens et al. (2005) measured the carbon associated with aggregates of an Andisol and reported that no significant difference was observed in total carbon content among different size fractions. Sessitsch et al. (2001) indicated that the higher organic carbon and microbial biomass were observed in microaggregates (<0.063 mm). Unique structure and texture for different types of soils may partly explain the inconsistent results in the carbon associated with soil aggregates. For the Andisol used in the present study, < 0.1 mm size aggregates had the higher carbon content in comparison to the other fractions, since the < 0.1 mm size aggregates were mainly formed by clay particles with high carbon content.

Comparing the distributions of carbon associated with soil aggregates under the two treatments, the total carbon content of aggregates in >1 mm size class under the no-tillage treatment was slightly higher than that under the tillage treatment. In contrast, total carbon in <0.25 mm fraction was higher for the tillage treatment in comparison to the no-tillage treatment, but the difference was not significant ($P>0.05$) (Fig. 30). The possible explanation of the result is that soil micro-aggregates, fine silt and clay particles with higher organic carbon are bound with macroaggregates or protected by the macroaggregates before tillage. After tillage, macro-aggregates are destructed to the micro-aggregate, sand, silt and clay particles. Therefore, under the tillage treatment, relatively larger amount of microaggregates and clay particles increase the carbon content in <0.25 mm fractions, and the sand particles decrease the carbon content in >1 mm fraction.

Ashman et al. (2003) simulated slaking and tillage soils by laboratory experiments to study the models of carbon dynamics in soil aggregates. The slaking soil could be considered as the no-tillage soil. The result showed that more large stabilized aggregates were observed in the slaking soil in comparison to the tillage soil. Comparing the two treatments, macroaggregates of the slaking soil contained more organic carbon, and the microaggregates of the tillage soil contained more organic carbon. Ashman et al. (2003) indicated that the macroaggregates were formed by a large aggregate core with lower organic carbon content bounded with the fine particles with higher organic carbon content. After tillage, fine particles with high carbon that separated from the large cores increased the carbon content of microaggregates, and the remaining large aggregate cores contributed to the lower carbon content of the macroaggregates.

The micro-aggregates and clay particles with higher carbon content are bared to microbes, water and O₂ after tillage, which increase the carbon decomposition rate (La Scala et al., 2009). Six et al. (1999) and Jiang et al. (2011) reported the organic carbon under the no-tillage treatment was significantly higher than that under the tillage treatment in most fractions of soil aggregates. However, no significant difference in the carbon content between the two treatments was observed except for the 0.1–0.053 mm fraction in the present study. Similar to the study of the carbon stock, the long-term incubation experiment is required to study the effects of tillage practice on the carbon associated with the soil aggregates.

4.2.3 Soil carbon mineralization associated with aggregates

Microbial biomass and microbial activities are affected by the size of the soil aggregates (Sollins et al., 1996; Helgason et al., 2010). It is important to know how and what extent size of soil aggregates affects the decomposition of organic carbon. However, the studies on the carbon mineralization rates associated with aggregates are insufficient. Soil carbon mineralization rates (soil respiration rates) associated with different sizes of aggregates were also determined in the present study.

The average soil respiration rates of soil aggregates during the 15 days of bottle incubation under no-tillage and tillage treatments are shown in Fig. 31. Microaggregates (<0.1 mm) with higher carbon content showed higher respiration rate, and accordingly, lower respiration rate for 0.5–0.25 mm size of aggregates with lower carbon content was observed. This is consistent with the result of distributions of total carbon in different sizes of soil aggregates. Comparing the two treatments, there was no significant difference in the soil respiration rate was observed among different sizes of aggregates. The results indicate that the respiration rate of aggregates was affected by the size of aggregates but not the tillage practice. The O₂ level is relatively high in the incubators (500 ml glass bottles) with small amount of soil samples in comparison to in the field soil. And thus, the O₂ concentration is not the limit factor for the soil aggregates respiration, implying that soil carbon mineralization of aggregates might be much depended on the available carbon content.

These results are also supported by other studies. Jha et al. (2012) reported the lowest CO₂ production was recorded in the aggregates of 1–2 mm size class, and the finer aggregates (<0.25 mm) mineralized more organic carbon. Soil cumulative carbon mineralization showed significant positive correlation with the soil organic carbon

content. Jiang et al. (2011) reported that the readily mineralizable organic matter was related to the size of soil aggregates, but not the tillage practice. Thus, no significant differences in the mineralizable organic carbon associated with aggregates were found between no-tillage and tillage treatments. The highest respiration rate was observed in 1.0–2.0 mm size aggregates, while the lowest respiration rate was observed in micro-aggregates (0.25–0.053 mm).

The soil respiration rates of aggregates measured by the bottle incubation experiment were in the range of 0.18 to 0.23 g-C kg⁻¹-soil h⁻¹. However, the respiration rate measured by the column experiment was about 0.069 and 0.076 g-C kg⁻¹-soil h⁻¹ for no-tillage and tillage treatments, suggesting the values were lower than that measured by the bottle incubation experiments. Soil CO₂ flux measured by bottle incubation experiments overestimated the CO₂ flux estimated in the field. The results of this study indicate that in comparison to the bottle incubation experiment, the column incubation experiment was more similar to the field experiment for studying the greenhouse gas flux.

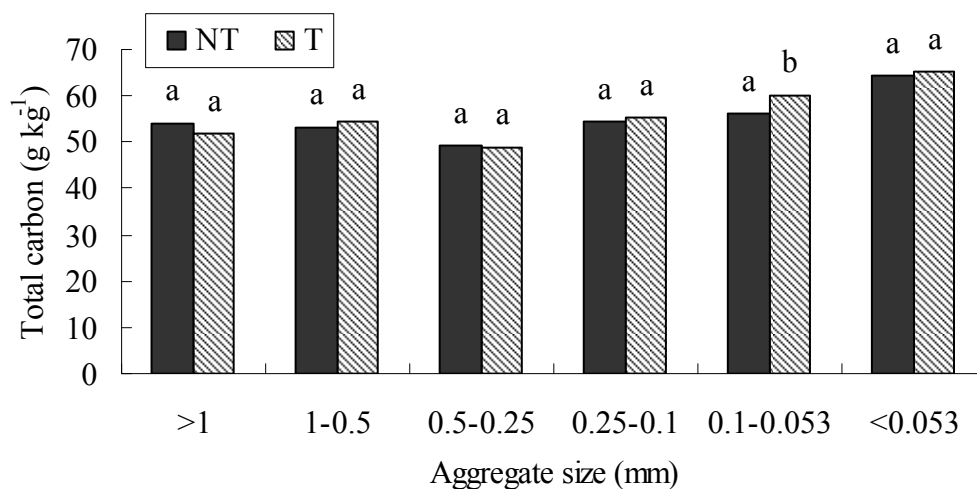


Fig. 30 Soil carbon associated with different sizes of aggregates under NT and T treatments at depths of 0–15 cm. Significant differences between treatments are indicated with different letters ($P<0.05$, $n=4$)

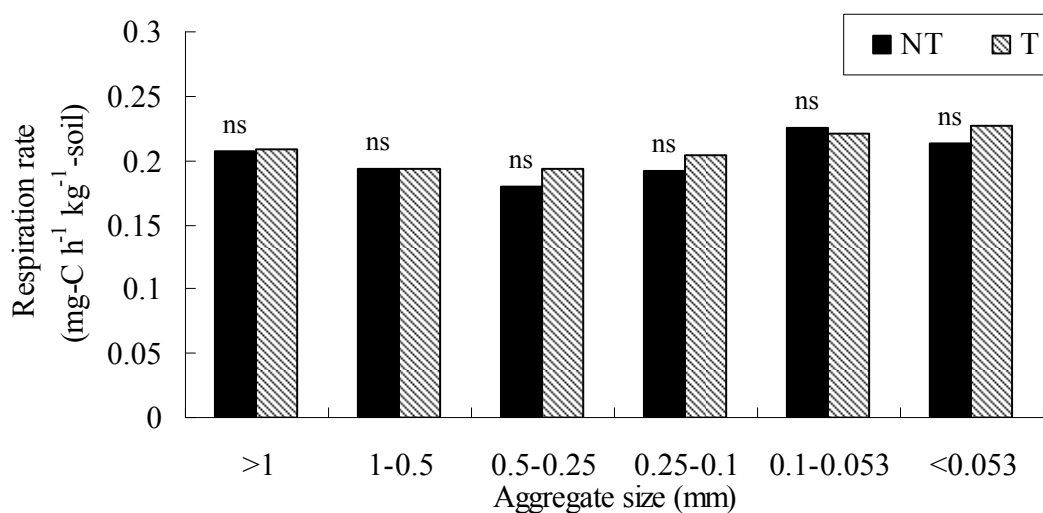


Fig. 31 Soil mineralization carbon associated with different sizes of aggregates under NT and T treatments at depths of 0–15 cm. ns, no significant difference ($P>0.05$, $n=4$)

4.3 Distribution and temporal variation of carbon dioxide concentration in the soil profile

To understand the CO₂ behavior in soils, not only soil surface CO₂ flux but also soil CO₂ production and transport in soils should be evaluated. By using the column incubation experiment, soil CO₂ concentration was measured under the two treatments in the present study, which could be used to evaluate soil CO₂ flux and production. Distributions of the CO₂ concentration in soil profiles for different sampling days are shown in Fig. 32. For both no-tillage and tillage treatments, soil CO₂ concentration increased with depth. Average soil CO₂ concentration of the 150-d incubation at the depth of 2.5 cm was 0.107% for the no-tillage treatment and increased to 0.254% at the depth of 30 cm. For the tillage treatment, the soil CO₂ concentration at depths of 2.5 cm and 30 cm was observed to be 0.099% and 0.187%, respectively. Gas transport in the soil vadose zone is governed by the gas advection and diffusion. In natural soil, variations of the air pressure during the whole soil profile are small, and thus, the CO₂ transport can be assumed to be governed by the gas diffusion.

Temporal variations of the CO₂ concentration at depths of 2.5, 7.5, 12.5, 20 and 30 cm during the incubation period are shown in Fig. 33. Similar to the soil CO₂ flux, no noticeable increase or decrease in soil CO₂ concentration was observed except the first day. At the first day, the CO₂ concentration was higher for the two treatments especially at the deeper layers. Before the incubation experiment, to avoid the loss of water, the soil columns were covered and stored in the laboratory. This also prevented the CO₂ in the soil from emitting to the atmosphere. Since soil air-filled porosity and soil gas diffusivity were changed with the volumetric water content, the changes in the water content may cause fluctuations of the CO₂ concentration in soils. As shown in Fig. 34,

the positive correlation was observed between soil CO₂ concentration and the volumetric water content. The room temperature was 30°C for daytime, and thus, soil temperature is not an important contributor of the variations of the CO₂ concentration. The measurement errors may be another cause for the variations of soil CO₂ concentration in different sampling days.

The CO₂ concentration was similar at the depth of 2.5 cm for both treatments. At the deeper layers, the soil CO₂ concentration under no-tillage was higher than that under the tillage treatment, especially at depths of 12.5, 20, and 30 cm. This result is similar to that reported by Yonemura (2009), who indicated that the CO₂ concentration at the depth of 20 cm under no-tillage and conventional tillage treatments was 0.4–2.5% and 0.2–1.2%, respectively. Soil CO₂ concentration gradient under the tillage treatment was obviously smaller than that under the no-tillage treatment, especially at depths of 2.5–7.5 cm.

For soils with the same structure, the difference in soil CO₂ concentration could be due to the CO₂ production (Pumpanen et al., 2003; Hashimoto and Komatsu, 2006). But due to tillage, soil structure is significantly changed by tillage. Soil gas diffusion changed with the changing of soil structure, which could lead to the difference in soil CO₂ concentration between the two treatments. As discussed in Chapter 3, soil gas diffusivity during the incubation period was predicted by the BBC model in the present study, since this model performed well for gas diffusivity prediction under no-tillage and tillage treatments. The tillage treatment clearly showed greater gas diffusion coefficient in comparison to the no-tillage treatment at depths of 0–15 cm (Fig. 26). High air-filled porosity and gas diffusivity in the tillage soil led to the lower CO₂ concentration in soil profile. The result is consistent with the previous studies, which

reported the CO₂ concentration in soils was affected by the gas diffusivity, especially at the deeper layers (McCarty et al., 1999; Hashimoto and Komatsu, 2006). Lower soil gas diffusivity induced by the tillage operation leads to the relatively higher O₂ concentration. Soil microbial respiration may be accelerated under the higher O₂ level, and this may be another reason contributed to the higher CO₂ flux.

However, the similar CO₂ concentration of topsoil was observed between the two treatments. The air in the topsoil is easily exchanged with the atmospheric air. Thus, soil CO₂ concentration at the depth of 2.5 cm is considerably affected by the CO₂ concentration of the atmosphere. The CO₂ concentration of the deeper soil is more affected by the gas diffusivity and the CO₂ production. Therefore, greater soil gas diffusivity under the tillage treatment is the main contributor to the lower CO₂ concentration in the soil profile, especially at deeper layers.

