SOIL RESPIRATION IN ARID ECOSYSTEMS OF THE GURBANTŰNGGŰT DESERT REGION IN NORTHWESTERN CHINA

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静岡大学博士論文

SOIL RESPIRATION IN ARID ECOSYSTEMS OF THE GURBANTŰNGGŰT DESERT REGION IN NORTHWESTERN CHINA

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Abstract

Global climate change has drawn increasingly attentions since it may threaten human being’s existence and further developments. The increasing concentrations of carbon dioxide (CO_2) as one of the greenhouse gases, is considered to be a main reason for causing global change. Soil respiration (SR) plays a key role by releasing carbon into atmosphere and hence may influence global carbon cycling considerably. Compared to many terrestrial ecosystems, such as agricultural, grassland or forest ecosystems, arid and semiarid desert ecosystems are relatively less investigated regarding SR studies, due to the low productive characteristics of such ecosystems as well as harsh conditions for carrying out monitoring. However, arid land ecosystems should not be neglected in the global carbon cycling system since they occupy approximately 40% of the global total land surface area. In this study, monitoring and controlling experiments were designed and conducted in the Gurbantünggüt desert ecosystems in Xinjiang province in northwestern China which is featured by typical temperate continental dry climate, for better understanding the SR characteristics and for exploring its potential mechanisms in these ecosystems.

The first step of this study was based on continuously measuring the temporal variation and magnitude of the SR, in which the diurnal and seasonal variations of SR of four different land covers (bare soil, crust, under canopy, litter) in the Gurbantünggüt desert ecosystems were mainly focused on. In chapter 2, an automatic chamber system was assembled with a gas analyzer (Li-cor 840) to measure SR throughout the entire growing season of 2013 in Fukang ecological experiment station located just next to the Gurbantünggüt desert. Meanwhile, soil temperature, near-surface temperature, soil moisture and soil electric conductivity (EC) were measured in order to reveal the correlations between SR and environmental factors. Similar experiments were also attempted to be implemented inside the desert site, but due to the absence of sustaining power supply in this savage area, only two or three days of data could have been acquired for every month. The results showed that the average rates of SR in this arid desert ecosystem ranged from about 0.3 to 0.8 μmol/m^2/s, which were, as expected, rather lower than forest or grassland ecosystem, and the SR rates of the desert site were lower than those of Fukang site. Furthermore, different surface covers exhibited different SR rates, with higher rates mostly occurred in under-canopy spots compared to those located in the interspaces. Diurnal variations of SR rate displayed an intimate tie with the fluctuation of the soil temperature while seasonal variation was supposed to be complicated by more factors including soil temperature, soil moisture, precipitation events and the activities of soil microorganisms. Moreover, in these drought-stress ecosystems, the abrupt variations of soil moisture tended to change SR rates to greater extents, particularly by dramatic fluctuation of precipitation.

The spatial variation of SR is significant in various terrestrial ecosystems, particularly in fragile arid land ecosystems, where vegetations distribute sparsely and the climate changes drastically. In chapter 3, SR in three typical arid ecosystems: desert ecosystem (DE), desert-farmland transition ecosystem (TE) and farmland ecosystem (FE) in this region were investigated to evaluate their spatial variations in 2012 and 2013. Along with SR, soil surface temperature, soil moisture and soil EC were also detected to estimate the spatial variations and the correlations among them. The results revealed that averaged SR rate was much lower in DE than those in TE and FE. No single factor could adequately explain the variations of SR, except a negative relationship between soil temperature and SR in FE ($P<0.05$). Geostatistical analysis showed that the spatial heterogeneity of SR in DE was insignificant but notably in both TE and FE, especially in FE, which was mainly attributed to the different vegetation and soil moisture characteristics among the three ecosystems. The results obtained in this chapter will thus provide a better understanding on spatial variations of SR and soil properties and to offer fundamental information on larger-scale carbon cycling evaluations in arid desert ecosystems.

In many arid and semiarid areas worldwide, land degradation is considered as one of the biggest threats to sustainable crop production. Salinization is a process which has a positive effect on increasing the salt concentration of soils and then causes land degradations. In our study site, especially in Fukang site, where the salinity content is high, it is inevitable that salinity affects soil properties and influences series of processes including SR. In chapter 4, a salinity control experiment was described. To investigate the effects of salt types and contents on SR, soil samples of Fukang site and Desert site were collected, then three salt types ($NaCl$, Na_2CO_3 and Na_2SO_4) were added into the soil samples at four gradients of 0% (control, CK), 2%, 5% and 10% (w/w). SR rates were monitored for all the samples periodically. The results indicated that SR of both two soils showed different responses to different salt types, and SR tended to decrease with the increase of salt salinity contents in the long run.

The results presented in this study produced a fundamental overview of SR in arid desert ecosystems, including important issues of temporal and spatial variations, the influencing factors and some specific features including effects of salinization on SR, etc, in order to provide critical information in such a data poverty area and hence help for further global carbon cycling researches.

Chapter 1 General introduction

1.1 Background

1.1.1 Global warming and carbon cycling

Global warming has drawn increasingly attentions since it may threaten the existence and development of human society (Scheffran and Battaglini, 2011) (Figure 1-1). Global warming is supposed to be the reason of some observed and expected environmental effects such as extreme weather (extremely wet or dry events), rise of sea level and various disruptions of ecological balance, which can further influence our social systems and human existence (Dai, 2011; Mousavi et al. 2011; Schiermeier, 2011). Therefore, global climate change has been considered to be the major subject and hotspot issue for scientists as well as policymakers. Increasing concentrations of atmospheric carbon dioxide (CO_2) is identified as a main reason for the far reaching global change (Davis et al. 2010; IPCC, 2014). It is reported that the concentration of CO_2 in the atmosphere has been rising drastically during the last two centuries (Subke, 2002), from 280ppm in 1750 to 400ppm in 2015, and it is still projected that the level will continue to rise rapidly in the future (Figures 1-2). Increasing intensity of human activity since the Industrial Revolution, which contributed to 40% increase of atmospheric CO_2 concentration, has been proved to be the most important reason for such increases (Dlugokencky and Tans, 2015).

Monitoring and modeling soil CO_2 efflux are necessary for understanding the carbon cycle in global scale (Xie et al., 2009; Kuzyakovand Gavrichkova, 2010). Soil constitutes the largest carbon pool of the terrestrial ecosystems which contains approximately 2000 Pg carbon. Plant biomass and atmosphere are another two major carbon pools, which contain about 500 Pg carbon and 785 Pg carbon, respectively (Janzen, 2004). For thousands of years, the atmosphere CO_2 concentration was reasonably constant since the carbon flows among soil, plant and atmosphere pools are balanced (Pongratz et al., 2009). However, this balance was disrupted by anthropogenic activities including the combustion of fossil fuel as well as the change of land use, which caused a large amount of carbon emission into the atmosphere (Houghton, 2012) (Figure 1-3). The destiny of the excess CO_2 emitted into the atmosphere has been widely discussed, while the results are still uncertain (Li et al., 2015). For example, the global annual CO_2 emission was more than 8 Pg carbon budget during 1990s, of which 6.3 Pg carbon from fossil fuels combustion and 2 Pg carbon from land use changes. However, only 3.2 Pg carbon was observed as increased atmosphere CO_2, the whereabout of the remaining 5 Pg carbon was unclear (Janzen, 2004). Although it was suggested that about 2 Pg carbon was absorbed by the oceans (Nakazawa, 1997; Le Quere et al., 2003), the other 3 Pg carbon was still difficult to explain (Janzen, 2004). Some scientists assumed that these carbons might have entered terrestrial ecosystems as "residual terrestrial sink" (Schimel et al., 2001; Subke, 2002; Houghton, 2002) or "missing sink" (Wofsy, 2001; Xie et al., 2009). However, the exact fate of this additional atmosphere CO_2 is still uncertain and remains controversial.

Studies on carbon cycling and efflux have been carried out in various terrestrial ecosystems, especially in forest and grassland ecosystems (Butterlyet al. 2010; Cleveland et al. 2010; Scott et al. 2010), which have high living biomass thus can accumulate large amounts of carbon by photosynthesis (Pan et al. 2011). It is hence hypothesized that such ecosystems may have the capacity of assimilating the additional CO_2 from artificial activities. However, in fact, no obvious role has been detected until now (Schimel et al., 2001; Woodbury et al., 2007). Other ecosystems, such as tundra, croplands and wetlands ecosystems, have been also proved to be not significant enough to account for this massive missing carbon (Schlesinger, 2000; Wang and Hsieh 2002; Goodale and Davidson, 2002). Recently, scientists have paid some attentions on the arid or semiarid ecosystems, i.e. sparsely vegetated and unproductive areas where are definitely not the conventional hotspots for carbon cycle study-to explore their functions in the global carbon cycle (Gao et al. 2012; Harrison and Dorn, 2014; Li et al. 2015). In comparison with forest ecosystems, some studies suggested that desert ecosystems may play a certain role in absorbing the atmosphere CO_2 and the long-sought "missing C sink" (Stone, 2008; Li et al. 2015). For instance, in a desert ecosystem of arid land, Li et al. (2015) found that dissolved inorganic carbon (DIC) could be washed down into the groundwater by irrigations and then possibly formed a huge carbon sink under the vast desert. Although the mechanism and magnitude of such carbon sink in desert areas are still unclear (Xie et al., 2009; Schlesinger et al., 2009; Ma et al., 2013), accumulating evidences from previous studies indicate that desert ecosystems may be an essential part of terrestrial carbon sink (Jasoni et al., 2005; Xie et al., 2009; Li et al. 2015) and thus play a non-negligible role in the global carbon cycling system. More importantly, more than 40% of the earth’s surface is dominated by arid and semi-arid ecosystems (Schlesinger, 2013), meaning that perturbations that take place in such areas potentially impact global-scale ecological processes. As a result, studies on carbon cycling characteristics of arid and semi-arid desert ecosystems are necessary to evaluate the global C cycling.

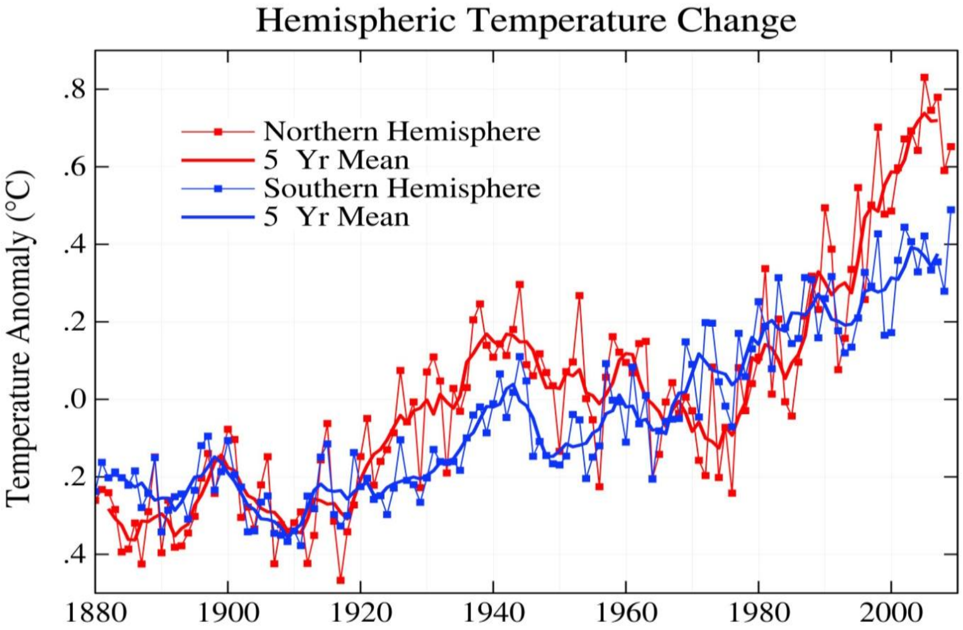

Figure 1-1 Earth's surface temperatures have increased since 1880. Source: NASA, 2009. http://www.nasa.gov/topics/earth/features/temp-analysis-2009.html