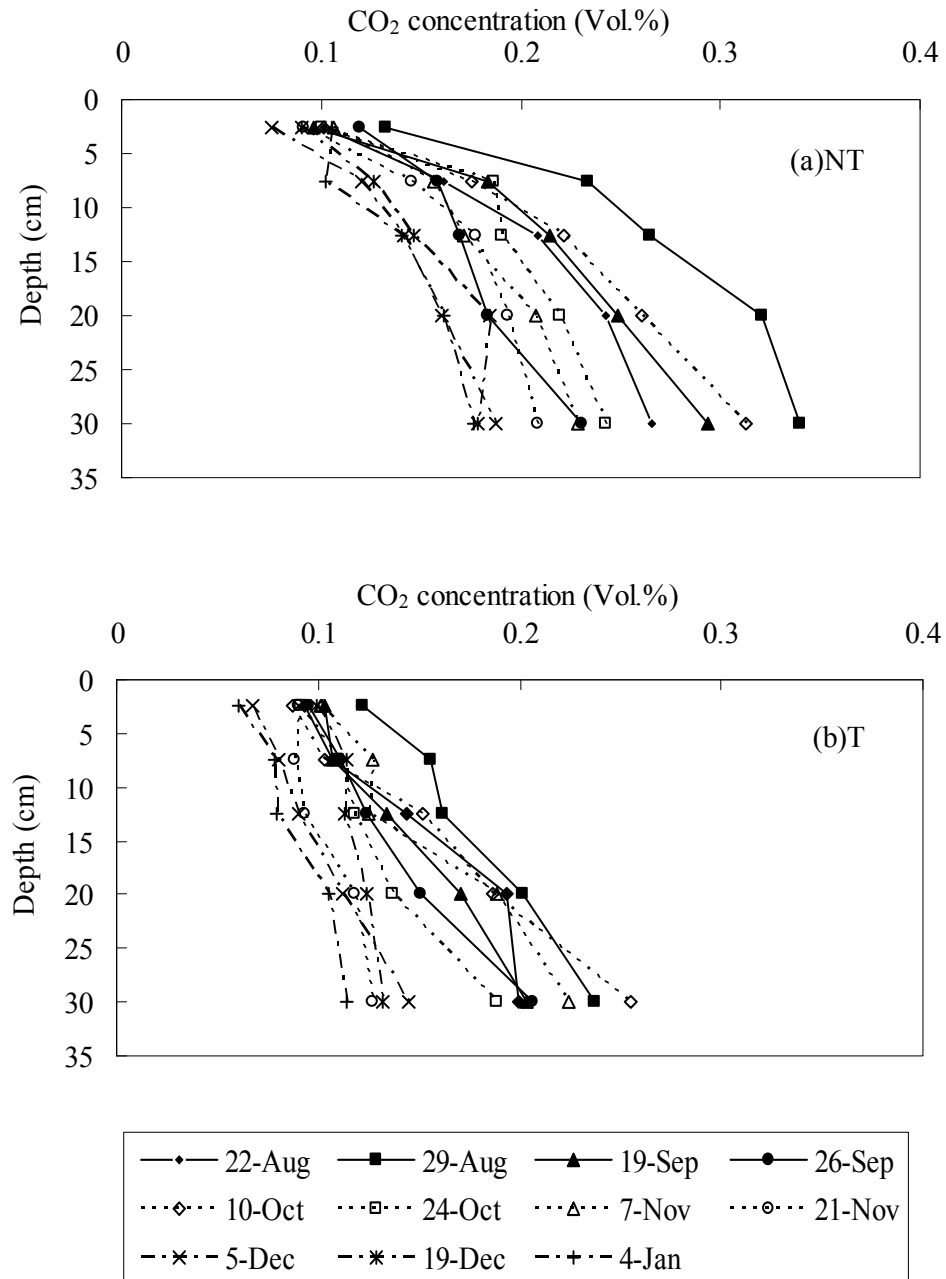


Fig. 32 Distributions of the CO₂ concentration in soil profiles under NT (a) and T (b) treatments during the 150-d incubation period

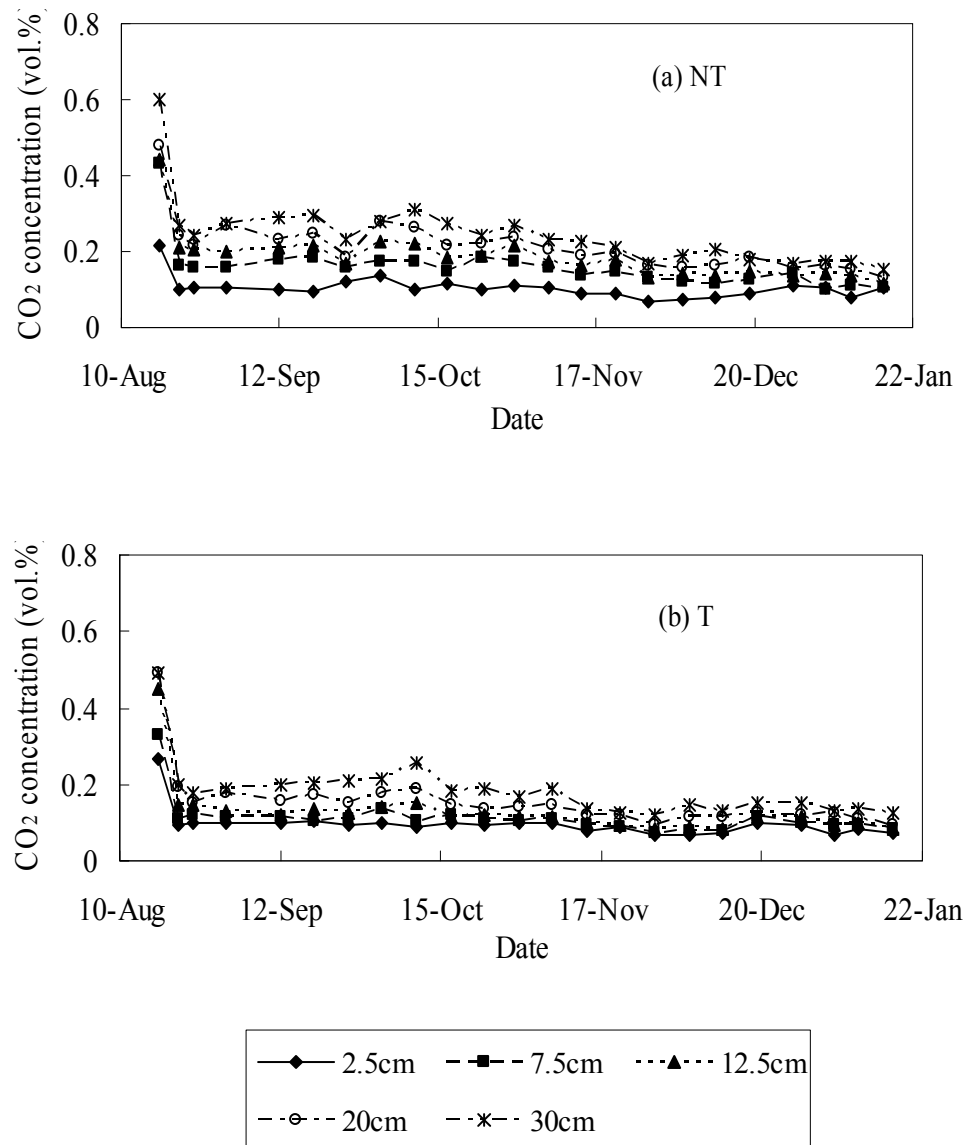


Fig. 33 Temporal variations of soil CO₂ concentration at depths of 2.5, 7.5, 12.5, 20 and 30 cm under NT (a) and T (b) treatments

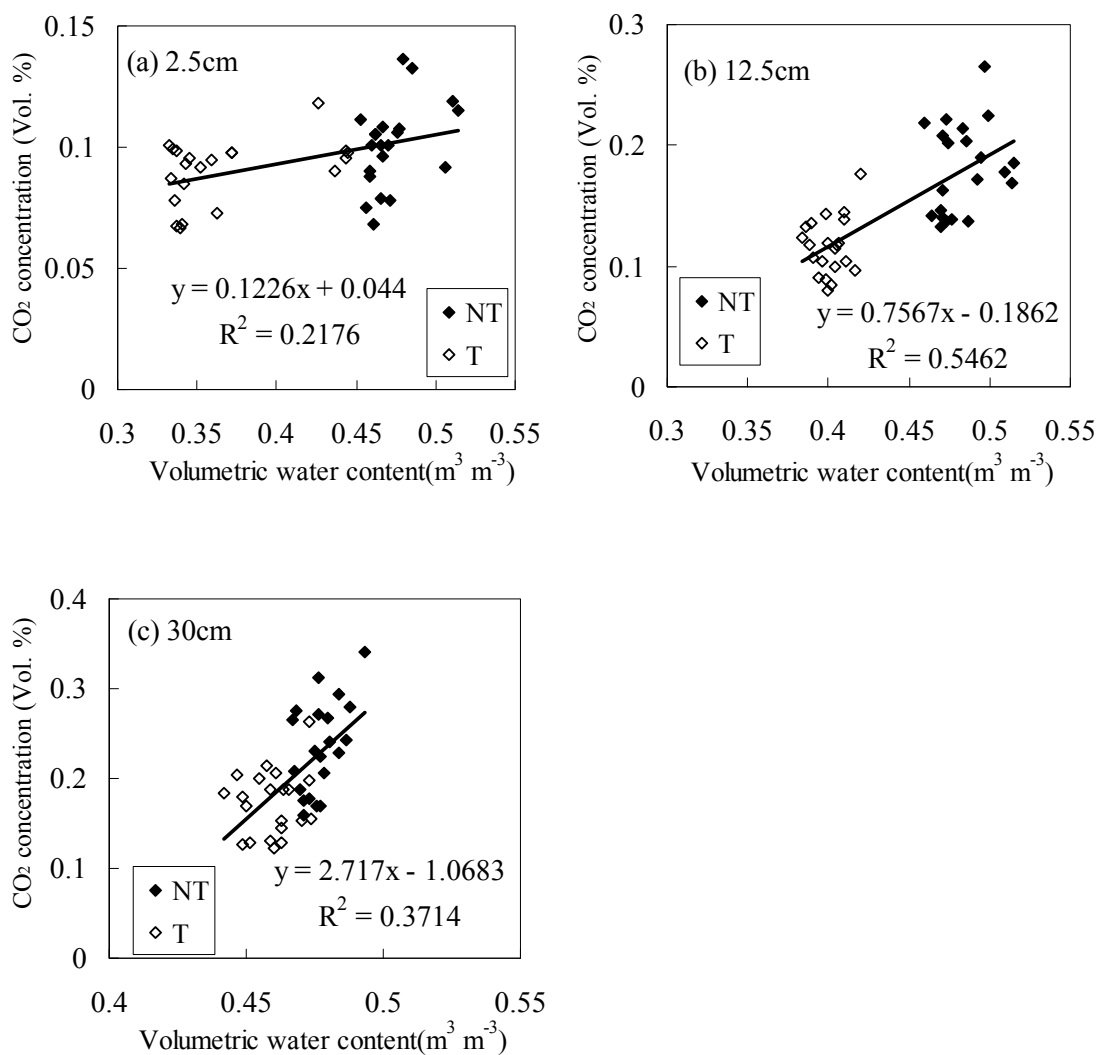


Fig. 34 Relationship between the CO₂ concentration and volumetric water content at depths of 2.5 (a), 12.5 (b) and 30 cm (c) under NT and T treatments

4.4 Relationship between soil carbon dioxide flux and concentration

The CO₂ flux through the soil layers was calculated by using soil CO₂ concentration gradient combined with the gas diffusivity [p.50, Eq. (9); Fig. 35]. The CO₂ flux was greater for shallow layers, since CO₂ flux from the surface soil reflected the CO₂ production of the soil at depths of 0–40 cm. Soil CO₂ flux through the depth of 25 cm consisted of the CO₂ production at depths of 25–40 cm. Therefore, the CO₂ flux was smaller through the depth of 25 cm. In comparison to the deeper layers, the shallower layer exhibited greater variation in the CO₂ flux during the incubation period.

The chamber method usually has been using for assessing the CO₂ flux from the soil surface. However, the circumstances in the chamber are difficult to control during the measurement. Such as, the CO₂ flux is difficult to be precisely measured with the chamber method especially in a rainy day, since the climate conditions are different within and without the chamber in the rainy day. Thus, alternative or supplemental estimations of the CO₂ flux from soils would be beneficial. The estimated CO₂ flux from soil surface showed linear relationship with the measured CO₂ flux, and the correlations were significant ($P < 0.05$) (Fig. 36). A source of errors for this method is that this assumption neglects the soil CO₂ production in 0–2.5 cm deep layer. The shallow soil layer could be active in CO₂ production since soil O₂ level might be high due to gas exchange with the atmosphere. However, with compensation by using monitored CO₂ flux, this method may give the CO₂ flux with acceptable quality. Although some potential errors are found in this method, the result indicated the estimated soil CO₂ flux was closely related to the measured flux under variable moisture conditions. This method can estimate temporal changes in the soil CO₂ flux by using the temporal changes in soil CO₂ concentration and gas diffusivity. Not like surface CO₂

flux measurement, measurements of soil CO₂ concentration and moisture are not considerably affected by climatic conditions, so this method can serve supplemental data to examine CO₂ flux from the soil.