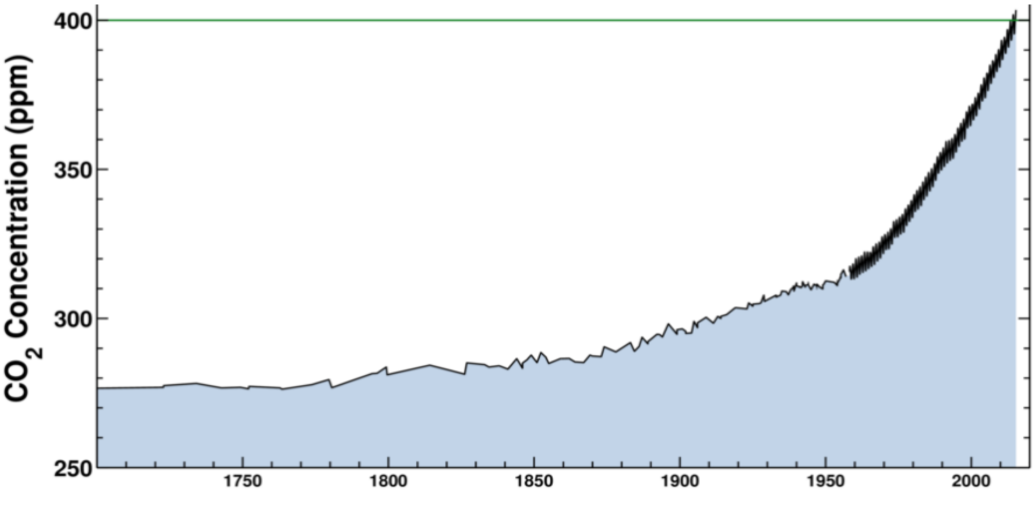

Figure 1-2 Keeling curve, a graph that plots the onging change in concentration of CO_2 in earth's atmosphere. Latest CO_2 reading by June 16, 2016 was 406.89ppm.
Source: https://scripps.ucsd.edu/programs/keelingcurve/

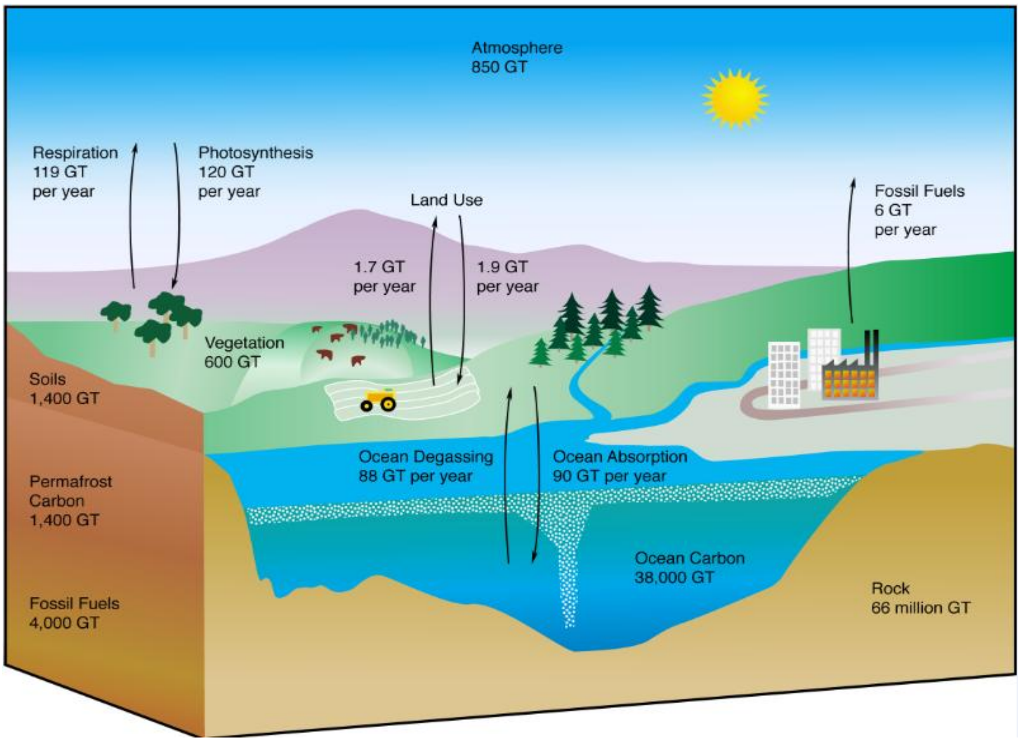

Figure 1-3 Diagram of the global carbon cycling with estimated volumes. https://tothepoles.wordpress.com/2013/09/09/the-greatest-climate-threat-under-the-ground-and-under-the-radar/

1.1.2 Soil respiration of terrestrial ecosystems

Soil respiration (SR), which consists of autotrophic respiration (roots), heterotrophic respiration (soil organisms) and chemical oxidation of carbon compounds, is the primary pathway of soil CO_2 efflux (Lloyd and Taylor, 1994) (Figure 1-4). It is the second largest carbon efflux between soils and the atmosphere (Luo and Zhou, 2006), emitting approximately 75×10^{15} gC yr^{-1} from soils to the atmosphere (Field et al., 1998; Schlesinger and Andrews, 2000). Previous studies have indicated that SR rates of different ecosystems varied considerably, which possibly due to the contrasting vegetation covers in different ecosystems (Fernandez et al. 2006; Cable et al. 2008; Zhao et al. 2011). Generally, SR rates in the coldest tundra, northern bog and driest desert biomes are relatively lower in comparison with grassland, forest and cropland (Table 1-1) (Raich and Schlesinger, 1992). Therefore, major vegetation biomes such as grassland, forest and cropland tend to attract more attentions than other biomes.

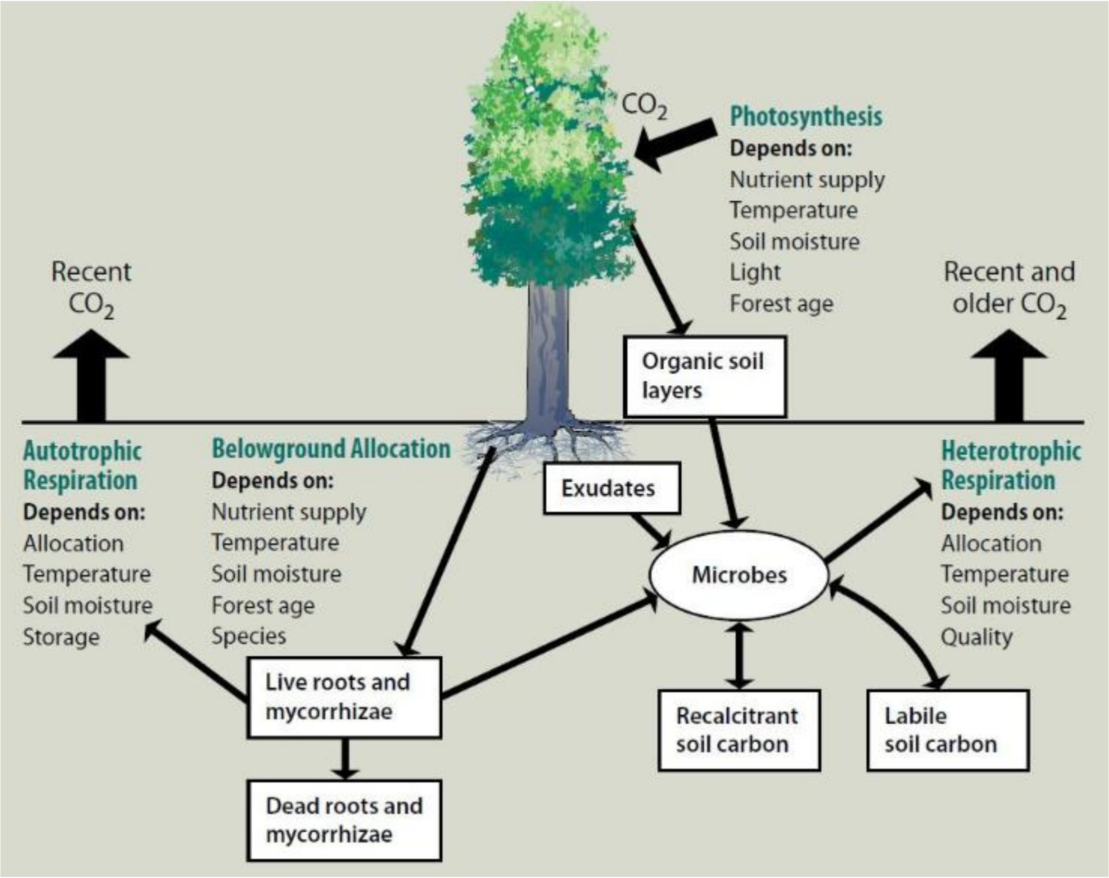

Figure 1-4 Conceptual model of the components and responses of CO_2 efflux from soil (Ryan and Law, 2005).

Up to now, scientists have tried to clarify SR of terrestrial ecosystems from various aspects: (1) processes of soil CO_2 production, mainly the root respiration and microbial respiration (Fierer et al. 2003; Ruehr et al. 2010; Grandy et al. 2013); (2) controlling factors of SR, including soil substrate supply, ecosystem productivity, soil/air temperature, soil moisture, soil oxygen, soil texture, soil pH and so on (Yan et al. 2011; Balogh et al. 2011; Wang et al., 2014); (3) temporal and spatial variations of SR, such as the diurnal, seasonal, inter-annual, decadal and centennial variations of SR (Chen et al. 2010; Zimmermann et al. 2010); spatial patterns of SR at the stand scale, landscape scale, regional scale and the global scale (Fiener et al. 2012; Luan et al. 2012; Oyonarte et al. 2012); (4) Separation of source components of SR, which is critical for exploring the internal mechanisms. In the present study, two parts of these themes were mainly investigated and discussed: temporal and spatial variation of SR, and relationships between SR and its controlling factors in arid desert ecosystems.

Table 1-1 Estimated soil carbon stock (kg/m^2), mean soil respiration rates (gC/m^2/yr).

Vegetation type	Area (10^6km^2)	Soil C (kg/m^2)	Soil Respiration (gC/m^2/yr)	Turnover (yr)
Tundra	5.6	20.4	60	490
Boreal forests	13.7	20.6	322	91
Temperate forests	10.4	13.4	662	29
Temperate grasslands	15	18.9	442	61
Cultivated lands	13.5	7.9	544	21
Desert scrub	27.7	5.8	224	37
Tropical grasslands	27.6	4.2	629	10
Tropical lowland forests	17.5	28.7	1092	38
Swamps and marshes		72.3	200	520
Global total:				
1515 PgC in soil, CO_2 efflux of 68 PgC/yr				32

Modified based on Jobbagy & Jackson, 2000 and Raich & Schlesinger, 1992.

1.1.3 Methods of soil respiration measurements

Accurate measurement of CO_2 effluxes is of great importance in the development of SR researches (Raich and Schlesinger, 1992; Rochette and Hutchinson, 2005; Luo and Zhou, 2006). In the past several decades, scientists have conducted large amounts of investigations to develop a variety of SR measurement methods. The methods can be roughly categorized into chamber methods and CO_2-well methods (Luo and Zhou, 2006). Generally, selecting a suitable method should be determined by the requirement for temporal and spatial sampling, resource and equipments availability, assumptions and measurement artifacts, accuracy required for the measurement, and evidence which the method can be conducted in the field condition (Lund et al., 1999; Keith and Wong, 2006). However, no matter what the methods is, a disturbance on the soil seems to be inevitable, creating inaccuracy of the measurement result. Therefore, the first thing to note before the measurement is to consider how to minimize such disturbance.