Generally, an increase in soil CO₂ production causes higher soil CO₂ concentration, which leads to more CO₂ emission from the soil (Sey et al., 2007; Vodnik et al., 2009). Kusa et al. (2010) reported that for a Gray Lowland soil, the soil CO₂ production was enhanced during summer due to higher microbial activities. Further, higher CO₂ production resulted in the higher CO₂ concentration and flux from the soil. However, in the present experiment, we observed a higher soil CO₂ concentration and lower CO₂ flux in the soil under the no-tillage treatment, which is not consistent with the result of previous studies. Based on Fick's law of diffusion, the CO₂ flux depends on the CO₂ concentration gradient and the gas diffusivity in the soil. Smaller soil gas diffusivity of the soil under the no-tillage treatment may be the main reason for higher soil CO₂ concentration with lower CO₂ flux. Gas diffusivity of the soil under the tillage treatment is obviously higher than that under the no-tillage treatment, and the higher gas diffusivity promotes soil CO₂ emission and reduces soil CO₂ concentration.

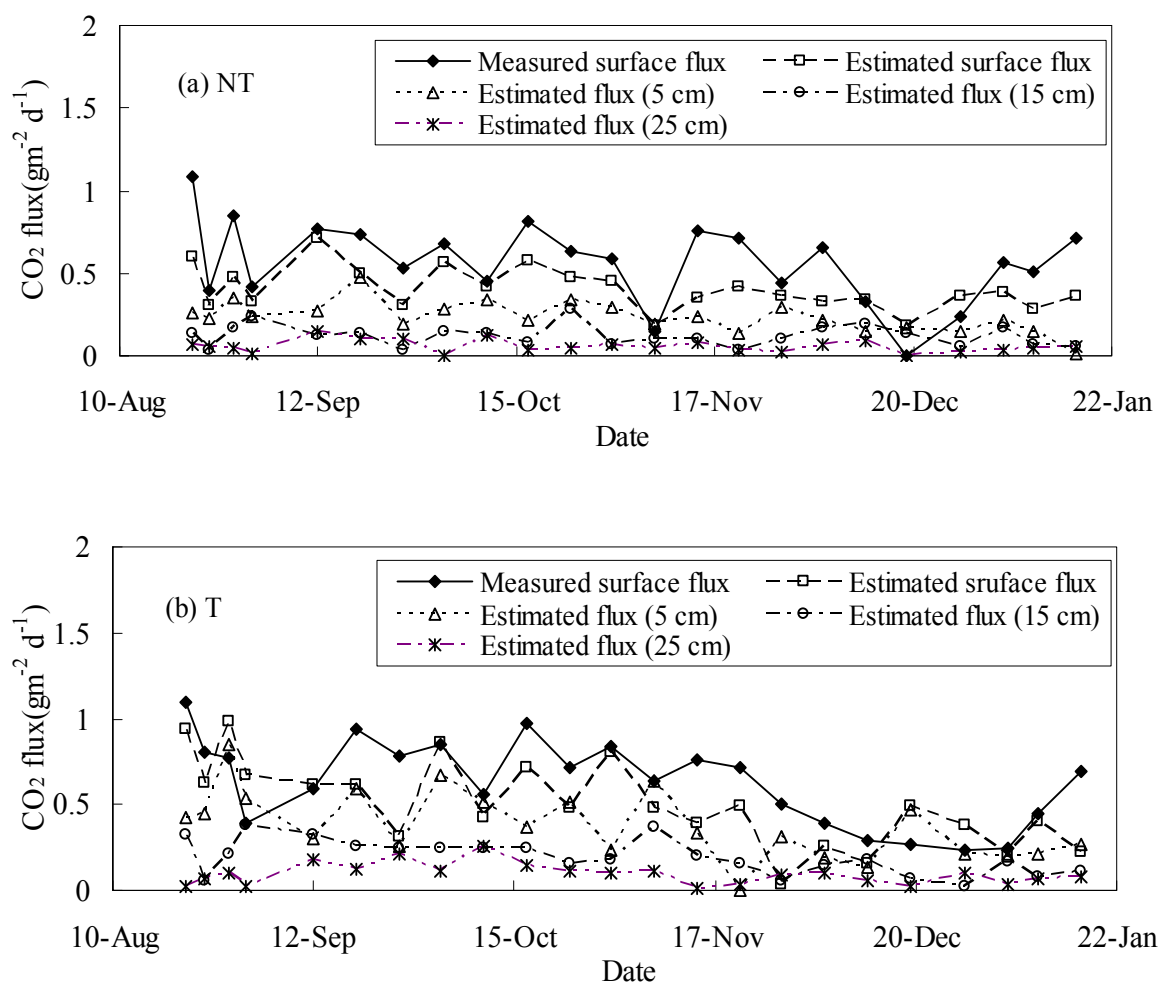


Fig. 35 Soil CO₂ flux from the soil surface and through the soil profile under NT (a) and T (b) treatments

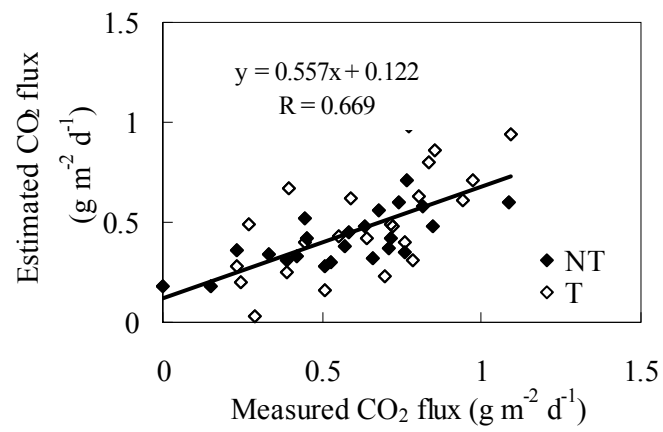


Fig. 36 Relationship between calculated soil surface CO₂ flux and measured soil surface CO₂ flux under NT and T treatments

4.5 Carbon dioxide production in the soil profile

The CO₂ production in soil profile during the 150-d incubation period was estimated as a cumulative difference between the inflow and outflow CO₂ flux at each layer [p.50, Eq. (10)]. The CO₂ production in soil profiles under no-tillage and tillage treatments for different sampling days is shown in Fig. 37. The cumulative CO₂ production for the 150-d incubation was calculated (Fig. 38). The soil CO₂ production at depths of 0–35 cm under the tillage treatment was higher than that under no-tillage treatment.

Soil CO₂ production was different at different depths (Fig. 38). The CO₂ production during the 150 days of incubation for no-tillage and tillage treatments at depths of 0–15 cm was 43.4 and 44.3 g m⁻², respectively, which accounts for 70.5% and 60.4% of the whole CO₂ production of the 0–35 cm soil column, respectively. The result shows that a large portion of CO₂ emitted from the soil to the atmosphere was produced at shallow layers. The compost tends to accumulate on the topsoil for the no-tillage treatment, and for the tillage treatment, the compost is distributed in the tilled layer. For the present experiment, higher carbon content at depths of 0–15 cm was mainly due to compost application, which contributed to more labile carbon decomposition. Since O₂ concentration in the atmosphere is higher than that in the soil, the soil microbes were more active at shallow depths with higher O₂ concentration. Greater CO₂ produced at depths of 0–15 cm for both treatments may also be due to the higher carbon decomposition induced by the active microbial respiration. However, since the compost was left on the surface of the soil under the no-tillage treatment, the organic carbon in the compost was exposed to the O₂ of the atmosphere, which enhanced the mineralization of the carbon. This may result in the higher CO₂ production at depths of

0–5 cm under the no-tillage treatment than that under the tillage treatment. Compared to soil CO₂ production under the no-tillage treatment, higher soil CO₂ production under tillage treatment at depths of 5–15, 15–25 and 25–35 cm was observed. Tillage incorporated the compost to about the depth of 15 cm. Soil organic carbon at depths of 5–15 cm under the tillage treatment was higher than that under the no-tillage treatment. O₂ concentration was higher under the tillage treatment due to the higher gas diffusivity in comparison to the no-tillage treatment. Microbial respiration at depths of 5–35 cm may be more active in the soil under the tillage treatment. Therefore, changes in carbon distribution and microbial respiration rate caused by tillage contributed to the difference in CO₂ production under the two treatments.

The cumulative CO₂ production under the tillage treatment tended to be higher than that under the no-tillage treatment. The no-tillage system has the potential to reduce the CO₂ flux from the Andisol. The rate of soil CO₂ production is affected by activities of microorganisms and resource of carbon supply to microorganisms. Soil microbial activities are governed by the soil conditions (i.e., water, temperature and O₂). The effects of the tillage practice on the soil temperature were minimal in this study, and thus, the temperature was not a limited factor when discussed the difference in the CO₂ production between the two treatments in the present study. As another important factor affecting the soil respiration, soil mass water contents of the two treatments were similar for the two treatments during the incubation period, but the fluctuation of the water content induced by the irrigation contributed to the temporal variation of the CO₂ concentration and gas diffusivity. During the incubation period, the soil gas diffusivity governed by the air-filled porosity was higher under the tillage treatment than that under the no-tillage treatment. High aeration due to high gas diffusivity increased the O₂ level

in the soil, which accelerated the microbial respiration.

Tillage significantly destructed the macroaggregates, and this led to the carbon associated with soil aggregates exposed to microbes and O₂. In the present study, although the carbon inputs for no-tillage and tillage treatments were the same, the available carbon under the tillage treatment might be higher than that under the no-tillage treatment. This might also increase the carbon decomposition in soils and produce more CO₂.

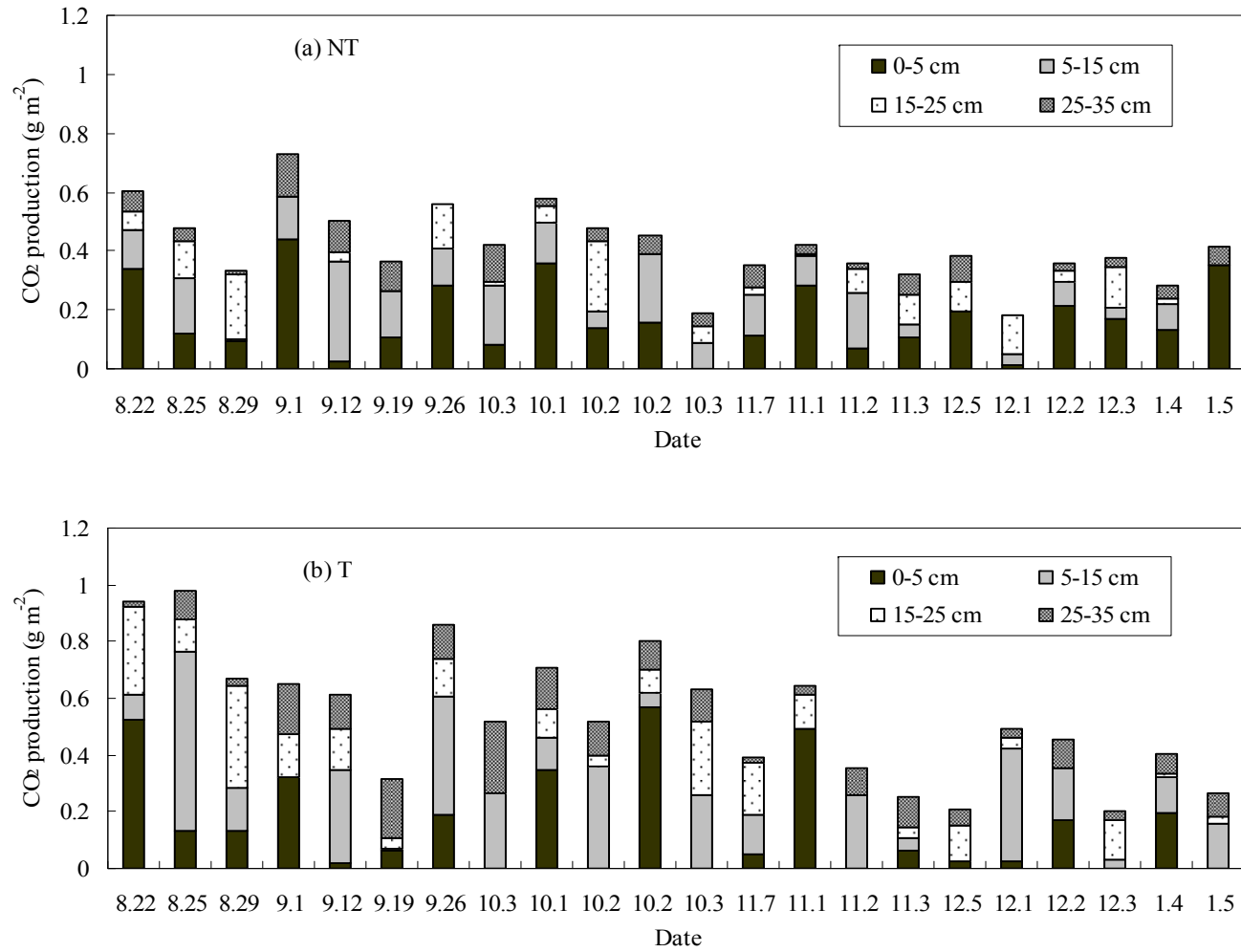


Fig. 37 CO₂ production in soil profiles under NT (a) and T (b) treatments for different sampling days

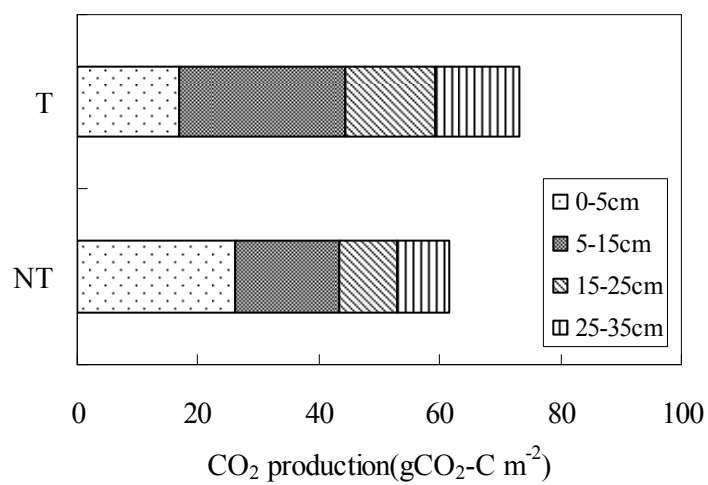


Fig. 38 Cumulative CO₂ production in soil profiles under NT and T treatments during 150 days of incubation

Chapter 5 Effects of tillage depth on behavior of carbon dioxide in soils

The repacked soil column experiment was conducted to study the effects of the tillage depth and soil macropore on soil physical properties, CO₂ flux, CO₂ concentration and soil total carbon. The effects of the depth of tillage on the CO₂ behavior are shown in this chapter.

5.1 Soil physical properties

Soil dry bulk density and saturated hydraulic conductivity were measured under no-tillage (RNT), conventional tillage (RCT) and deep tillage (RDT) treatments. For the conventional tillage, the soil was chiseled to a depth of 15 cm, and the soil was chiseled to a depth of 25 cm for the deep tillage. Soil dry bulk density was significantly affected by the tillage depth (Fig. 39). Soil dry bulk density under the RCT treatment at depths of 0–15 cm was decreased by tillage. However, when the tillage depth increased from 15 cm to 25 cm, lower dry bulk density was observed at depths of 0–25 cm under the RDT treatment. At the sub-layers that were below the chiseled layers, no difference in soil dry bulk density was found among RNT, RCT and RDT treatments.

Since the soil column under the no-tillage treatment was homogeneous, similar soil saturated hydraulic conductivity was observed for each layer (Fig. 40). Soil saturated hydraulic conductivity was increased by tillage, therefore, higher soil saturated hydraulic conductivity was observed at depths of 0–15 cm for the RCT treatment and 0–25 cm for the RDT treatment. No difference in soil saturated hydraulic conductivity was observed below the chiseled layer under the three treatments. The deeper the soil is disturbed, the greater the soil displacement in the direction of tillage

occurred, and hence, soil physical properties are significantly affected by the tillage depth (Sarkar and Singh, 2007). In the present study, soil dry bulk density and saturated hydraulic conductivity were significantly affected by the depth of tillage. Therefore, the CO₂ behavior in the soil profile that affected by soil physical properties may be changed with the depth of tillage.

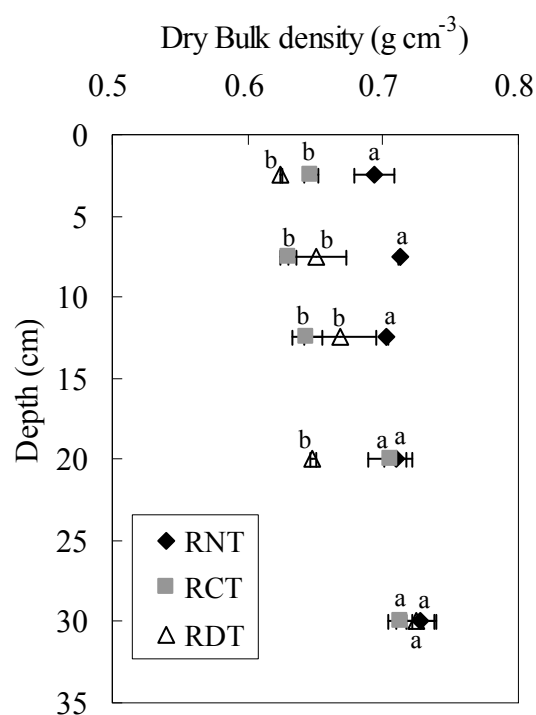


Fig. 39 Soil dry bulk density under RNT, RCT and RDT treatments. Significant differences among treatments are indicated with different letters (P<0.05, n=3)

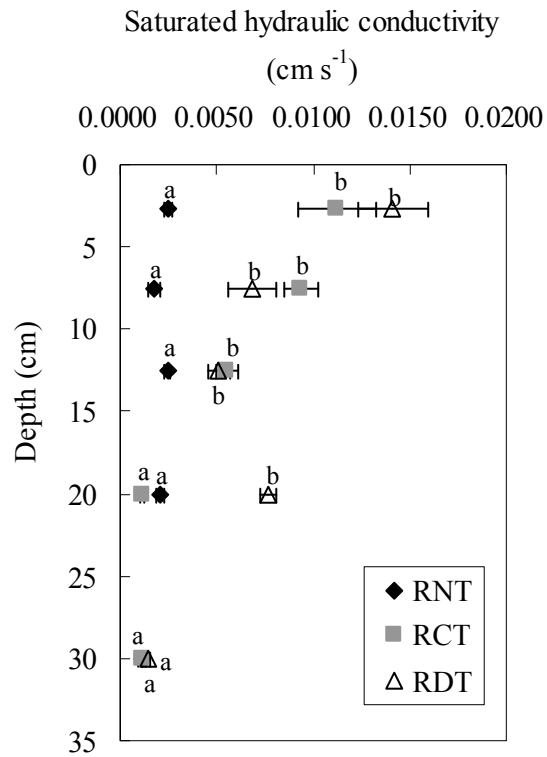


Fig. 40 Soil saturated hydraulic conductivity under RNT, RCT and RDT treatments. Significant differences among treatments are indicated with different letters ($P < 0.05$, $n=3$)

5.2 Soil carbon dioxide flux

Soil CO₂ flux under the three treatments is shown in Fig. 41a. At the first day after tillage, the CO₂ flux under the deep tillage treatment was distinctly higher in comparison to the other two treatments, followed by that under the conventional tillage treatment. The CO₂ flux under the no-tillage treatment was the lowest. The CO₂ flux at the first day under RNT, RCT and RDT was 0.122, 0.655 and 1.657 g CO₂-C m⁻² d⁻¹, respectively, suggesting the CO₂ flux of the first day was related to the depth of tillage. Tillage increased the CO₂ flux from soil at the first day of the incubation, since the CO₂ in soil pores was quickly released to the atmosphere after tillage. In addition, tillage led to the quick exchanging of the air between the soil and the atmosphere, which might temporally increase the O₂ concentration in the soil. Soil microbial respiration could be accelerated under the higher O₂ concentration, and this might increase the CO₂ production. The influence of tillage on soil CO₂ flux at the first day was related to the volume of soil disturbed by tillage, and thus, the CO₂ flux at the first day was clearly affected by the tillage depth.

After the first day, no clear difference in the CO₂ flux was found among the three treatments. Soil CO₂ flux for RNT, RCT and RDT treatments fluctuated in the ranges of 0.012–0.649, 0.035–0.761 and 0.081–0.994 g CO₂-C m⁻² day⁻¹, respectively.

During the 150-d incubation, the cumulative CO₂ flux for RNT, RCT and RDT treatments was 53.37, 59.71 and 63.11 g CO₂-C m⁻², respectively. The RDT treatment tended to show the highest cumulative CO₂ flux and the RNT treatment showed the lowest (Fig. 41b). Soil properties, such as the gas diffusivity and aggregation, considered as important factors to influence the soil CO₂ flux were affected by the depth of tillage. Therefore, soil cumulative CO₂ flux was influenced by

the depth of tillage.

Reicosky and Archer (2007) evaluated the effects of various methods of strip tillage on the CO₂ loss from an loam soil, and the results indicated that the cumulative CO₂ loss under different tillage treatments (tillage depth of 0.102, 0.152, 0.203 and 0.280 m) were 3.8, 6.7, 8.2, and 10.3 times larger than that under the no-tillage treatment. Positive linear correlation was observed between soil CO₂ flux and the tillage depth. Chatskikh et al. (2008) reported the soil CO₂ flux under the reduced tillage treatment (the tillage depth of 8–10 cm) was 29% lower than that under the conventional tillage treatment in an Anthric Umbrisol. These results of previous studies are similar to that obtained by this study, but no positive linear correlation was observed in this study. However, Alvaro-Fuentes et al. (2008) reported that the CO₂ flux was similar between the conventional tillage (the tillage depth of 40 cm) and the subsoil tillage (the tillage depth of 25 cm) treatments, since the conventional tillage treatment was lack of soil inversion.

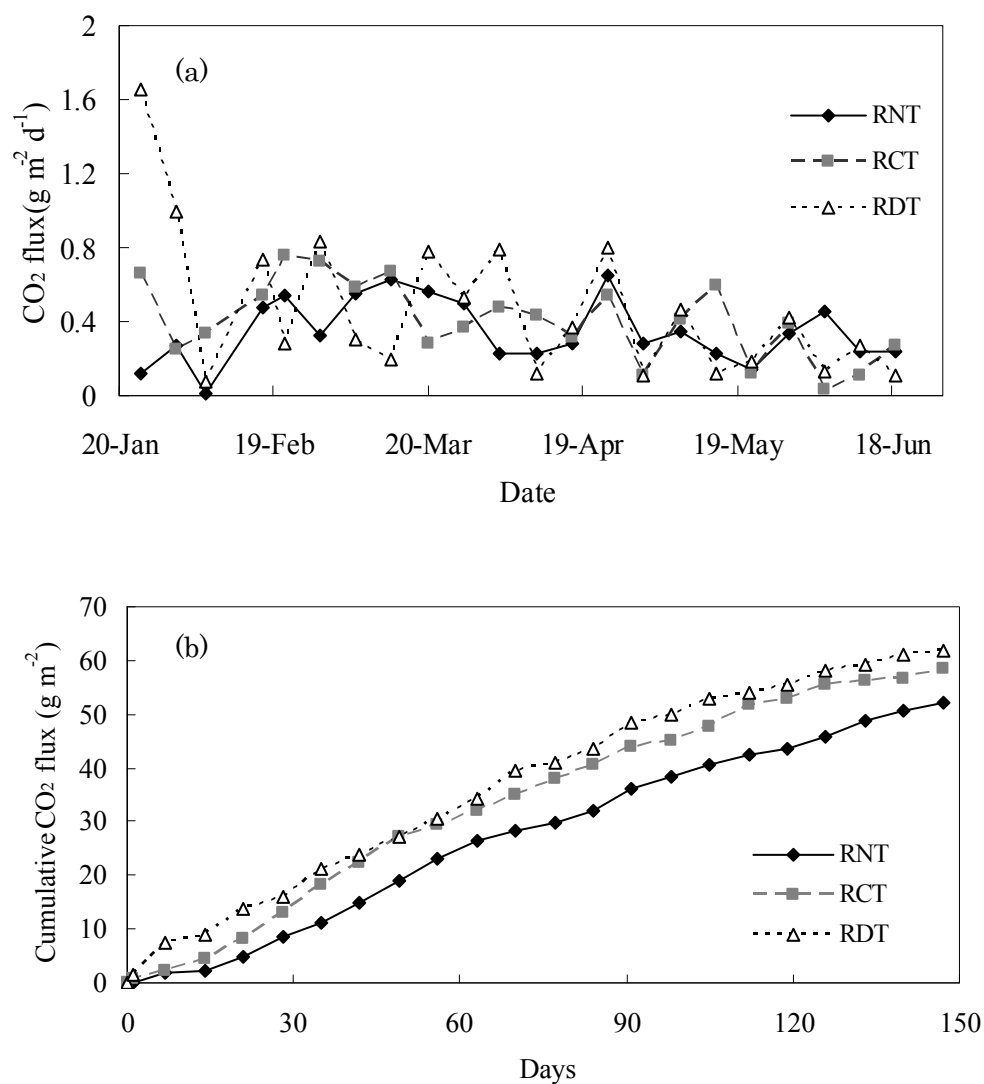


Fig. 41 Soil CO₂ flux (a) and cumulative CO₂ flux (b) under RNT, RCT and RDT during 150 days of incubation

5.3 Distribution of carbon in the soil profile

Tillage depth affected distributions of the total carbon in soil profiles, since tillage incorporate the manure of the topsoil into the deep soil. The soil columns were repacked homogenously, and thus, the total carbon was evenly distributed in the soil profile before tillage (Fig. 42). The leaf compost was applied to the soil at depths of 0–5 cm before tillage operation was conducted, and this increased the carbon content of the soil at depths of 0–5 cm.