Nowadays, well-designed chamber methods are most commonly exploited in the SR investigations, which can directly measure the surface soil CO_2 efflux (Davidson et al., 2002; Luo and Zhou, 2006; Vargas et al., 2011). This method can be further separated into dynamic chamber methods and static chamber methods (Figure 1-5). The dynamic chamber method can measure CO_2 concentration within the chamber over a short period, since in this method, the air can circulate between the chambers and the measurement equipment like an infrared gas analyzer (IRGA). Until now, the most widely used method in both laboratory and field experiments is the closed dynamic chamber method, which is also the design principle of our own chamber system used in our continuous SR measurements (Chapter 2). Before using this method, a completely enclosed mode on soil surface was established. Thereafter, changes in CO_2 concentration in the closed chamber over a short time were measured (10 minutes in our case). Once the soil surface is covered by a closed chamber, the CO_2 concentration in the chamber increases because the CO_2 release from the soil. With the concentrations rise from the starting time to the ending time, the increases in the concentration of CO_2 in the chamber can be used for estimating the SR rate using the following formula (Field et al., 1989).

$$\mathrm{F} = \frac{(\mathrm{Cf} - \mathrm{Ci})\mathrm{V}}{\Delta\,\mathrm{tA}}$$

where Ci is the initial concentration of CO_2, Cf is the concentration of CO_2, V is the chamber volume and a little tube volumes, Δt is the time span from the start to the end of the measurement, and A is the soil surface area covered by the chamber, i.e. the base area of the chamber.

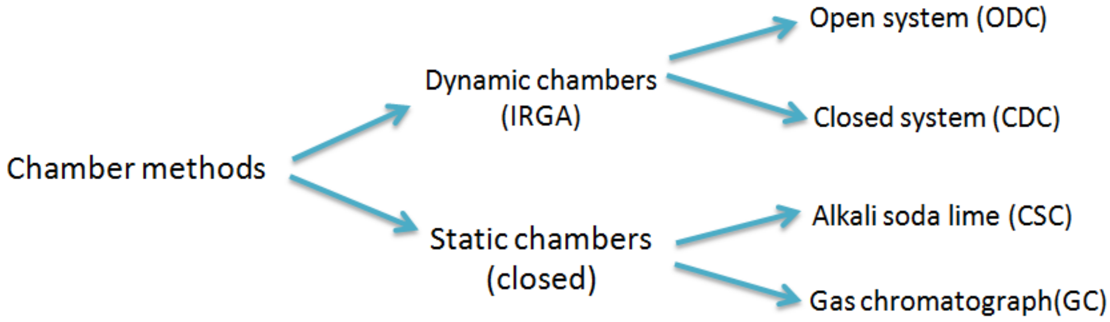

Figure 1-5 Classification of chamber methods of measuring soil respiration (Luo and Zhou, 2006).

The closed static chamber method is also a sealed air chamber isolated from the external environment during a measurement period, which is consistent with the closed dynamic chamber method. However, the closed static chamber method uses alkali solution or soda lime to absorb soil CO_2. The rate of SR can be estimated from the trapped CO_2. This method is the earliest method of SR determination since it is economical and practical and easy to carry out (Jensen et al., 1996; Grogan 1998; Luo and Zhou, 2006), which is very useful to estimate the mean SR rate at different sites where lots of measurements are required at the same time to investigate the spatial variation (Rochette et al., 1997; Janssens et al., 2000; Rochette and Hutchinson, 2004; Keith and Wong, 2006). Soda lime is mixed by calcium and sodium hydroxides that reacts with CO_2 to form carbonates. After the reaction, the soda lime gains weight which is the absorption of $CO_{2.}$ Then we can calculate the average SR rate during the sampling time. The detailed experiment design and procedure will be given in Chapter 3.

1.2 State of the art

1.2.1 A general view of soil respiration research

The history of SR research is very long, which can trace back to the early 20th century. Early measurements of soil carbon efflux have focused on agriculture ecosystems to evaluate fertility and biological activities of soils with a view to agricultural productivity (Subke, 2002; Luo and Zhou, 2006) and the main method used was the alkali absorption method. From the late 1960s, studies of SR were mainly concentrated on the ecological perspective, and carbon cycles of different ecosystems have thus been widely investigated (Lou and Zhou, 2006). During this period, infrared gas analyzer (IRGA) and eddy flux came into use to measure SR in the field condition (Luo and Zhou, 2006; Smith et al., 2010). The investigations in this period provided opportunities to summarize and compare results of various ecosystems (Luo and Zhou, 2006). After then, since 1990s, SR studies mainly focused on the global change and provided insights into the global carbon cycle of terrestrial ecosystems (Luo and Zhou, 2006; Wang, 2015). Advances in SR measurement methods have stimulated the SR studies from various aspects. Many companies have developed a variety of chambers that are greatly convenient for the measurements in field conditions.

1.2.2 Soil respiration research in arid desert ecosystems

SR studies have been conducted for more than a century, but most of the studies, however, focused on forest ecosystems, grassland ecosystems and agricultural ecosystems. By contrast, studies on the SR of desert ecosystem are relatively few (Chen and Tian, 2005). Existing studies mainly concentrated on the following aspects:

(1) SR and its controlling factors in ecosystems of arid land. This topic has been highlighted in a relative plenty of studies. For instance, Jin et al. (2010) investigated SR and NPP in desert shrub systems and found that SR was significantly correlated to the surface soil moisture (0-10cm). In seven deserts across North America and Greenland, Cable et al. (2011) indicated that the response of SR to temperature spanning 67^{o}C and detected variable temperature responses for SR. Zhang et al. (2010) pointed out that air temperature was the primary driver of seasonal variation of SR, while in mid-summer, the increase of SR was likely controlled by high temperature and low soil moisture. Ma et al (2012) found that the response intensity of SR to temperature was enhanced by greater soil water content. Sponseller (2007) also suggested that precipitation was a major factor of biological process in arid and semiarid ecosystems and soil biogeochemical processed in these water-limited systems were intimately related to episodic rainfall events. In cold desert ecosystems, Fernandez et al. (2006) pointed out that SR was mainly controlled by the temperature and moisture. In conclusion, air and soil temperatures are identified as the dominant factors that influenced SR, while soil moisture can also affect the temperature sensitivity and magnitude of SR. Jin et al. (2010) suggested that the dynamics of SR could be predicted well by applying an integrated model which incorporated both air temperature and soil surface moisture. As a result, the interaction effects of soil temperature and moisture should be considered in order to improve the assessment of SR.

Besides the controlling factors of SR, the temporal and spatial patterns of SR in desert ecosystems were also taken into considerations in previous studies (Cable et al., 2010; Wang et al., 2013). In most cases, diurnal variation of SR is supposed to be caused by changes in soil temperature, which changes considerably on the context of diurnal course (Rayment 2000; Luo and Zhou, 2006). By contrast, seasonal variation of SR in desert ecosystems is more complex, since seasonal SR is affected not only by the temperature and moisture, but also the photosynthetic production and/or their interaction effects (Wang et al., 2010; Suseela et al., 2012). Generally, the highest and lowest SR rates are usually observed in summer and winter, respectively, since soil temperature may be the primary factor that controls the seasonal pattern of SR (Davidson et al., 2000). Moreover, in an arid region, Zhang et al. (2007) also found that the seasonal variation of SR showed a single-peaked curve, which increased from May and decreased at October following the variation of near surface temperature. In general, seasonal variations of SR are quite different in different regions, which may caused by the different soil and vegetation types as well as the climate conditions (Luo and Zhou, 2006).

As compared to temporal variation, spatial variation of SR in desert ecosystems is relatively less studied (Maestre and Cortina, 2003). Spatial variation in SR occurred at different scales, from square centimeter to hectare and up to the region and the global scale (Wei et al. 2010; Yu et al. 2010). High spatial variability of soil makes it difficult to estimate SR, especially in arid regions (Schlesinger and Pilmanis, 1998; Wang et al., 2013). Different sampling strategy on different land use/cover in arid region (like between the shrub and interspace) is frequently adopted to investigate the spatial variation such as in Zhang et al (2007) and Maestre (2003)’s researches, suggesting that significant difference among different land covers. Another sampling strategy, such as grid distribution of sampling point, was also used to display an overall composition of spatial variation (Wang et al., 2013). In our study, we also chose this sampling strategy on different arid ecosystems.

1.3 Objectives of this study

In the present study, temporal and spatial variations of SR, and effects of soil temperature, soil moisture and soil salinity/alkalinity (electrical conductivity) on the SR release in the Gurbantünggüt desert ecosystems in Xinjiang province, northwest China, were studied. Three monitoring and control experiments were conducted: chapters 2 and 3 mainly focused on temporal and spatial patterns of SR rate under diverse field conditions, while the chapter 4 presented laboratory controlled experiments to investigate the effects of soil types and salinity content on SR. The results from this study were intended to provide insights into the SR variation characteristics of desert ecosystems in arid land. The dataset obtained in this study should be not only helpful for well understanding of the global carbon cycle, but also valuable for developing ecosystem models to predict the whereabout of carbon under global climate changing backgrounds. The main objectives of the present study include:

(1) to establish a chamber based system that provides continuous and reliable measurements of SR in arid desert ecosystems;

(2) to obtain diurnal variations and monthly fluctuations of SR through the entire growing season and to evaluate the temporal variations of SR in different soil surface types;

(3) to estimate and compare the magnitudes of SR in different arid ecosystems and to figure out their controlling factors and also to illustrate their spatial variations by using geostatistic analysis;

(4) to evaluate the important role of soil salinity in determining SR rate through a controlling experiment.

Chapter 2 Temporal variations of soil respiration under different soil surface covers in desert area

2.1 Introduction

SR rate often exhibits strongly temporal variation, from diurnal variation to centennial variation (Luo and Zhou, 2006). High temporal variations of SR not only leads to large measurement errors, but also results in difficulty when employ point measurements to the estimation of regional or global scale C budgets (Tang and Baldocchi, 2005; Law et al., 200; Luo and Zhou, 2006).Consequently, it is necessary to accurately record the temporal variation of SR both diurnally and seasonally, especially in less studied arid desert areas.

As a composite effect of ecological processes, SR is affected by various environmental factors such as soil physical/chemical properties, vegetation types and climatic parameters. Therefore, SR shows great variations with time and space. Q_{10}, defined as an increase index in the rate of a reaction when temperature increase by 10^{o}C, is an indicator of temperature sensitivity (Epron et al., 2004; Xu and Qi, 2001). It is frequently used for estimating the seasonal variation of SR and also its annual magnitude (Jia et al., 2013). On the other hand, temporal variations of SR are commonly influenced by soil/air temperature, soil moisture and other environmental variables (Tang and Baldocchi, 2007; Epron et al., 1999). Hence, the relationship between SR and the influence factors are important, and the models between them can be used to make the predictions (Tang and Baldocchi. 2007). However, how do these factors affect SR in arid ecosystems are still uncertain (Fernandez et al., 2006; Zhang et al., 2007).

In this study, SR and abiotic factors throughout the entire growing season of 2013 were continuously measured to assess the temporal variations under different soil surface covers in typical arid desert ecosystems. The results indicated that there were significant fluctuations both diurnally and seasonally with diurnal patterns closely correlated with soil temperature (Tsoil). In addition, diurnally hysteresis effect between SR and Tsoil showed that SR rate usually approached the maximum value earlier than Tsoil, with both SR and Tsoil exhibited similar unimodal curve trend. These phenomena suggested that in these dry desert ecosystems, temporal fluctuations, especially diurnal variations, are closely related with soil temperature, and modified by the soil moisture, such as precipitation, while seasonal variations are influenced not only by soil temperature but considered to be resulted from more comprehensive function of multiple factors.

An open dynamic chamber system was established to continuously measure the SR rate throughout the growing season of 2013 in Fukang Station of Desert Ecology, Chinese Academy of Sciences and Gurbantünggüt desert area. The objectives of this chapter were: (1) to investigate the diurnal and seasonal variations of SR in these arid desert ecosystems; (2) to compare the different SR characteristics among different soil surface covers; (3) to illustrate the role of soil temperature and soil moisture on controlling the temporal variations of SR in arid desert ecosystems.

2.2 Material and methods

2.2.1 General description of study sites

The measurements were conducted in Gurbantünggüt desert area in Xinjiang province, northwest China (Figure 2-1). The desert has a continental arid and temperate climate with an annual mean temperature of 6.9^{o}C (Wang et al., 2013). This desert is mainly covered by semi-mobile sand dunes, and the summer is dry hot while the winter is cold. Annual mean precipitation and the pan-evaporation are about 200mm and 2000mm, respectively (Zheng and Wang, 2012). The meteorological background was given in Figure 2-2. Two sites were selected within this area. One experiment site was inside the Fukang Station (F Site for short) of Desert Ecology (44°17’N, 87°56’E), Chinese Academy of Sciences. This station is located at the desert-farmland transition area, with the dominant species of *Tamarix ramosissima*. The soil is silty clay loam with high salinity content about 17mg g^{-1} and soil organic carbon (SOC) between 1.20~15.70mg g^{-1}(Guan, 2015). The other site was located inside the Beishawo desert site (D Site for short) (44°25’N, 87°54’E), which was characterized by the thriving *Haloxylon ammodendron* and the soil is mainly aeolian sandy soil with SOC between 0.80~7.08 mg g^{-1} and salinity content about 0.251~0.686 mg g^{-1}(Guan, 2015).