After incubation, soil total carbon contents at depths of 0–5 cm under RNT, RCT and RDT treatments were 57.75, 55.36 and 54.08 g kg⁻¹, respectively, and at depths of 25–35 cm, the total carbon contents were 53.52, 53.64 and 53.29 g kg⁻¹, respectively. Due to the application of the leaf compost, carbon content of the topsoil (0–5 cm) under the no-tillage treatment was greater than that of deeper soils. Under the RCT treatment, tillage redistributed the leaf compost throughout the entire chiseled layer (0–15 cm), which resulted in a decrease in the soil carbon content at depths of 0–5 cm. Similarly, under the RDT treatment, soil carbon was incorporated into the soil at depths of 0–25 cm. However, since the soil was chiseled to a depth of 15 or 25 cm but not fully overturned, the distributions of total carbon in soils at chiseled layers were not homogeneous. No clear difference in total carbon content was observed below the chiseled layer among the three treatments.

Soil cumulative CO₂ flux tended to show as RDT>RCT>RNT, implying an increase in the depth of tillage has the potential to increase the carbon decomposition in the soil. However, no difference in the carbon stock among the three treatments was observed. Soil carbon stocks at depths of 0–35 cm under RNT, RCT and RDT treatments were 13.20, 13.15 and 13.09 kg m⁻², respectively (Fig 43). This result is

similar to that of the undisturbed soil experiment, and two main reasons may contribute to the result. First, the carbon loss induced by the soil CO₂ flux during the 150 days of incubation was extremely small in comparison to the carbon stocks in the soil. Second, the leaf compost for the no-tillage treatment was distributed on the top layer (0–5 cm for the present study), and the organic carbon could easily contact with the O₂ in the atmosphere to be decomposed.

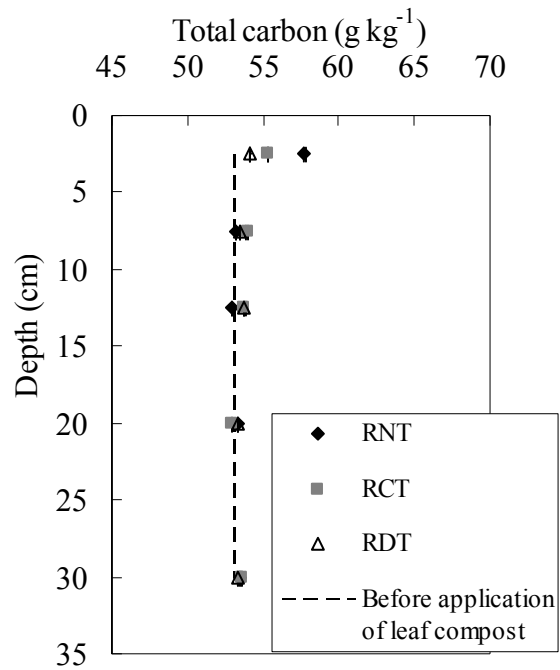


Fig. 42 Distributions of the total carbon in soil profiles under RNT, RCT and RDT treatments

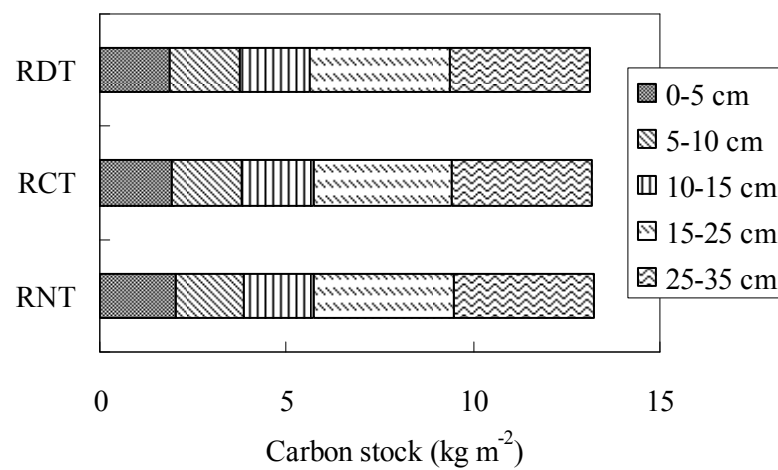


Fig. 43 Soil carbon stocks under RNT, RCT and RDT treatments

5.4 Distribution and temporal variation of carbon dioxide concentration in the soil profile

Distributions of the CO₂ concentration in soil profiles under RNT, RCT and RDT treatments are shown in Fig. 44. Soil CO₂ concentration increased with the depth in the soil profile for all the treatments. We found that both the CO₂ concentration and the CO₂ concentration gradient in repacked soils were smaller than that in undisturbed soils. During sampling and repacking the soil, CO₂ stored in the soil was released to the atmosphere, which led to a decrease in the CO₂ concentration in repacked soils.

Temporal variations of the CO₂ concentration in soil profiles are shown in Fig. 45. As an important factor of the CO₂ production, the temperature was controlled at 30°C for daytime during the incubation period. The variations of soil CO₂ concentration during the incubation period were mainly attributed to the changing water contents following the irrigation of every five days.

No clear difference in the CO₂ concentration among RNT, RCT and RDT treatments at shallow layers (2.5 and 7.5 cm) was observed. At shallow layers, soil CO₂ concentration was considerably affected by the CO₂ concentration of the air in the atmosphere, since the air in the soil quickly exchanged with the air in the atmosphere, and hence, no clear difference in the CO₂ concentration among treatments was observed. Average CO₂ concentration was the highest under the RNT treatment, and was the lowest under the RDT treatment at depths of 20 cm and 30 cm. At deeper layers, soil CO₂ concentration is much related to soil gas diffusivity. As shown in Fig. 46, the soil gas diffusivities after the incubation period were predicted by using the BBC model. Soil gas diffusivities were affected by the depth of tillage. At depths of 0–15 cm, soil gas diffusivities under RCT and RDT treatments were distinctly higher

than that under the RNT treatment. At depths of 15–25 cm, soil gas diffusivity under RDT treatment was higher than that under RCT and RNT treatments, since the tillage depth for the RDT treatment was 25 cm. Tillage enhanced the soil air-filled porosity and gas diffusivity, and thus, soil CO₂ concentration at deeper layers was decreased by tillage. Soil CO₂ concentration was affected by the depth of tillage, and the lowest CO₂ concentration was observed under the deep tillage treatment.

In general, the depth of tillage is a factor affecting the CO₂ behavior (i.e., CO₂ flux and diffusion) in the soil. The difference in the tillage depth may be responsible to the variations in the results of soil CO₂ flux under different tillage systems reported by previous studies. In addition, since the carbon distribution in the soil profile is affected by the tillage depth, the soil sampling for evaluating the carbon store should be conducted after considering the tillage depth.

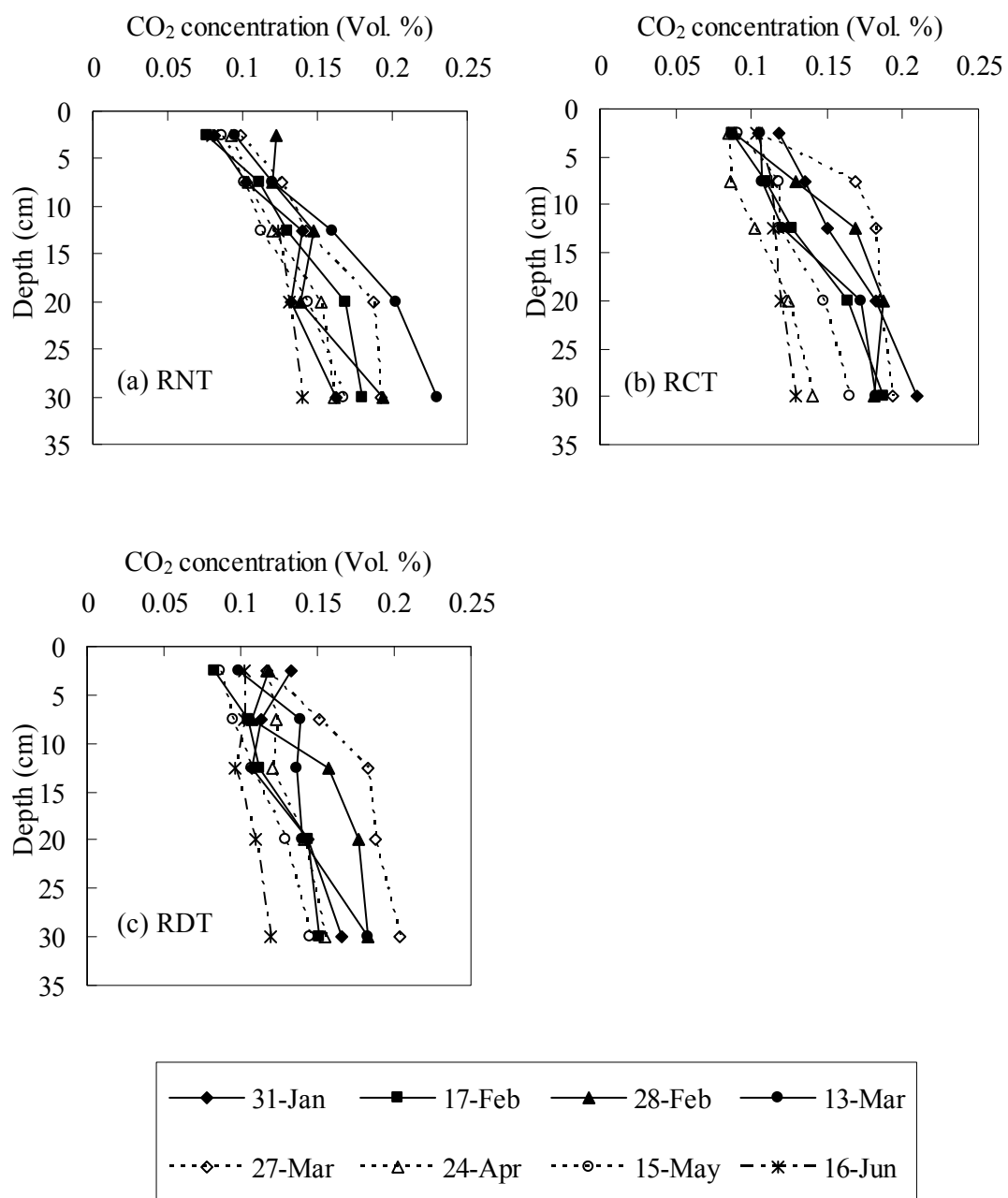


Fig. 44 Distributions of the CO₂ concentration in soil profiles under RNT (a), RCT (b) and RDT (c) treatments

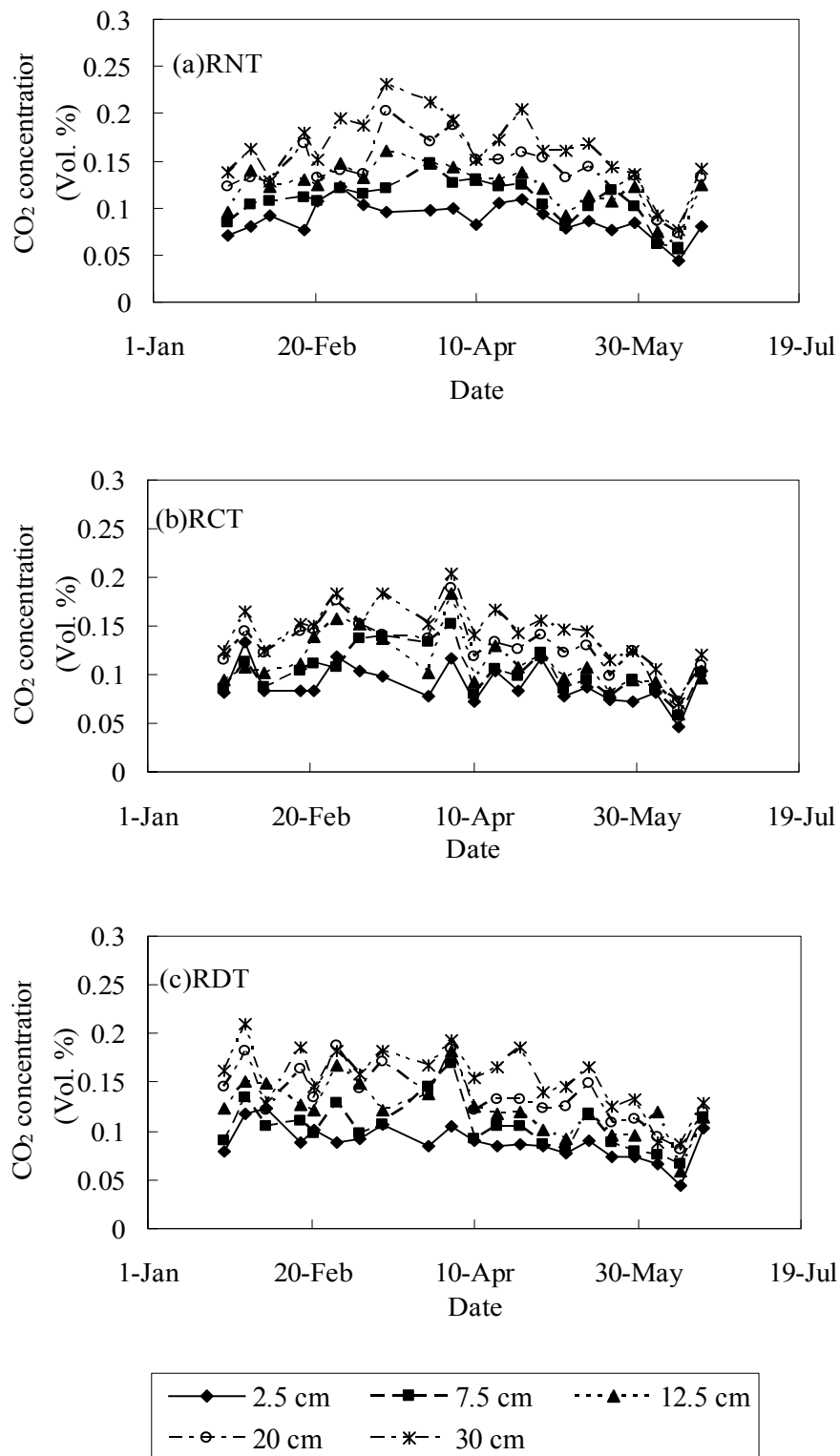


Fig. 45 Temporal variations of soil CO₂ concentration under RNT (a), RCT (b) and RDT (c) treatments

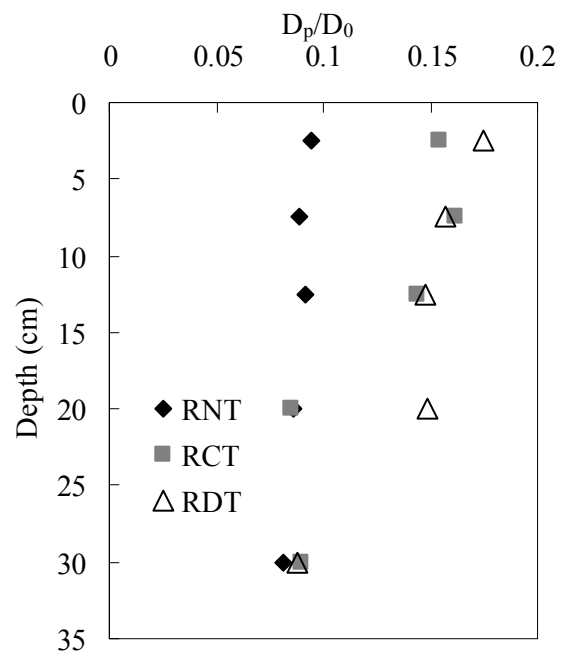


Fig. 46 Predictive soil gas diffusivities under RNT, RCT and RDT treatments. The data were estimated by the BBC model

Chapter 6 Effects of the macropore on behavior of carbon dioxide in soils under different tillage systems

6.1 Soil physical properties

Dry bulk density and saturated hydraulic conductivity of the repacked soils under no-tillage (RNT), no-tillage-with macropore (RNT-M) and conventional tillage-with macropore (RCT-M) treatments were measured. For the RNT-M treatment, the soil with a macropore (the diameter of 3 mm) was not applied any tillage practice. For the RCT-M treatment, the soil was chiseled to a depth of 15 cm, and hence, the soil macropore at depths of 0–15 cm was destroyed. No difference in soil dry bulk density was found between RNT and RNT-M treatments. Due to tillage, soil dry bulk density under the RCT-M treatment was clearly lower than that under RNT and RNT-M treatments at depths of 0–15 cm (Fig. 47).

Tillage increased soil saturated hydraulic conductivity at the chiseled layer, and hence, the saturated hydraulic conductivity at depths of 0–15 cm under the RCT-M treatment was higher than that under RNT and RNT-M treatments (Fig. 48). At deeper layers (15–35 cm), no difference in soil saturated hydraulic conductivity was observed. The dry bulk density and saturated hydraulic conductivity were measured by using the soil cores sampled from the area without the macropore. Therefore, similar soil dry bulk density and saturated hydraulic conductivity were observed between the no-tillage soils with the macropore and without macropore. Since the soil physical properties played important roles in the soil respiration, the effects of the macropore on soil physical conditions are required to be observed in the further study.

Iversen et al. (2012) reported that a strong relationship was found between the

macropore density and the soil saturated hydraulic conductivity. But a poor relationship was found between the macropore density and the hydraulic conductivity in the unsaturated soil. The soils were unsaturated during the incubation period in the present study. Even after irrigation, no ponds were observed on the surface of the soil columns. Although the macropore was reported to contribute to the rapid movement of the water in the soil column (Rawls et al., 1996), the effects of the macropore in the present study might be not so obvious.

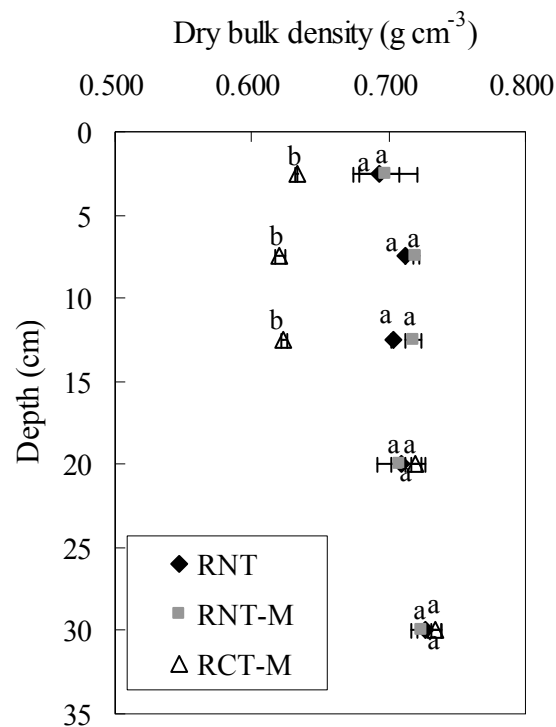


Fig. 47 Soil dry bulk density under RNT, RNT-M and RCT-M treatments. Significant differences among treatments are indicated with different letters ($P < 0.05$, $n=3$)

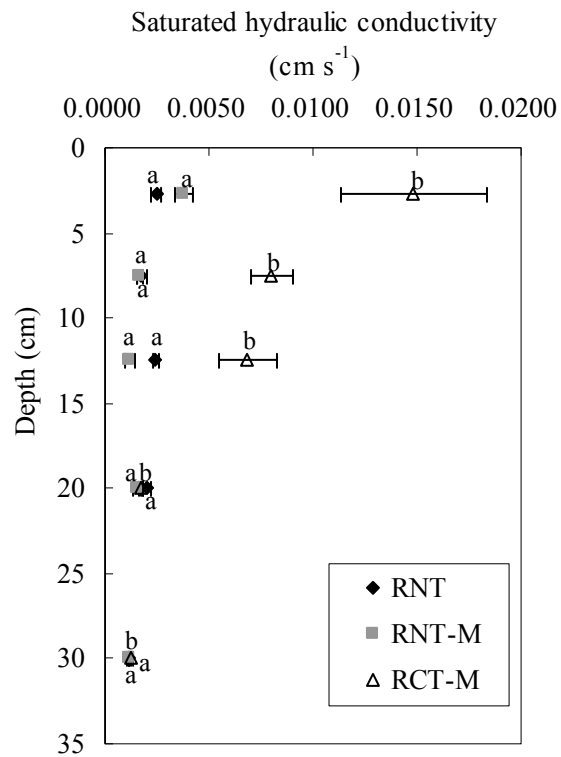


Fig. 48 Soil saturated hydraulic conductivity under RNT, RNT-M and RCT-M treatments. Significant differences among treatments are indicated with different letters ($P < 0.05$, $n = 3$)

6.2 Soil carbon dioxide flux

Soil CO₂ flux was measured under RNT-M, RCT-M and RNT treatments (Fig. 49a). No obvious difference in soil CO₂ flux was observed except the first day. The average soil CO₂ flux (except the first day) under RNT, RNT-M and RCT-M treatments was 0.356, 0.377 and 0.406 g CO₂-C m⁻² d⁻¹, respectively. Owing to tillage, soil CO₂ flux under the RCT-M treatment was higher than that under RNT-M and RNT treatments at the first day.

The RCT-M treatment tended to show higher soil cumulative CO₂ flux than RNT-M and RNT treatments (Fig. 49b). The cumulative CO₂ flux under RNT, RNT-M and RCT-M was 53.37, 56.46 and 60.96 g CO₂-C m⁻², respectively. Soil cumulative CO₂ flux under the RNT-M treatment was slightly higher than that under the RNT treatment. However, in comparison to the difference in the CO₂ flux between no-tillage and tillage treatments, the difference between the soil with macropore and without macropore was small. The gas transport in the soil with macropores is higher in comparison to the homogeneous soil (Brito et al., 2009). Microbial respiration is accelerated by the increased O₂ concentration, and thus, CO₂ production may increase. However, an increase in the CO₂ emission owing to the macropore was extremely small in this study. The possible reason is that the volume of the macropore is so small in comparison to the total pore volume in the soil, since the Andisol has the unique characteristic of a high porosity. In the present study the macropore just increased the air-filled porosity by about 0.21%. Although tillage destroyed the macropore, the cumulative CO₂ flux of the soil with macropore tended to be increased by tillage.

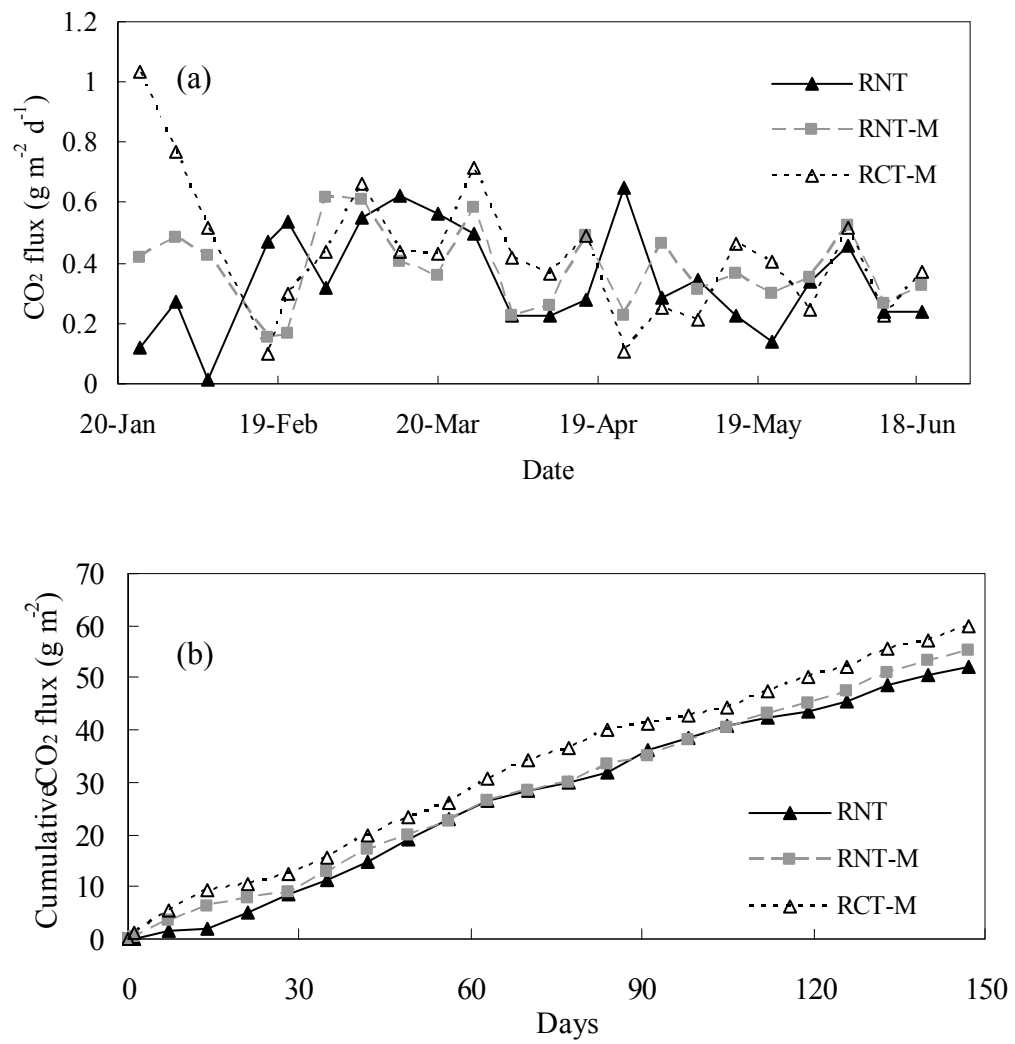


Fig. 49 Soil CO_2 flux (a) and cumulative CO_2 flux (b) under RNT, RNT-M and RCT-M treatments during 150 days of incubation

6.3 Distribution of carbon in the soil profile

Before applying the leaf compost and conducting the tillage operation, the carbon was evenly distributed in the soil profile (Fig. 50). After the incubation experiment, total carbon contents of the topsoil (0–5 cm) under RNT and RNT-M treatments were greater than that of the deeper layers, since the leaf compost was applied to the soil at depths of 0–5 cm. The distributions of the carbon in soil profiles under RNT and RNT-M were similar. Tillage incorporated the leaf compost into the depths of 0–15 cm, which led to an increase in the soil total carbon at depths of 0–15 cm under the RCT-M treatment. No clear difference was found among the three treatments at depths of 15–35 cm. The distributions of the carbon content in the soil profile were affected by the tillage practice, but not the macropore.