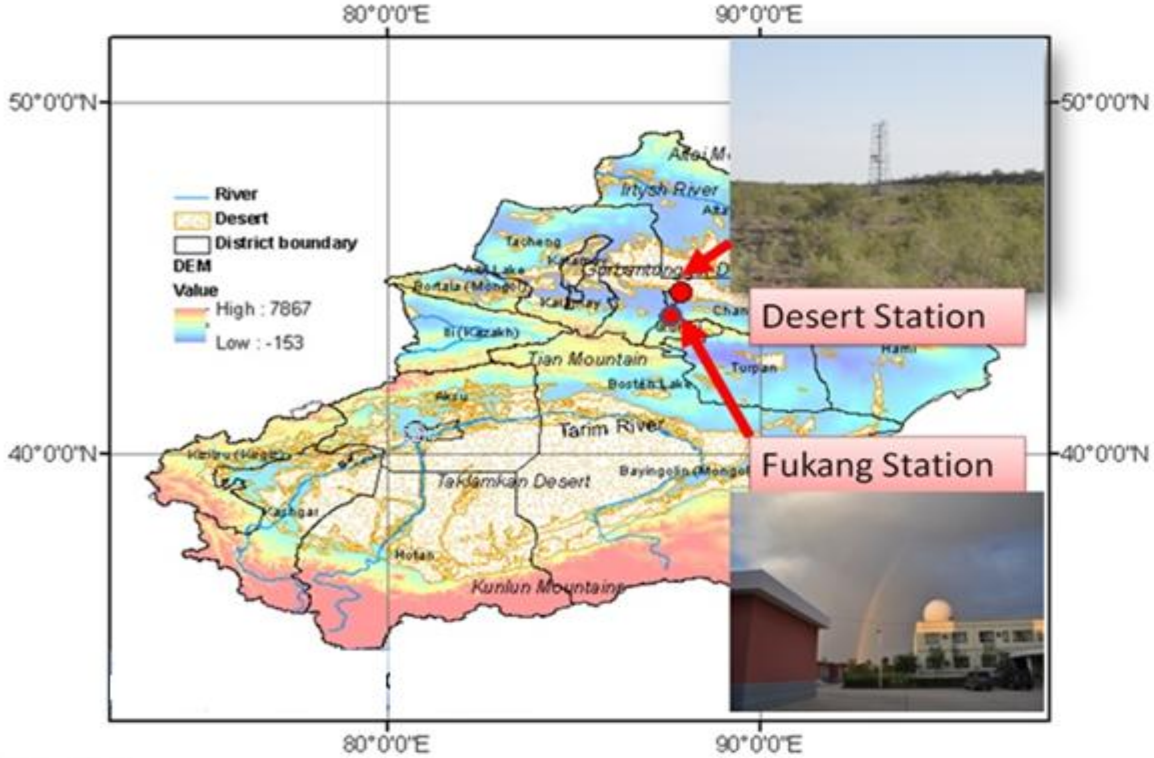

Figure 2-1 Location map of the experiment sites.

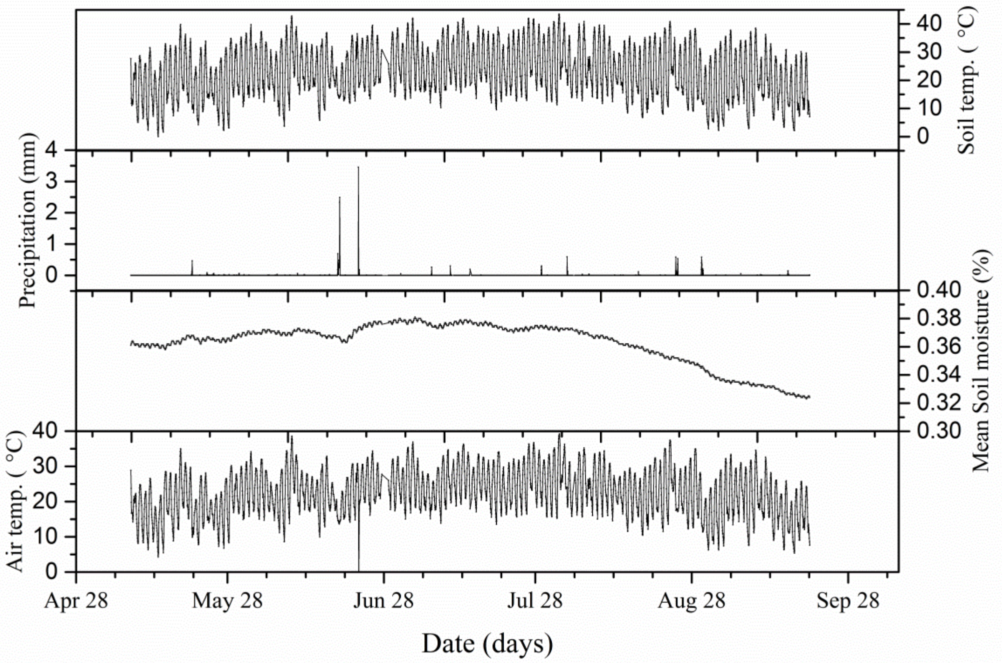

Figure 2-2 The environment background (soil temperature of 1m depth, soil moisture of 1m depth, air temperature and precipitation event) from May to September, 2013 in this study area.

2.2.2 Measurements of soil respiration

In F site, measurements were conducted throughout the growing season-start from May and end in October, 2013, which were sometimes interrupted by the equipment trouble or power failure of the automatic chamber system but generally it could be fixed promptly to ensure the continuity. However, in D site, far away from the civilized area, there is no continuous power supplied for long time measurements. Therefore, only two or three days of continuous measurement were conducted every month, using batteries as the power supply. We chose the middle days of the month under clear weathers to conduct the experiments in D site. Four chambers were installed in both F site and D site, and four different soil surface types (bare soil, crust, under canopy, litter-covered) were selected to set the chambers. However, unfortunately, during the measurement period, due to the extreme high temperature, and occasional power failure, it was unable to obtain a complete running of the chambers and inevitably suffered by data gaps.

SR rates were calculated according to concentration accumulation of CO_2 within the chambers which were connected with a gas analyzer Li-Cor 840 (Li-Cor Inc., Lincoln, Nebraska, USA). The volume of the chamber is length 50cm×width 30cm ×height 30cm and the measurement time was approximately up to 9 minutes for each chamber (Figure 2-3). Thus it spent about 40 minutes totally to complete a set of measurements. Four chambers functioned successively, i.e. when one chamber was used for the measurement, the other three chambers stopped running and the windows opened. There are two windows at the two side of a chamber (Figure 2-3), which were closed during the measurement periods and turned to be open during the intervals. In order to reduce the error from the disturbance on the soil environment, the chambers were set up with care several days before the measurement.

2.2.3 Measurements of controlling factors

Soil surface temperature was detected using TR-74Ui detector (T&D, Japan). Two detectors were set both inside and outside of the chamber to detect the temperature difference. Soil temperature in the depth of 5cm under the surface was measured with RT-13 (ESPEC MIC Corp., Japan). Both soil surface temperatures and soil temperatures were measured continuously and simultaneously. Instantaneous soil temperature, soil moisture and soil EC were detected using Time Domain Reflectometer (HH2 moisture meter, Delta-T devices, UK) near each chamber. Moreover, soil samplings are collected every month to the lab for the soil property analysis.

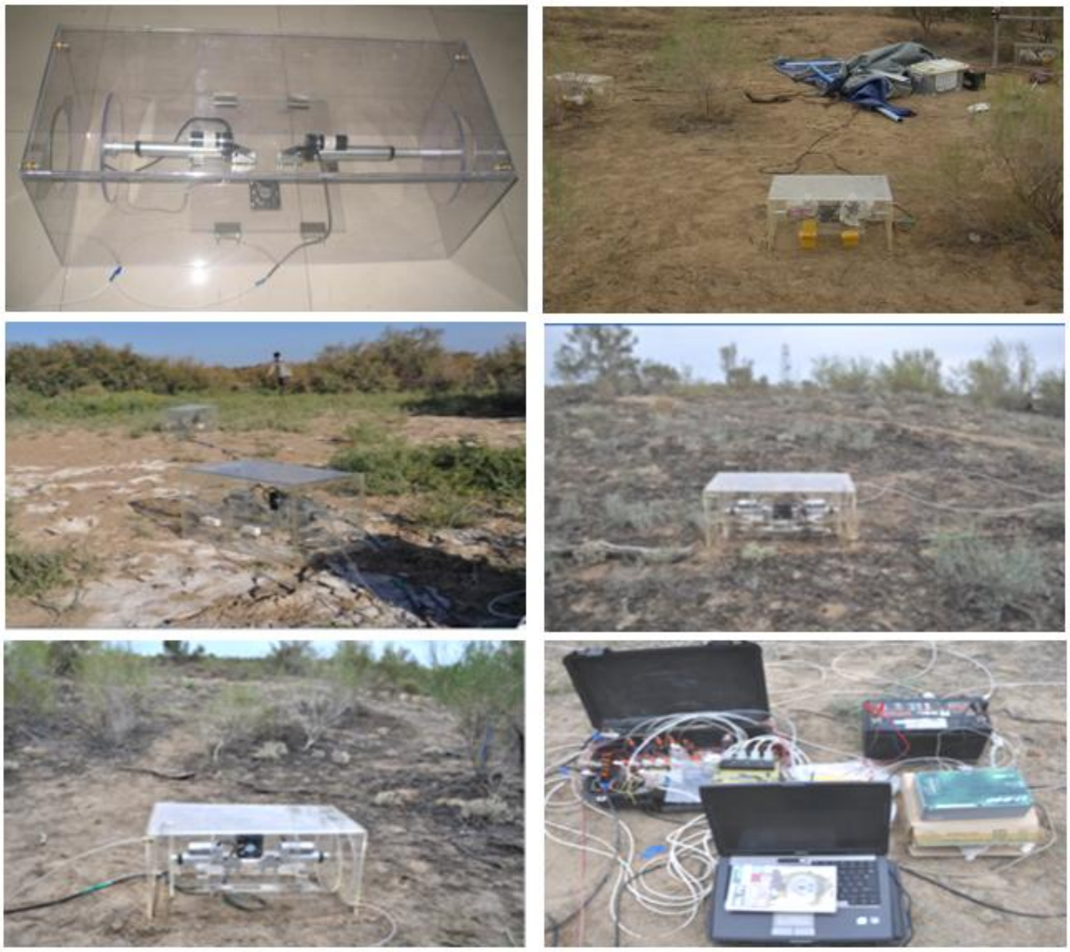

Figure 2-3 Photographs of the chambers and measuring equipment when operating in the field.

2.2.4 Statistics processing

The CO_2 concentration increments inside the chambers were recorded by a Licor-840 gas analyzer. Then the data were used for calculating SR. Regression analysis was performed to evaluate the relationships between SR and soil temperature. In general, the relationship between temperature and SR is usually expressed by an Arrhenius equation or an exponential equation. A simple empirical exponential model was proposed by Van’t Hoff to illustrate the biochemical reactions in response to change in temperature (2.1) and then modified by Arrhenius with an activation energy parameter (2.2).

$$Rs = ae^{bT} \text{ and } Q_{10} = e^{10b} \qquad (2.1)$$

$$Rs = ae^{[-E/(T+273.2)]} \qquad (2.2)$$

Where Rs is SR, a and b are fitted parameters, Q_{10} is the temperature sensitivity of SR.