Soil carbon stocks under the three treatments are shown in Fig. 51. The CO₂ cumulative flux from the soil under different treatments tended to show as RNT < RNT-M < RCT-M. However, the carbon stocks for RNT, RNT-M and RCT-M treatments were 13.20, 13.12 and 13.07 kg m⁻², respectively. No distinct difference among the three treatments was observed. The reason was similar to the case of undisturbed soils that has been discussed in Chapter 3, and long-term experiments are required to study the effects of the macropore on the carbon stock.

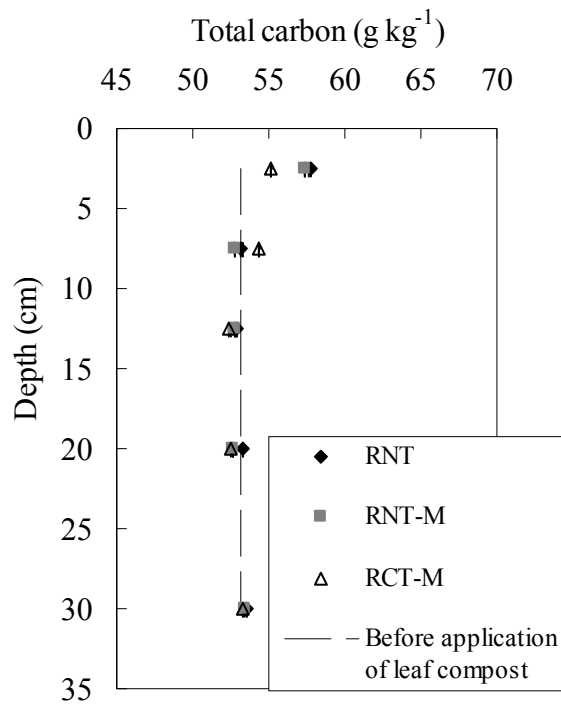


Fig. 50 Distributions of total carbon in soil profiles under RNT, RNT-M and RCT-M treatments

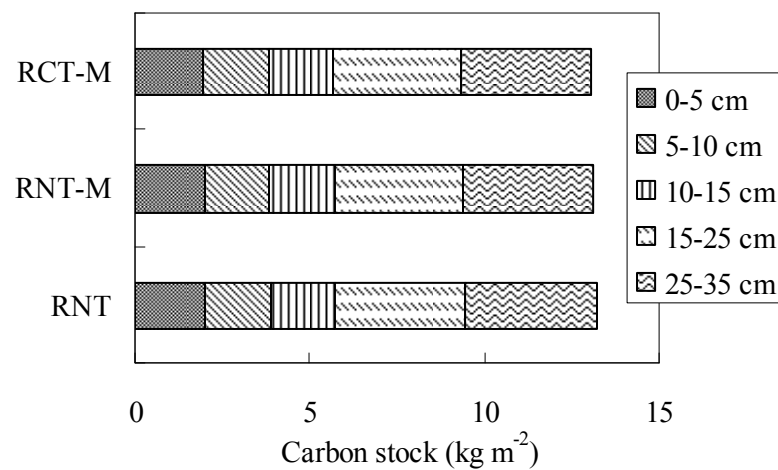


Fig. 51 Soil carbon stocks under RNT, RNT-M and RCT-M treatments

6.4 Distribution and temporal variation of carbon dioxide concentration in the soil profile

The distributions and temporal variations of the CO₂ concentration the soil profiles during the 150 days of incubation are shown in Fig. 52 and Fig. 53. Soil CO₂ concentration increased with depth under RNT, RNT-M and RCT-M treatments, and this tendency was the most distinct for the RNT treatment. No noticeable rise or decline in soil CO₂ concentration was observed during the incubation period for the three treatments.

The CO₂ concentration for RNT, RNT-M and RCT-M treatments at a depth of 2.5 cm was 0.088%, 0.084% and 0.085%, respectively. No distinct difference in the CO₂ concentration was observed at the depth of 2.5 cm, since the CO₂ concentration was considerably related to the CO₂ concentration of the air in the atmosphere. But at the deeper layers (7.5, 12.5, 20 and 30 cm), the CO₂ concentration under the RNT (i.e., 0.107%, 0.121%, 0.140%, 0.161%) was higher than that under the RNT-M (i.e., 0.096%, 0.111%, 0.134%, 0.149%), and the CO₂ concentration was the lowest under the RCT-M (i.e., 0.092%, 0.105%, 0.116%, 0.128%) treatment.

The CO₂ concentration in the no-tillage soil with a macropore (RNT-M) was lower than that in the no-tillage soil without macropore (RNT) except at the depth of 2.5 cm. Dziejowski et al. (1997) observed the higher O₂ concentration in the soil column with a macropore compared to that in the homogeneous soil column. He suggested that the macropore in the soil increased the gas transport between the soil and the atmosphere. Since the CO₂ concentration in the soil was higher than that in the atmosphere, the macropore in the soil might decrease soil CO₂ concentration. Therefore, in comparison to the RNT treatment, lower soil CO₂ concentration under

the RNT-M treatment was observed in the present study. But compared to the effects of the macropore, the effects of tillage on the CO₂ behavior were much obvious.

The lowest CO₂ concentration was observed under the RCT-M treatment, and this was due to the higher soil gas diffusivity. Soil gas diffusivity under the RCT-M treatment was higher than that under RNT and RNT-M treatments at depths of 0–15 cm (Fig. 54). Although the tillage practice destroyed the macropore in soil, it increased the soil CO₂ diffusion. For RNT and RNT-M treatments, no difference in the soil gas diffusivity estimated by the BBC model was observed, implying that the soil air-filled porosity increased by the macropore was minimal. However, in comparison to the RNT treatment, the lower CO₂ concentration under the RNT-M treatment was observed. The result suggests that the gas diffusion governed by the air-filled porosity was not the only mechanism of the gas transport in the soil with a macropore.

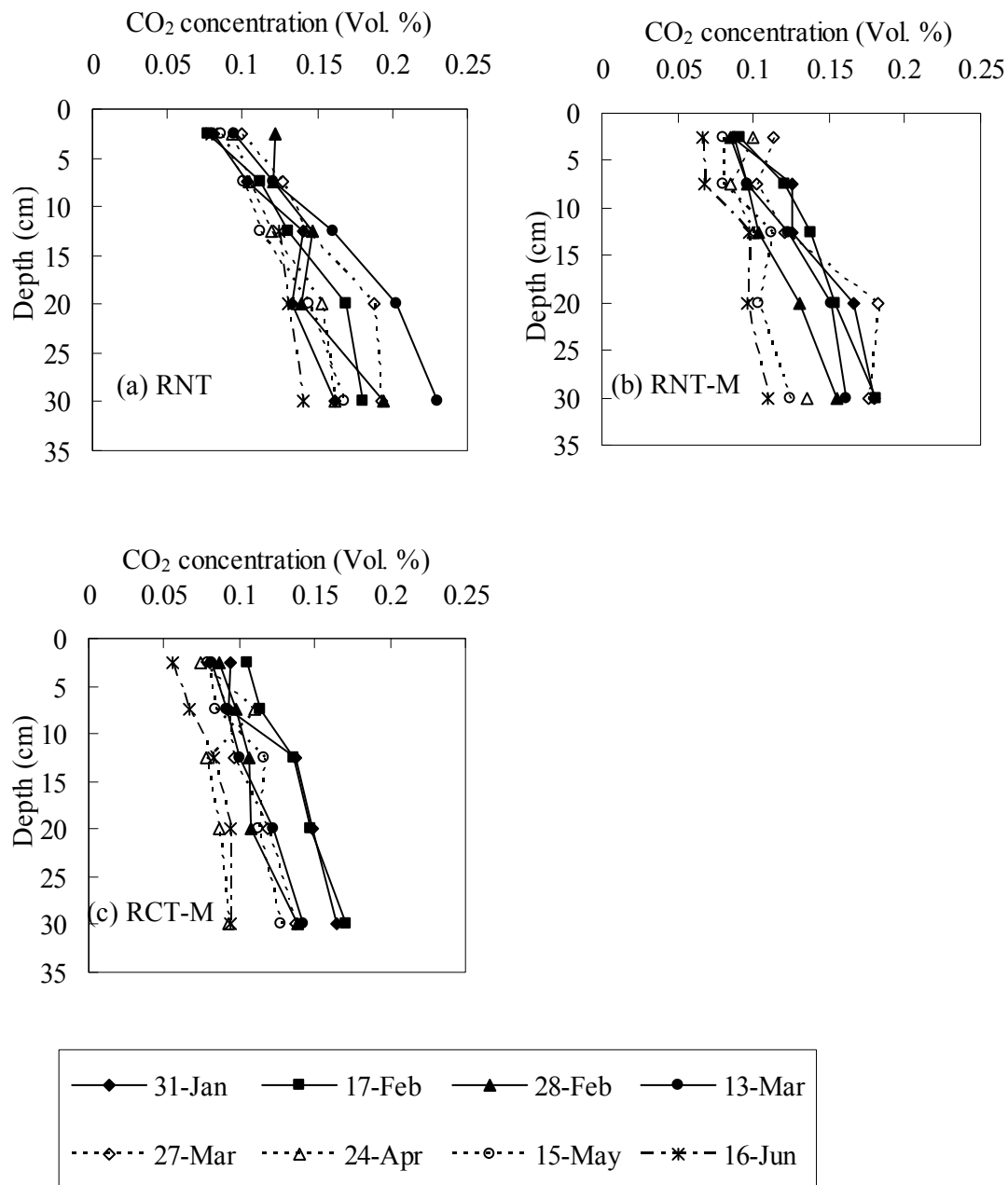


Fig. 52 Distributions of CO₂ concentration in soil profiles under RNT (a), RNT-M (b) and RCT-M (c) treatments

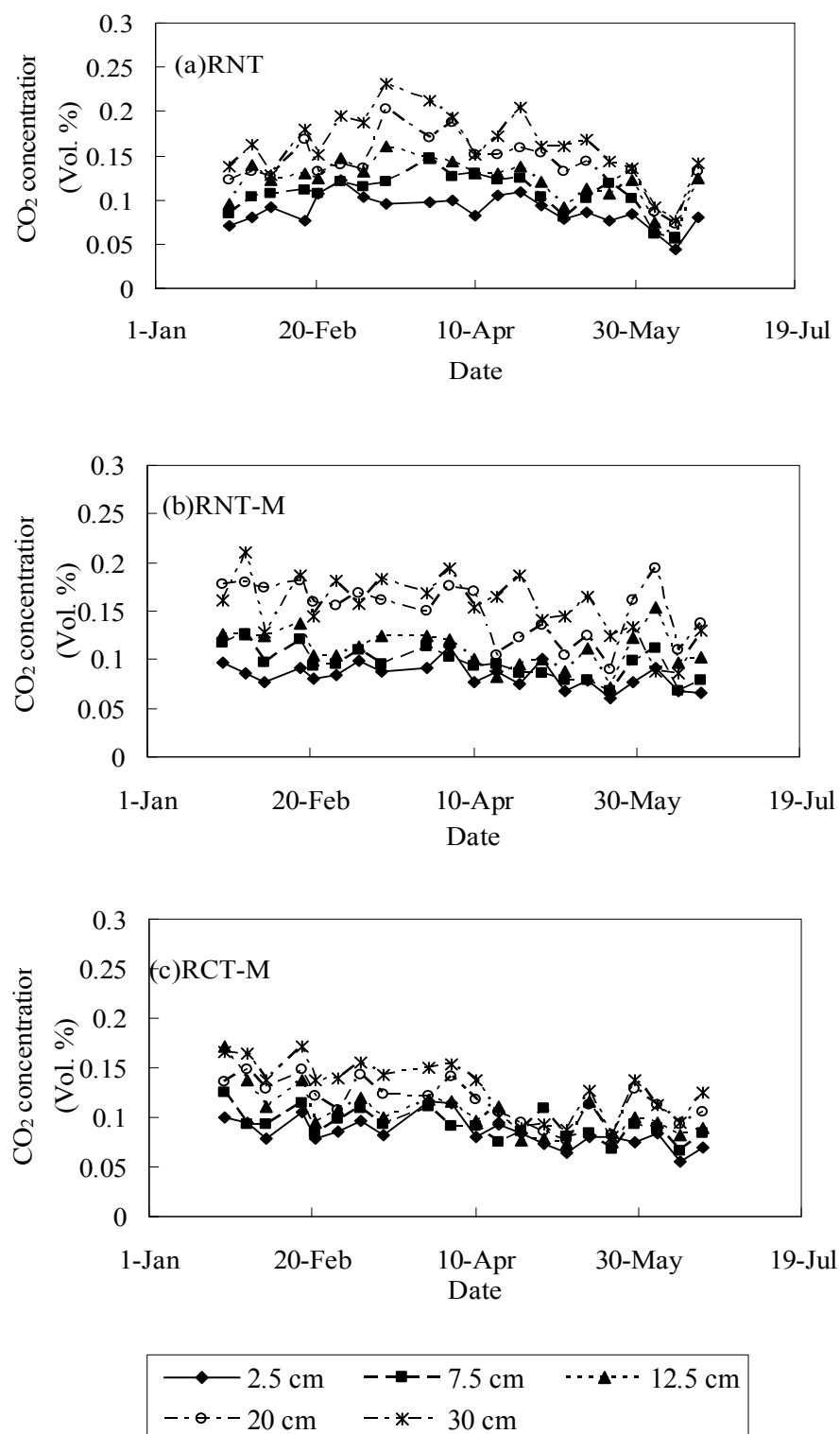


Fig. 53 Temporal variations of soil CO₂ concentration under RNT (a), RNT-M (b) and RCT-M (c) treatments

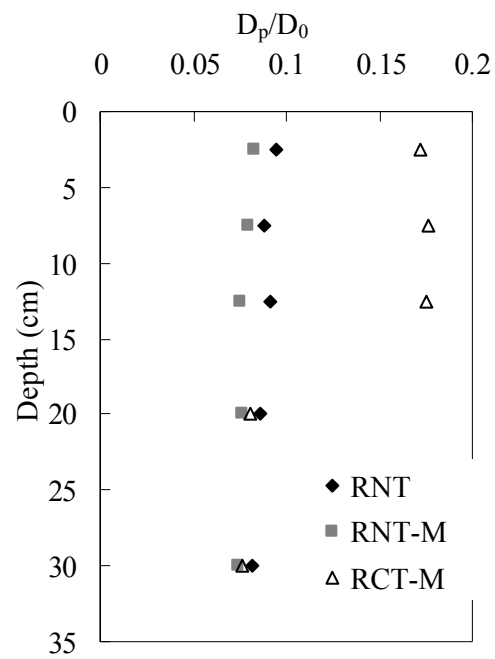


Fig. 54 Predictive soil gas diffusivities under RNT, RNT-M and RCT-M treatments.

The data were estimated by the BBC model

6.5 Soil gas diffusivity affected by the macropore

The soil gas diffusivity under the RNT-M treatment could be considered as the total gas diffusivity consisted of that in the soil and in the macropore:

$$D_p' = D_0 v_0 + D_p v_p \quad (15)$$

where the D_p' is the soil gas diffusivity under RNT-M treatment ($\text{m}^2 \text{s}^{-1}$), D_0 is the gas diffusivity in the free air ($\text{m}^2 \text{s}^{-1}$), v_0 is the volume fraction of the macropore, D_p is the gas diffusivity in the soil ($\text{m}^2 \text{s}^{-1}$), and v_p is the volume fraction of the air-filled pores.

The volume of the macropore accounts for only 0.21% of the total air-filled porosity, and hence, the contribution of the macropore to the gas diffusivity could be neglected. Therefore, the calculated gas diffusivity by using the gas diffusivity model under the RNT-M treatment was similar to that under the RNT treatment (Fig. 54). The soil gas diffusivity can also be evaluated by the CO_2 concentration gradient and the CO_2 flux with Fick's law [p.50, Eq. (9)]. The mean relative gas diffusivities under the RNT and RNT-M treatments were 0.13 and 0.15, showing the gas diffusivity under the RNT-M treatment was higher than that under the RNT treatment.

The controversial results imply that there were alternative mechanisms of the gas transport except the diffusion in the soil through macropores. Dziejowski et al. (1997) observed the preferential flow of O_2 in soils with macropores. He suggested that the O_2 concentration was clearly increased due to the preferential flow caused by macropores. In comparison to the soil without macropore, the preferential flow might be an important mechanism of the gas transport in the soil with a macropore. For the present study, the lower soil CO_2 concentration was observed under the RNT-M in

comparison to the RNT treatment.

The result showed that the effects of the macropore on the CO₂ behavior (flux and diffusion) were smaller than that of the tillage practice in the present study. However, the study was conducted with the soil column with one artificial macropore. Suppose to study on the soil with several macropores, the effects of macropores on the CO₂ behavior may be more obvious in comparison to the case of the present study. Since tillage destroyed the macropores in the soil, the effects of tillage on the CO₂ behavior may offset the effects of the macropore. And hence, no significant difference in the CO₂ flux from the soil with macropores may be observed between no-tillage and tillage systems.

But the effects of soil macropores on the behavior of CO₂ are not fully understand. The present study only observed the effects of the macropore on soil CO₂ flux and concentration, and the studies on the effects of the macropores on soil physical conditions and other CO₂ behavior are required. The situation of the soil with a straight macropore was studied in the present study, but the size and distribution of the artificial macropore were different from that in the field soil. In future experiments the CO₂ behavior of soils with various macropore distributions are required.

Chapter 7 Summaries and conclusions

Global warming caused by an increase in the greenhouse gas concentrations in the atmosphere is one of the significant threats for a sustainable development. Agricultural managements have a potential to enhance or restrict the greenhouse gas emission from soils. Tillage plays an important role in agricultural production, and the effects of tillage on soil CO₂ behavior have been studied in this paper. Although many studies reported the effects of tillage on the CO₂ flux from different types of soils, contradictory results have been observed from these studies. We also found that the studies on the CO₂ behavior (except the CO₂ flux), such as transport and production are limited. The effects of tillage on the CO₂ behavior are not fully understood, and hence, more studies on this subject are required. The objectives of this study are:

(1) To study the effects of the tillage practice on soil CO₂ flux, transport and production from an Andisol. For this purpose, a 150-d soil column incubation experiment was conducted.

(2) To evaluate the influence of the tillage operation on soil physical properties, and study how the changes in soil physical properties induced by tillage affect the soil CO₂ behavior in the Andisol. Since the gas diffusivity is an important factor to affect the soil CO₂ flux and can be used to estimate the CO₂ production, the performances of models on the prediction of gas diffusion coefficients of soils under different tillage systems were evaluated.

(3) To evaluate the effects of the tillage depth and the soil macropore on the CO₂ behavior in soils.

The soil is sampled at the experimental farm of the University of Tokyo located in

Tokyo. The soil type is Andisol, which is an important agricultural soil in Japan. However, the previous studies of effects of tillage on the CO₂ behavior in the Andisol are limited.

In comparison to the field experiment, samplings and measurements are less laborious with the incubation experiment, and the conditions of the experiment are easily controlled during the incubation period. A 150-d column incubation experiment in a greenhouse was conducted to study the soil CO₂ behavior affected the tillage practice. The soil columns included undisturbed soil columns sampled from the field and the repacked soil columns prepared in the laboratory.

The undisturbed columns were used to study the effects of tillage on soil physical properties (Chapter 3) and CO₂ behavior (Chapter 4). The soil CO₂ flux, CO₂ concentration, soil temperature and moisture were monitored during the incubation period. After the incubation, the soil columns were separated to five layers (0–5, 5–10, 10–15, 15–25 and 25–35 cm), and the soil physical properties (i.e., bulk density, saturated hydraulic conductivity, water retention characteristics, aggregation and gas diffusivity) and the soil carbon (total carbon, total carbon associated with aggregates and carbon mineralization associated with aggregates) were determined. The CO₂ flux through the soil profile and the CO₂ production in the soil were estimated with the measured CO₂ concentration and gas diffusivity. Soil gas diffusivity was predicted by the model that fit well with the measured gas diffusivity of Andisol under no-tillage and tillage treatments. The results of the CO₂ behavior, carbon stocks and physical properties under no-tillage and tillage treatments have been obtained.

We designed another incubation experiment with repacked soil columns to study the CO₂ flux related to the influencing factors (i.e., tillage depth and macropore). The

CO₂ flux and CO₂ concentration were measured during the incubation under five treatments (i.e., no-tillage, conventional tillage, deep tillage, no-tillage with macropore and conventional tillage with macropore). After incubation, the soil physical properties (i.e., bulk density and saturated hydraulic conductivity) and carbon stocks are determined at five layers. The results and discussion are shown in Chapter 5 and Chapter 6.

The conclusions are as follows:

(1) Unlike the bottle incubation experiment, the column incubation experiment keeps the soil structure the same with that in the field, and thus, roles of soil structure on CO₂ behavior can be discussed. Additionally, soil column can be used to study the gas transport through the soil. The values of soil CO₂ flux observed by the column incubation experiment in the present study was similar to that reported from field experiments on Andisols. Therefore, soil column incubation may be an alternative method of the field experiment to study the behavior of greenhouse gases in the soil.

(2) The CO₂ flux under the tillage treatment was distinctly higher than that under the no-tillage treatment at the first day, but after the first day the difference in CO₂ flux was not so distinct. For 150-d incubation, no-tillage treatment tended to show smaller cumulative CO₂ flux than the tillage treatment.

(3) The CO₂ flux and the CO₂ production in the soil could be well estimated by using the soil CO₂ concentration gradient combined with soil gas diffusivity. Linear relationship was observed between the estimated and measured CO₂ flux. Since the measurements of CO₂ concentration and gas diffusivity were not bothered by the climate events, the evaluated result can be used as a supplement data of the surface CO₂ flux measured by the chamber method.

(4) For our Andisol, distributions of the CO₂ production in the soil profile were different for no-tillage and tillage treatments. At depths of 0–5 cm, higher CO₂ production was observed under the no-tillage treatment, but at depths of 5–35 cm, the results were opposite. Totally, the tillage treatment tended to show higher CO₂ production than the no-tillage treatment.

(5) Soil physical properties that play roles in soil respiration were distinctly affected by the tillage practice. Compared to the no-tillage treatment, soil macroaggregates were destructed by the tillage operation, and hence, the organic carbon protected by soil aggregates might be easily decomposed by the microbial respiration. Tillage modified the soil structure, and higher gas diffusivity under the tillage treatment than that under the no-tillage treatment was observed during the incubation. Higher gas diffusivity increased the gas transport, and thus led to the higher cumulative CO₂ flux and lower CO₂ concentration under the tillage treatment.

(6) Using values of air-filled porosity and water retention characteristics, soil gas diffusivity under no-tillage and tillage treatments could be adequately predicted by the BBC model. As this model considers pore structure to a greater extent than the other models, this model is recommended for predicting the soil gas diffusivities with variable structures. The predicted gas diffusivity can be used to estimate the soil CO₂ flux under no-tillage and tillage treatments.

(7) The depth of tillage is a factor to affect the CO₂ behavior in the soil. With the depth of tillage increased, larger volume of soils was disturbed, and thus the physical properties in the soil profile were changed. The highest soil cumulative CO₂ flux and the lowest CO₂ concentration at deeper layers have been observed under the deep tillage treatment.

(8) Macropores affected the soil CO₂ behavior, especially the CO₂ concentration. Since the macropore increased the soil gas transport, the CO₂ concentration in the soil with a macropore was observed to be lower than that in the soil without macropore. However, the effects of tillage on soil CO₂ behavior were more obvious than that of the macropore.

This study presents the effects of tillage on the CO₂ behavior with the 150-d column incubation experiment. However, some further researches are expected.

(1) Tillage practice has a potential to store or emit CO₂ from the soil. However, the difference in soil total carbon and carbon associated with aggregates were not significant between the two treatments for the 150-d incubation. Long-term incubation experiment is required to grasp the effects of the tillage practice on the soil carbon storage and organic matter decomposition.

(2) The present study observed the effects of the macropore on CO₂ flux and concentration. But this study only observed the situation of the soil with a straight macropore, and the size and distribution of the artificial macropore were different from that in the field soil. In field, macropores may change the water flow at specific climatic conditions, and this modifies the moisture condition in soil profile. Changes in soil moisture may affect CO₂ behavior. Thus, future studies on effects of macropores on the CO₂ behavior are required.

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