2.3 Results

2.3.1 Diurnal variation of soil respiration

The mean SR rate was estimated to be 0.57±0.16 $\mu molm^{-2}s^{-1}$ in F site, while in D site, SR rate was lower, with a mean value of 0.34±0.19 $\mu molm^{-2}s^{-1}$. In general, the diurnal variation of air and soil temperature of the terrestrial ecosystems are regulated by the solar radiation, which affects the activities of plant and soil organisms and finally the variation of SR (Wu et al., 2003; Zhang et al., 2007). Generally, for diurnal variation of SR, a unimodal curve was exhibited, with the maximum rates frequently appeared in the early afternoon, from about 13:00 to 14:00 while the minimum rates occurred during the night time, usually at the dawn of the day, from about 3:00 to 4:00. Negative soil respiration values, which meant soil absorption by soil (carbon sink), were frequently observed during the night time.

The moments of the extreme values were varying within a certain range. For instance, the maximum values of soil respiration in the hottest days of August (e.g. August 7th, 2013) tended to appear earlier (before the noon) than that of other cooler days, probably owing to the rapid rise of the temperature in the summer days. The variation of the minimum moments was even more significant, from early evening to late night, probably because of the fluctuated soil moisture status during the night time. In addition, two types of curves were detected-inverted U curve and inverted V curve (Figure 2-4). Inverted U curve indicated a sustained high values in the middle of the day, while the inverted V curve only showed an instant moment of extreme high value. These variation characteristic of SR was significantly consistent with the soil temperature change.

Among different soil surface covers, SR rate under the canopy was greater than those in other places, in both F site and D site (Figure 2-5). But in F site, where the *Tamarix ramosissima* was thriving with larger primary production compared with *Haloxylon ammodendron* in D site, the difference of the canopy and interspace was much more obvious. Additionally, the difference among the other three soil covers (litter, crust, bare soil) seems to be not very apparent in both F and D site.

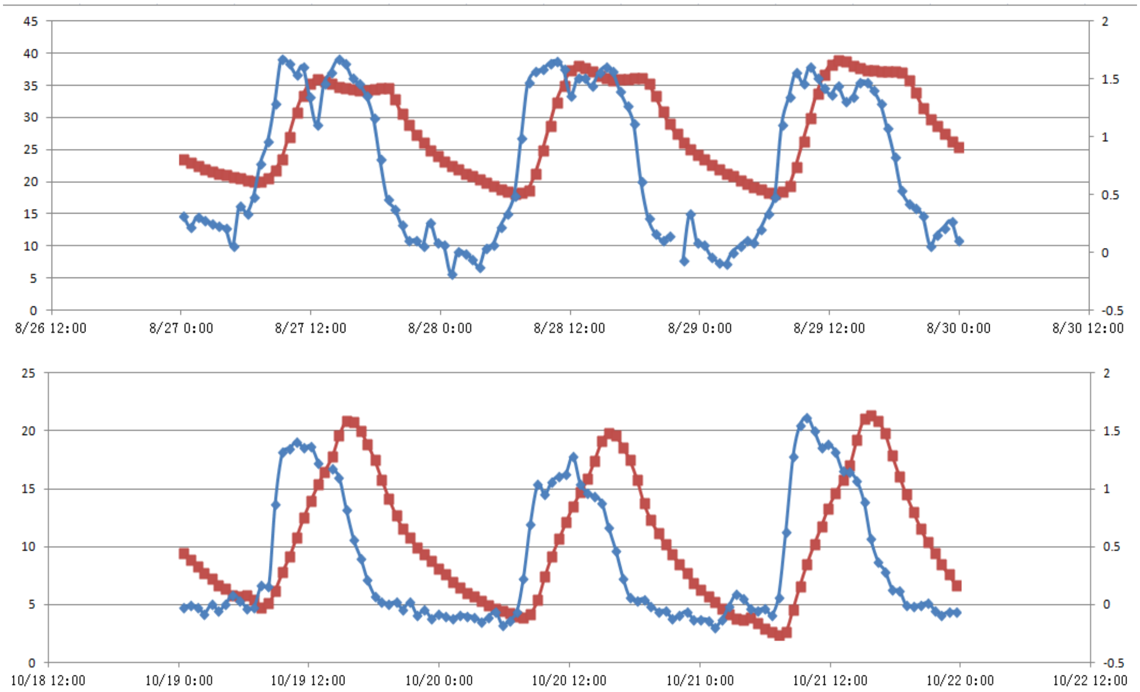

Figure 2-4 Typical diurnal variations of soil respiration and soil temperature in F site. Inverted U and inverted V curves were displayed. The blue lines stand for soil respiration rate (μmol/m^2/s) and the red lines are soil temperature (^{o}C).

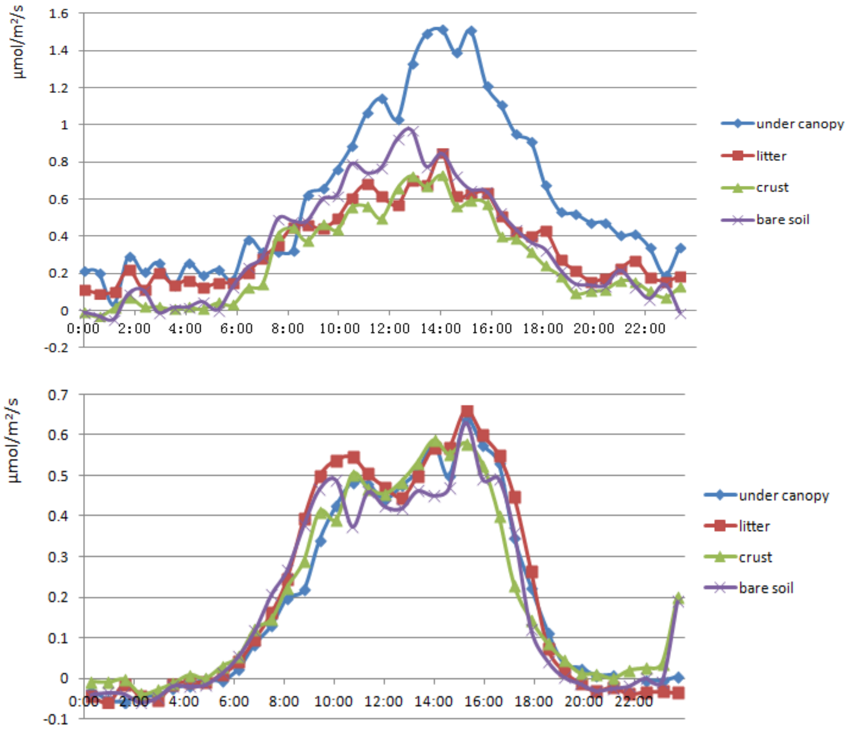

Figure 2-5 Diurnal variation of soil respiration among the four different soil cover types (above: F site; below: D site).

2.3.2 Seasonal variation of soil respiration

Mean SR rates of every month was monitored in the two sites. Clear days, which were considered to have representative climate status of the month, were summarized for the monthly estimation, and the results were showed in Figure 2-7. In F site, similar with the majority of other ecosystems, the seasonal variation displayed a single-peaked curve: SR rates of the summer months were greater than that of spring and autumn. The SR rates under the canopy points were higher than from the bare ground. Seasonal variation of SR rates was in agreement with seasonal change of soil temperature. On the contrary, SR rates in the desert site exhibited an obvious downward trend in the hottest July and August, which was assumed to be owing to the extreme high temperature and low soil moisture.

In the F site, as showed from the Figure 2-6, which presented the diurnal cycle of a normal weather day (generally the 5^{th} day of each month) from May to October respectively, it indicated that: 1) the maximum rate of August 5th is the largest value compared to other days of seasonal course, followed by July, June, September, and the minimum values appeared in May and October. Generally, the maximum value of a day among different months scattered into a relatively small range from 1.0μmol/m^2/s to 1.8μmol/m^2/s; 2) In July 5th and August 5th, the SR rates fluctuated around a high value during the midday and early afternoon (inverted U), with the value of 1.3μmol/m^2/s and 1.5μmol/m^2/s, respectively. But unlike these cases, May 5th and June 5th, as well as October 5th, showed no such stable state of high values, but only unimodal curves (inverted V); 3) Negative carbon efflux phenomenon (soil as carbon sink) was detected during the night time, as can be seen from the figures, small negative values appeared at both the early mornings and the night periods.

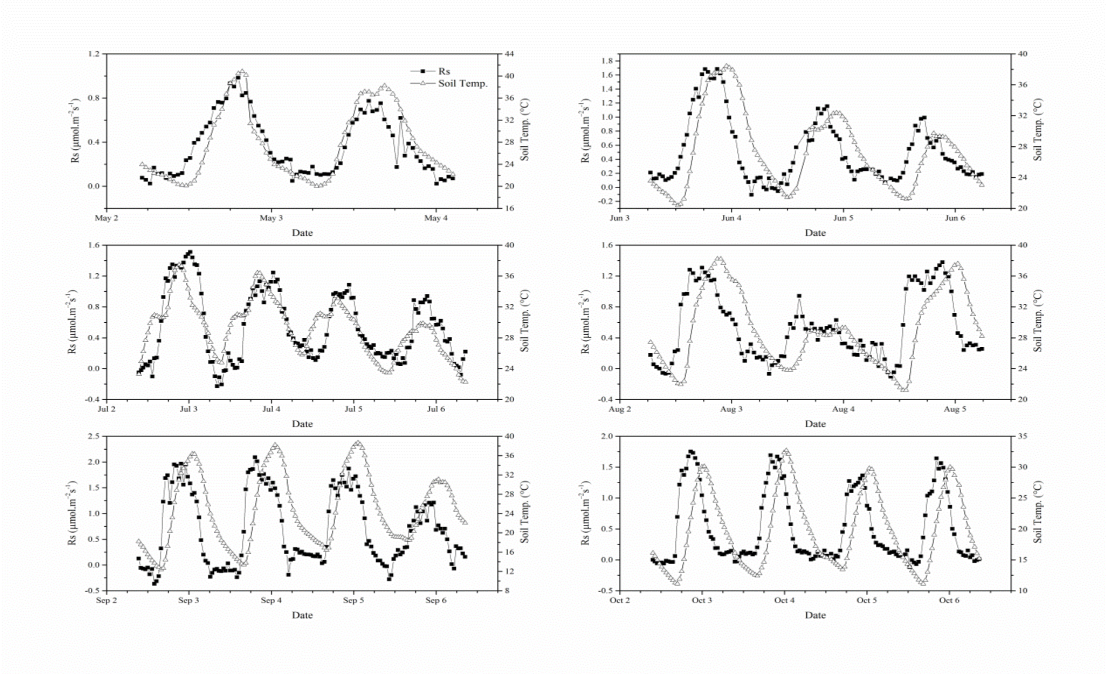

Figure 2-6 Continuous diurnal variations of respiration and soil temperature of the months in F site.

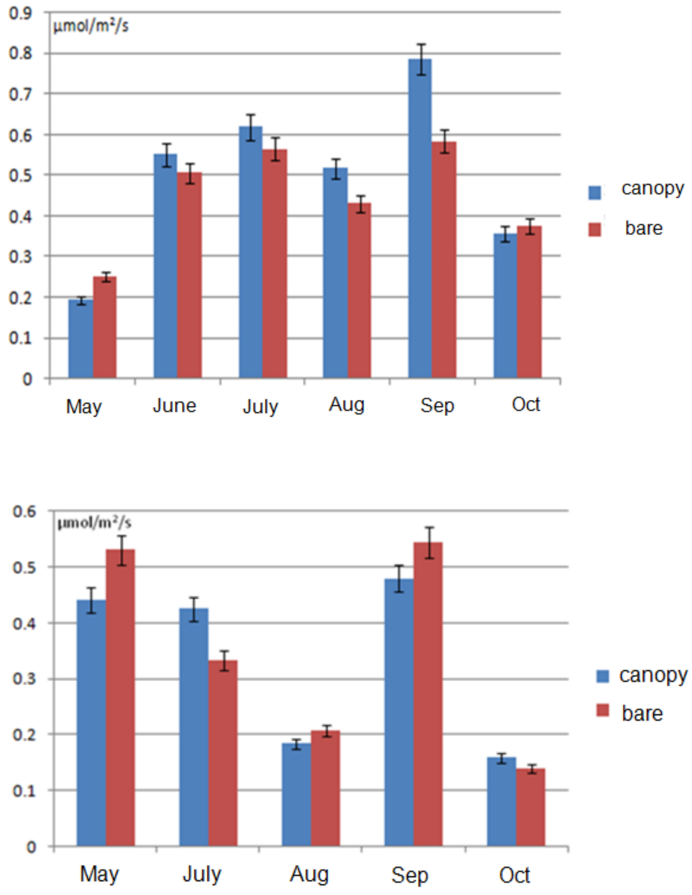

Figure 2-7 Variations of soil respiration of the growth season months in F site (above) and D site (below). Canopy and bare means soil sampling under canopy and bare soil, respectively.

2.3.3 Relationship between soil respiration and related factors

Regression analysis was conducted for SR and soil temperature. Mean SR and soil temperature of a clear day from each month in a chamber were used for the analysis (Figure 2-8). Linear regression, exponential regression and power function regression were verified respectively, which all indicated that SR rate was positively correlated with soil temperature (*P*<0.001).

$$y=0.0129x + 0.2125$$
$$R^2=0.6478$$
$$P<0.001$$

$$y=0.1055x^{0.5045}$$
$$R^2=0.7101$$
$$P<0.001$$

$$y=0.2556e^{0.0284x}$$
$$R^2=0.7116$$
$$P<0.001$$

As for soil moisture, unlike soil temperature, continuous measurements were difficult to implement. In fact, diurnal variation of soil moisture was not as significant as soil temperature. Thus, a small controlling experiment was conducted, as watering treatments were applied on the two sites soil samples. It suggested that SR of the two samples increased with soil moisture, and the correlation in D site soil sample was more significant than F site soil (Figure 2-8).

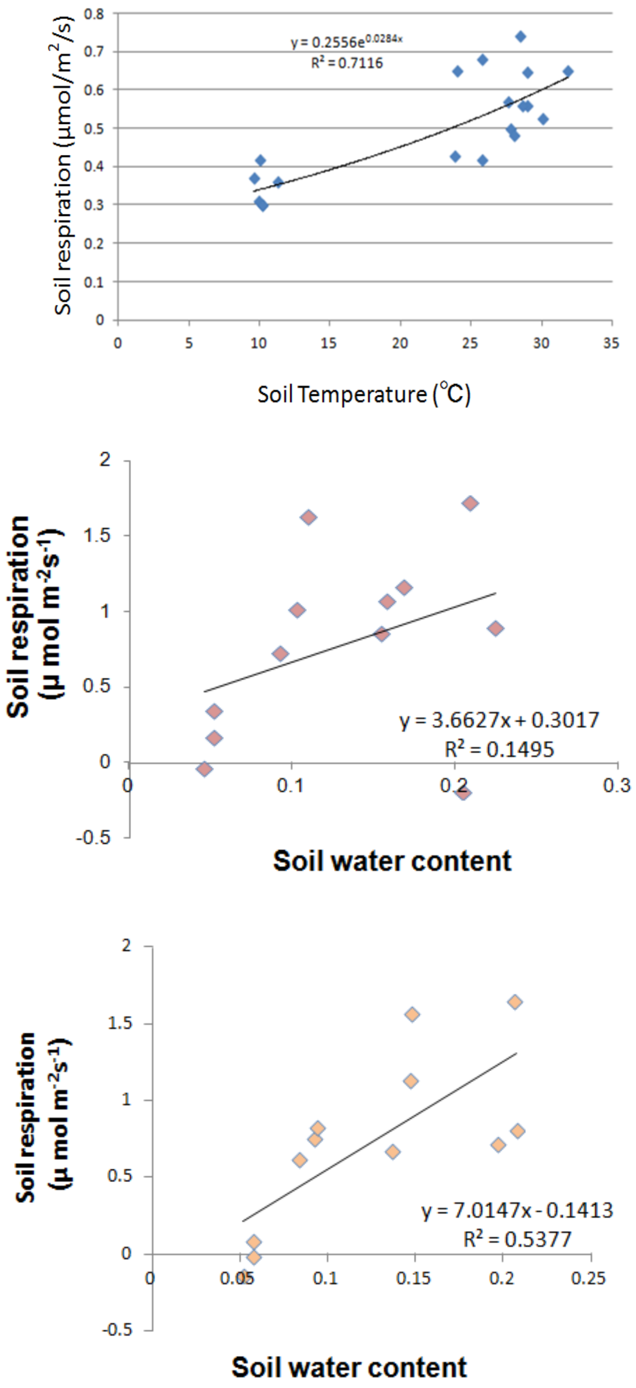

Figure 2-8 Regression analysis between soil respiration and soil temperature (F site) and soil moisture (upper: F site, below: D site).

2.4 Discussion

Temporal variations of soil respiration in arid ecosystems

The mean SR rate was 0.57±0.16 μmolm^{-2}s^{-1} in F site, which is very similar to

Zhang (2010)'s results of 0.58±0.26 μmolm^{-2}s^{-1} in another arid desert ecosystem in western China. In D site, SR rate was lower, with a mean value of 0.34±0.19 μmolm^{-2}s^{-1}. For diurnal variation of SR, the maximum rates usually appeared in midday, and the minimum rates were generally found during night time, especially before dawn, which was consistent with most of the study cases (Bijracharya et al., 2000; Xu and Qi, 2001a; Mo et al., 2005). However, the diurnal pattern of SR rates varied distinctly from time to time in seasonal course. Apparent variation of diurnal patterns among different months is easily predictable, but tremendous variations can also be detected from day to day, such as sudden precipitation can induce large and transient CO_2 efflux from the soil. The desert ecosystem is fragile and tends to suffer extreme weather change and therefore influence the SR dramatically. For the diurnal cycle, there are different patterns, including inverted U and inverted V patterns. Some other researches also showed the high value stagnation of SR during the midday and early afternoon in other desert areas, which was suggested to be the caused by the stomatal closure (Wang et al., 2014).

For seasonal variation, different patterns were found between the two sampling sites of F site and D site. In F site, SR rates of the summer months were greater than those of spring and autumn. On the contrary, SR rates in the desert site exhibited an obvious downward trend in the hottest July and August, probably due that the extremely high temperature and low soil moisture suppressed the soil microbial activity. In desert site with sparsely distributed *Haloxylon ammodendron*, soil microbial respiration is supposed to prevail against the root respiration in our case. Soil microorganism and enzyme were reported to be restrained in extreme conditions (Luo and Zhou, 2006), which could lead to the decline of SR in August. While in F site, summer time is the thriving period of the more vigorous *Tamarix ramosissima*, of which root respiration is considered to be much more intense. Our results was different from Zhang et al. (2007)'s study which claimed the single-peak curve for seasonal variation, but was consistent with Tang and Baldocchi (2005)'s results. They suggested that SR increased in spring until late April and then gradually decreased in summer, which closely related to the decreases in soil moisture but not soil temperature.

Influencing factors

Although several important factors can influence SR, including soil temperature (Kirschbaum, 1995; Reichstein et al, 2000), soil moisture (Howard and Howard, 1993; Xu et al., 2004), net primary or net ecosystem quality (Janssens et al., 2001), and substrate concentrations (Raich and Schlesinger, 1992), previous studies have indicated that soil temperature and soil moisture are the most dominant influence factors of SR (Raich and Schlesinger, 1992; Davidson et al., 2000). SR is often modeled as Q_{10} or modified by a scalar dependent on water availability (Reichstein et al., 2003). Therefore, temperature and moisture can play the primary roles in evaluating SR. Almost all aspects of SR process are impacted by temperature (Luo and Zhou, 2006). In our study, there were also close relationships between soil temperature and SR, especially from the view of diurnal variation.

However, for long term estimation, soil temperature could not explain SR much clearly. In our study, soil temperature approached its peak values but SR was somehow restrained, which was supposed to be owing to the extreme low soil moisture in the desert area. Previous studies also pointed out the important role of fungal and bacterial in heterotrophic respiration in this arid ecosystem (Li et al., 2007). These microorganisms were sensitive to environment changes, and tend to activate within a certain range of temperature (Ma et al., 2012). In extreme high temperatures and low moisture condition, microbial enzymes may degrade and respiration activity becomes depressed (Luo and Zhou, 2006). Therefore, soil temperature and moisture should be both incorporated for long time estimation of SR. In other words, the seasonal pattern of SR was simulated by a bi-variable model which controlled by soil temperature and moisture (Tang and Baldocchi, 2005).

SR can be stimulated by an optimum combination of soil temperature and soil moisture, such as SR can be significantly increased by the rain events (Tang and Baldocchi, 2005). In drought-stressed arid and semiarid lands, SR rates were closely related to soil temperature during most of the period, but were altered greatly by the dramatic change of soil moisture in the meantime. Accurately estimate of SR based on the bi-variable model could be essential for dealing with the future climate change.

Negative efflux during night

During the continuous measurements period, it is noticed that negative carbon efflux (minus SR rates) occurred during the night time, which means desert soil, in some way, absorb CO_2 from the atmosphere, although the magnitude of this carbon sink seemed very slight. This is contrary of the conventional image of the soil as carbon source in the global carbon cycling. On such carbon sink phenomenon of desert soil, it now still remains a controversial issue (Stone, 2008; Schlesinger, 2009). Researchers tried to clarify such unusual fluxes in various ways: night time absorption of CO_2 by CAM plants maybe partly of the explanations (Hastings et al., 2005); in the Mojave Desert, the existence of soil crust organisms may responsible for a large part of the carbon sink (Wohlfahrt et al., 2008); some abiotic processes, including leaching (Kindler et al, 2011; Battin et al., 2009), photo-degradation (Rutledge et al., 2010; Brandt et al., 2009; Austin and Vivanco, 2006) and CO_2 dissolution (Emmerich, 2003; Serrano-Ortiz et al., 2010; Ma et al., 2013) can also be considered as potential reasons for the negative carbon fluxes. In the similar ecosystems near the study site, Ma et al. (2013) conducted soil sterilization experiment and pointed out that an inorganic process of CO_2 dissolution into and out of the soil solution during night and day, respectively. However, whether such explanations could be used in other ecosystems is still unclear and need further investigations. It is still uncertain that such a case is unique under some certain circumstances or commonly happening in other similar conditions. Thus, the mechanism of carbon sink phenomenon during the night time in some arid desert ecosystems could remain a hot topic in future global carbon cycling study.

Hysteresis between soil respiration and soil temperature

SR is usually closely related to soil temperature, but significant hysteresis between the diurnal variations of SR and soil temperature, i.e. decoupling of SR from soil temperature has been detected in our study, and similar results were also reported in other researches (Parkin and Kasper, 2003; Jia et al., 2013; Wang et al., 2014) such as in an aspen forest (Gaumont-Guay et al., 2006), in a Mediterranean oak-grass savanna (Tang et al., 2005), in a conifer and oak forest (Vargas and Allen, 2008) and also in arid desert ecosystems (Zhang et al., 2007; Ma et al., 2012). To interpret the hysteresis, two explanations have been proposed which were based on biological and physical theories, respectively (Philips et al., 2011). In a desert area, Zhang et al. (2007) found that the highest rate of SR occurred earlier than that of the air temperature and soil temperature, indicating that the acclimation of SR to temperature might take a certain time thus produce the hysteresis. While Bowling et al. (2002) and Tang et al. (2005) demonstrated that the diversion of photosynthetic C supplements to the soil may postpone the CO_2 emission from the soil, since SR is largely affected by newly produced photosynthates. On the other side, Philips et al. (2001) claimed that the hysteresis might be a physical process and the lag could just result from the heat and CO_2 transport process across the soil profile. In addition, this hysteresis could be affected by other factors including soil moisture. Riveros-Iregui et al. (2007) qualified the degree to which hysteresis between SR and soil temperature was affected by soil moisture and how the nonlinearity impacted estimation of SR.

Precipitation pulse in arid ecosystems

Rapid pulses of SR after precipitation and rewetting of dry soil are reported by several studies in various ecosystems (Davidson et al., 1993; Liu et al., 2002; Borken et al., 2003; Austin et al., 2004; Ma et al., 2012). For example, Huxman et al. (2004) reported that discrete precipitation pulses were critical stimulus for biological activity in the arid and semiarid regions of North America. Same situation could occur in another drought stress ecosystems where the annual precipitation is small and the rainfall is infrequent but sudden (Ma et al., 2012). The mechanism of rewetting stimulus on SR remains debating since several possible hypotheses have been proposed. Firstly, the quick increase of soil moisture can trigger the soil microbial activity within minutes or hours (Garcia and Belnap, 1996; Prieme and Christensen, 2001). The timing and magnitude of the rainfall events change the soil moisture considerably and then impact the activity of plants and microorganisms. For example, large pulses or successively small pulses of rainfalls can increase the photosynthetic activity of vascular plants (Huxman et al., 2004). Secondly, degassing phenomenon, which refers to the process of emission of CO_2 originally stored in soil pores but then physically repelled by the rainfall water, may produce an obvious but short period pulse immediately after the rainfall (Ruehr et al., 2010). In addition, the magnitude of the pulses is also affected by initial soil conditions, including soil moisture status (Cable et al., 2008) and the soil physical structure (Huxman et al., 2004), as well as by the drought level before the rainfall event (Jenerette et al., 2008). Abrupt increases in SR often occur after rainfall events, especially after a long time of drought (Jensen et al., 1996; Curtin et al., 2000).

2.5 Summary

For diurnal variation of SR, unimodal curves were displayed everyday during the entire measurement period. The maximum rates always appeared during the middle of the day, ranged from 11:00 to 16:00, while the minimum rates occurred during the night time, ranged from 22:00 to 6:00 of the next morning, suggesting that the range during the night was larger than that of the day time. The minimum rates were frequently minus values, with the extreme low value of -0.3~-0.4μmol/m^2/s, indicating the carbon absorption phenomenon in these arid desert ecosystems. Within one clear day, the variation of SR kept consistent with 5cm depth soil temperature. Inverted U and inverted V curves for diurnal SR variation was detected, which was also consistent with the diurnal variation pattern of soil temperature, and inverted U curves tended to appear in the hot summer days. Additionally, although diurnal variation of SR was closely related to soil temperature, the hysteresis between them was obvious, which showed that the SR were reaching the highest value earlier than soil temperature.

For seasonal variation, there were different tendencies between the two study sites. In F site, which was located outside the desert with thriving *Tamarix ramosissima*, SR rate in summer showed higher average values than spring and autumn. While in D site, with drier soil and less productive vegetation of *Haloxylon ammodendron*, SR in August displayed the lowest rates. In F site, the predominant contribution of SR in summer was assumed to be root respiration, while heterotrophic respiration prevailed in the D site. Root respiration tended to be intensified in summer owing to the thriving *Tamarix ramosissima* growth, while soil microbial respiration in D site was suppressed by extremely high temperature and low moisture in the hottest summer days.

In this study, SR showed close relationship ($P<0.001$) with soil temperature of 5cm depth under the soil surface. SR could be largely interpreted by soil temperature, while soil moisture did not exhibit huge fluctuation and remained extremely low in short period. For diurnal variation, SR could be easily simulated by soil temperature while long term estimation models of SR must incorporate both soil temperature and soil moisture. In conclusion, in these drought-stressed arid ecosystems, SR rates were closely related to soil temperature and also could be modified by soil moisture, as well as altered greatly by the dramatic change of soil moisture owing to the infrequent precipitation pulses.

Chapter 3 Spatial variations of soil respiration in arid desert ecosystems

3.1 Introduction

The process of soil respiration is affected by various abiotic and biotic factors, which all undergo significant temporal and spatial changes and hence difficult to grasp (Maestre and Cortina 2003). Understanding on spatial variation of SR is crucial to estimate representative SR within an ecosystem (Fang et al. 1998), including those in arid ecosystems, where the distribution of ecological factors as well as soil organisms show notably patchy structure (Titus et al.,2002; Schlesinger and Pilmanis 1998; Maestre and Cortina 2003). As pointed out by Titus et al. (2002), spatial variations of soil characteristics are largely controlled by the spatial organization of perennial plants in desert ecosystems, noted as ‘islands of fertility’. Besides this effects of the patchy structure of the plantation, heterogeneity of soil physical/chemical properties, including soil temperature, soil moisture, soil salinity/alkalinity and soil microbial organic carbon, may further complicate the spatial variation of SR (Maestre and Cortina 2003). As such, the specific spatial patterns of SR and its relationship with these soil properties in arid ecosystems seem to be still poorly understood.

In the present study, we try to characterize plot-scaled spatial variation of SR in three typical arid ecosystems, including sandy soil in the desert ecosystem (DE), silty clay loam in desert-farmland ecotone (or the transition ecosystem TE) and sandy loam in farmland ecosystem (FE). SR was estimated using the soda lime method, along with related soil properties such as soil surface temperature (ST), soil moisture (SM) and soil electrical conductivity (ECb) being collected simultaneously. Our main objectives are to estimate and compare the magnitudes of SR in different arid ecosystems and to figure out their controlling factors and also to illustrate their spatial variations by using geostatistic analysis.

3.2 Material and methods

3.2.1 Study area

The Gurbantunggut desert is the second largest desert in China and is characterized by semi-mobile sand dunes (Zheng and Wang 2014). This region has typical continental arid climatic features of scarce precipitation, intense evapotranspiration, windy, strong sunshine and severe variability of temperature (Zhang and Chen 2001). Three study sites were selected near the southern edge of the Gurbantunggut desert: the desert ecosystem (DE), the transition ecosystem (TE) and the farmland ecosystem (FE) (Figure 3-1 and Figure 3-2, Table3-1). These three ecosystems were representative communities of this region, and were also set to form a transect from natural desert to cultivated land.

The desert ecosystem (DE) was located at 44°25’N, 87°54’E. The annual mean temperature in this site is estimated to be 6-9 ℃ and the annual mean precipitation is about 200mm, with a large annual evaporation around 2000mm (Luo et al. 2008). The dominant vegetation species is *Haloxylon ammodendron*, accompanied by only a few short-life vegetations in spring under the irrigation of snow melt water (Zheng and Wang, 2012), and the total vegetation cover is less than 30% (Zhang et al. 2006; Zheng and Wang 2014). This site is mainly covered by aeolian sandy soil, which has a pH value about 8.5, a salinity content of 0.44mg/g and an electrical conductivity (EC) around 0.14 ms/cm (Guan et al. 2015).

The transition ecosystem (TE) was located at 44°17’N, 87°56’E. This site belongs to Fukang station of Desert Ecology, Chinese Academy of Sciences. Its annual mean temperature and annual precipitation is about is 5-7℃ and 160mm, respectively, with an annual evaporation larger than 1700mm (Wang et al. 2008). The plant community is dominated by *Tamarix ramosissima*, a deep rooted halophyte shrub which has a canopy coverage of about 17% (Xu et al. 2007; Ma et al., 2013). The soil is a silty clay loam with high salinity content about 17mg/g, electrical conductivity EC value larger than 4 mS/cm and pH value around 8 (Guan et al. 2015; Ma et al. 2012). The salt is usually crystallized on the soil surface to form the white salt layer (Guan et al. 2015).

The farmland ecosystem (FE) was located at 44°17’N, 85°51’E in Shihezi oasis. This site belongs to the Wulanwusu Agrometeorological Station. Its annual mean temperature and precipitation is estimated to be 7℃ and 210mm, respectively. The annual evaporation reaches to the value of 1600mm (Wang et al. 2013a). Cotton is the major economic crop and is densely planted in the middle April and harvested in the middle of October. The soil texture is mainly sandy loam with the average soil bulk density of 1.30g/cm^3 (Wang et al. 2013a). A noteworthy feature is that this site was characterized by different irrigation methods including drip irrigation and flood irrigation. Flood irrigation was conducted in the middle part of this sampling site about 20 days before the experiment.

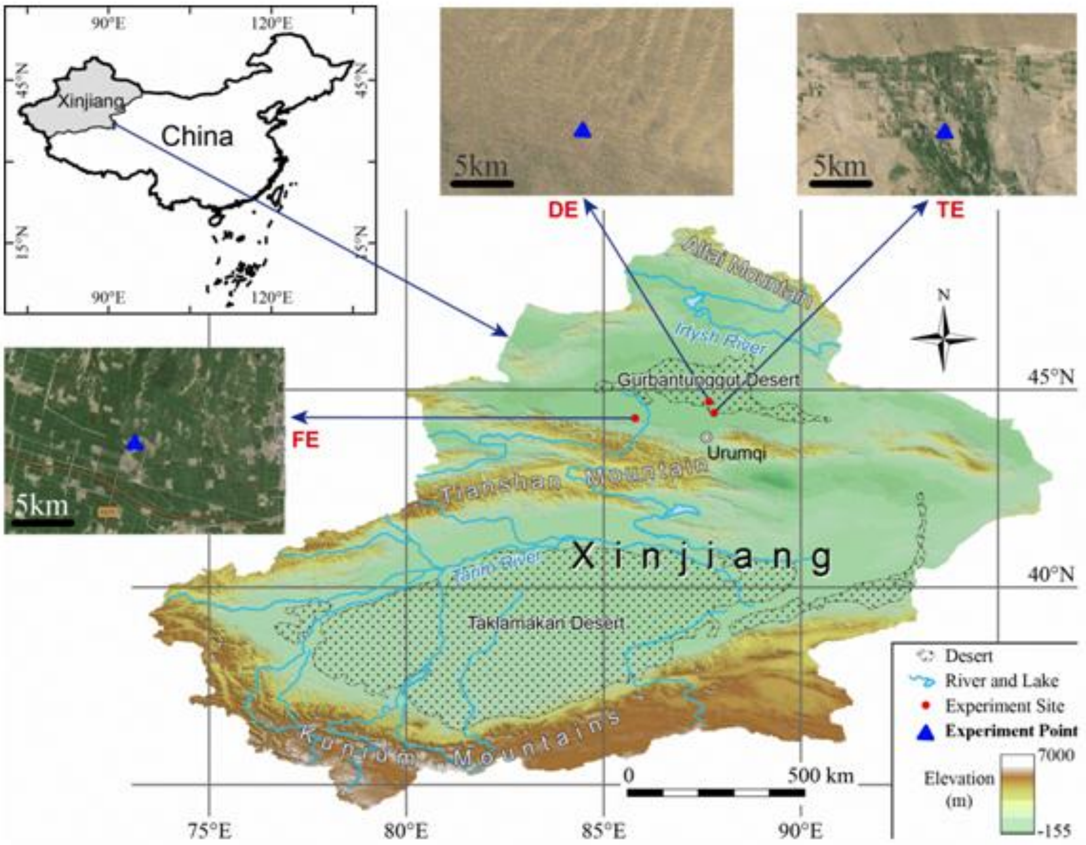

Figure 3-1 Location map of study sites and sampling designs. FE: farmland ecosystem, DE: desert ecosystem, TE: transition ecosystem.

Table3-1 Basic information of the three ecosystems—DE TE and FE.

Ecosystems	Location	Annual temperature	Annual precipitation	Annual evaporation	Dominant plantation	Soil type	Management
Desert (DE)	44°25’N 87°54’E	6-9 ℃	200mm	2000mm	*Haloxylon ammodendron*	Sandy soil	Natural No irrigation
Transition (TE）	44°17’N 87°56’E	5-7 ℃	160mm	1700mm	*Tamarix ramosissima*	Silty clay loam	Semi-natural No irrigation, Adjacent to the cultivated land
Farmland (FE）	44°17’N 85°51’E	7 ℃	210mm	1600mm	Cotton	Sandy loam	Artificially management, Irrigation

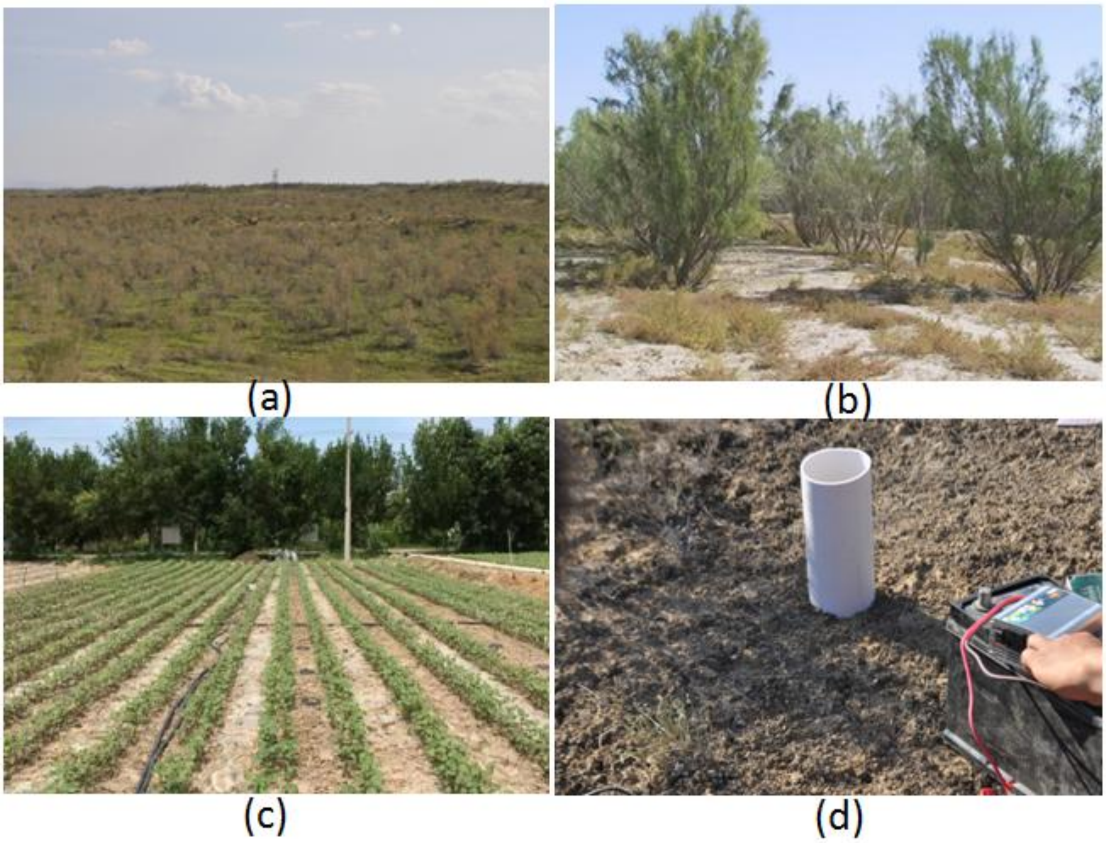

Figure 3-2 Photographs of the landscape of the three study sites and chamber *in situ*. (a): DE, desert ecosystem, (b): TE, transition ecosystem, (c): FE, farmland ecosystem, (d) chamber *in situ*.

3.2.2 Experiment design and soil respiration measurement

In both DE and TE sites, 36 soil sampling pixels were set up in late August 2012 at a 5×5m grid within a 30m×30m plot. The FE was investigated in early September of 2013 and 27 soil sampling pixels were set up at a 5m resolution within a 10m×40m plot subject to local conditionality (Figure 3-3). Although different sampling strategies were adopted between DE/TE and FE, each sampling design could reflect the respective spatial characteristic of the three sites. The experimental dates were decided when soil temperature and soil moisture are approaching their annual average levels.

Soil respiration was measured using soda lime absorption method followed the protocol of Keith and Wong (2006), which enabled us to conduct a number of measurements simultaneously. In all three ecosystems, SR was measured continuously over a 24h sampling period to provide a mean daily rate (gC/m^2/d). Before the measurements, the chambers (made of PVC collar with an area of 86 cm^2 and a volume of 1800 cm^3) were inserted into the soil surface to a depth of about 2 cm several days ahead of time when soda lime was placed in order to avoid effects from soil disturbance (Figure 3-4). The aerial part of live vegetation inside the chambers was also removed to prevent CO_2 uptake. Soda lime in granules of 2-4 mm mesh size was used. Approximately 15g (in DE and TE, 25g in FE) of soda lime per dish (aluminum dish with an area of 19.6cm^2 and a lid) was oven-dried at 105℃ for 20h until reaching a constant weight. The soda lime loaded dishes were weighed in order to record exact initial dry weights. Then the soda lime was rewetted using a spray and the dishes were covered with lids, put into airtight plastic bags and transported to the fields. Afterwards, we placed the dish on the soil surface inside the chamber, removed the lid of the dish and finally sealed the chamber tightly with plastic membrane. The closing and opening time of each chamber was recorded to exactly determine the absorption period.

After having absorbed CO_2 emitted from soil for about 24h, dishes were taken out and covered immediately before transported to the laboratory promptly, in which they were oven-dried at 105℃ to constant values for reweighing. In order to reduce experimental errors, soda lime was handled with care to prevent extra exposure to the air during the entire measurement period. Moreover, blank measurements were made to account for CO_2 that was not released by soil respiration but yet absorbed by soda lime during the experimental period, which were also followed Keith and Wong (2006)'s procedure.

The calculation formula is based on Keith and Wong (2006):

$$\text{Soil CO}_2\text{ efflux}\left(\text{gCm}^{-2}\text{day}^{-1}\right)$$

$$= \frac{[(\text{sample weigh gain(g)} - \text{mean blank weight gain(g)}) \times 1.69]}{\text{chamber area }(\text{m}^2)}$$

$$\times \frac{24(\text{h})}{\text{duration of exposure(h)}} \times \frac{12}{44} \tag{3.1}$$

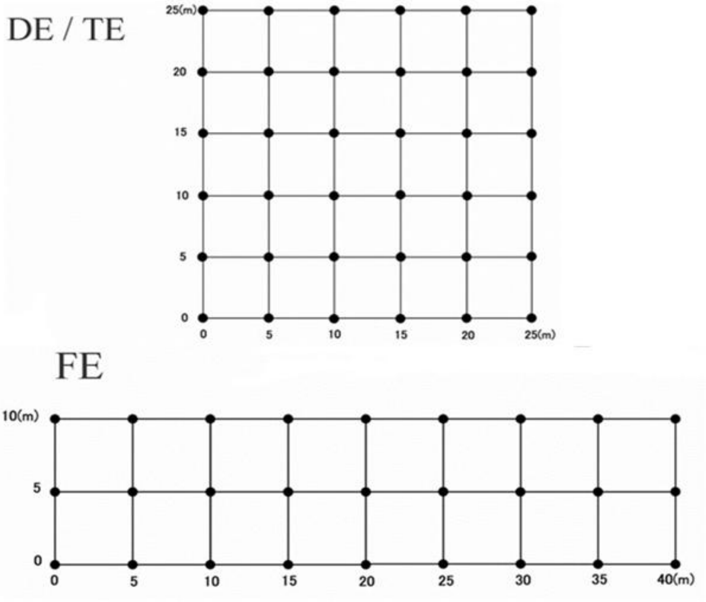

Figure 3-3 Sampling points in the three ecosystems. 36 points for DE and TE, 27 points for FE.

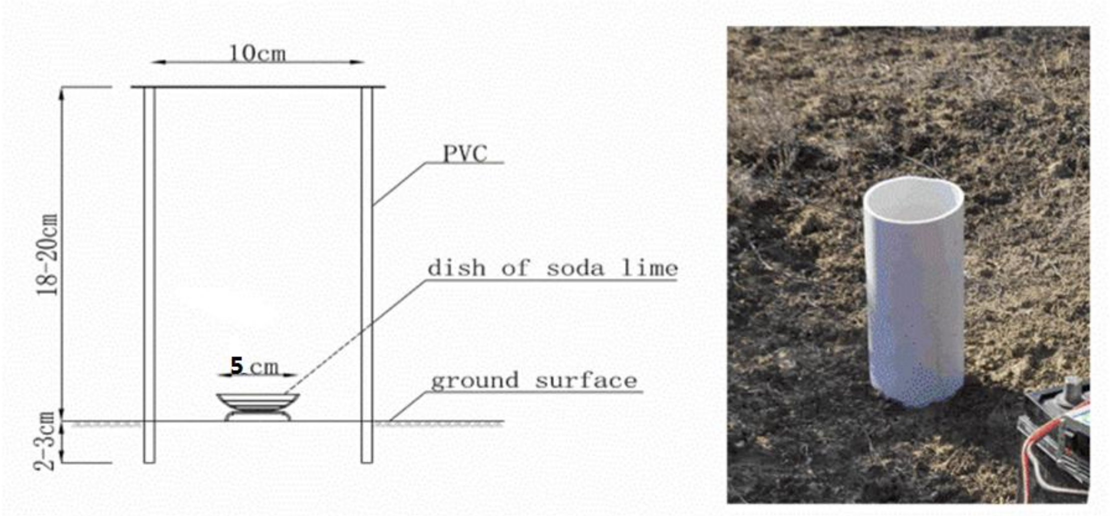

Figure 3-4 Illustration of the chamber and soda lime placement (left) and autograph of the chamber in the field (right).

3.2.3 Measurement of environmental factors

Along with soil respiration measurements, several controlling environmental factors were also recorded during the sampling periods. Soil moisture (SM), soil dielectric constant (εb), pore water conductivity (ECp), electrical conductivity (ECb) and soil surface temperature (ST) were measured using time domain reflectometry (TDR, Delta-T Devices, Cambridge, England). Additionally, ST was also measured using an infrared video thermography of FLIR CPA 0170 (FLIR Systems, Wilsonville, OR, USA). However, the data of ECp in DE and TE, and the ECb data in DE were not recorded accurately and thus eliminated from further analysis.

3.2.4 Statistics analysis

Descriptive statistics including mean value, standard deviation (SD) and coefficient of variation (CV) were calculated and one-way analysis of variance (ANOVA) and Tukey' s HSD test were used to verify whether there were significant differences among the mean values at the 95% confidence levels. The correlations between SR and ST, SR and SM, as well as SR and soil electrical conductivity were analyzed using Pearson correlation method.

Geostatistics were then used to evaluate spatial variation in these ecosystems. Geostatistics can be used to estimate of the magnitude of spatial dependence as well as to evaluate the scale of spatial autocorrelation among different measurement points (Goovaerts, 1998; Robertson 1987). The central tool in geostatistics is the semivariance statistic. The calculation of semivariances was conducted with the geostatistics software named GS+ (Gamma Design, 1995) and was estimated by the equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{n} [z(s_i) - z(s_i + h)]^2 \tag{3.2}$$

Where N(h) is the number of measurement pairs separated by distance h, $z(s_i)$ is the value of the variable of interest at location s_i, and $z(s_i + h)$ is its value at a location at distance h from $\mathrm{s_i}$ (Ettema and Wardle 2002). Graphing the semivariance values across all separation distances provided the semivariogram (Stoyan et al. 2000)..

3.3 Results

3.3.1 Descriptive statistics of soil respiration and controlling factors

For the three ecosystems, the statistical results of the SR and respective controlling factors of the three ecosystems were summarized in the Table 3-2, and the comparison of SR, ST and SM were showed in the Figure 3-5. The average value of SR of TE was the highest (0.166 gC/m^2/h) among the three sites, almost two times higher than the value of DE (0.061 gC/m^2/h), but only slightly higher than that of FE (0.147 gC/m^2/h). Considering the CV values of SR, TE had the maximum (57.8%), while DE (29.5%) was approximately at the same low level with that in FE (27.2%), indicating that the variation of SR in TE was much significant than in the other two ecosystems. The difference of soil moisture among the three ecosystems was also remarkable, with the value of 20.1% in FE, much greater than that of TE (9.70%) or DE (4.18%). However, TE presented the most significant CV value of 46.5%, suggesting the largest variation of soil moisture in this ecosystem.

Soil electrical conductivity (ECb) of DE could not have been detected precisely using TDR, mainly because of the extremely low salinity content close to zero (<0.5 mS/m) in this area (Guan et al. 2015), as the resolution of TDR on ECb was 1.0mS/m. Although in FE, ECb value was obviously larger than that in TE, the CV values of both two ecosystems were very similar. The average values of soil surface temperature in three ecosystems were different to each other, but their CV values remained relatively low levels (5.40% in DE, 7.40% in TE and 10% in FE), indicating that temperature was less variable in all three ecosystems. Small CV values of ST and large CV values of SR and SM suggested that the effect of soil temperature on SR variation was not significant, whereas the soil moisture may play a more important role in these arid ecosystems.

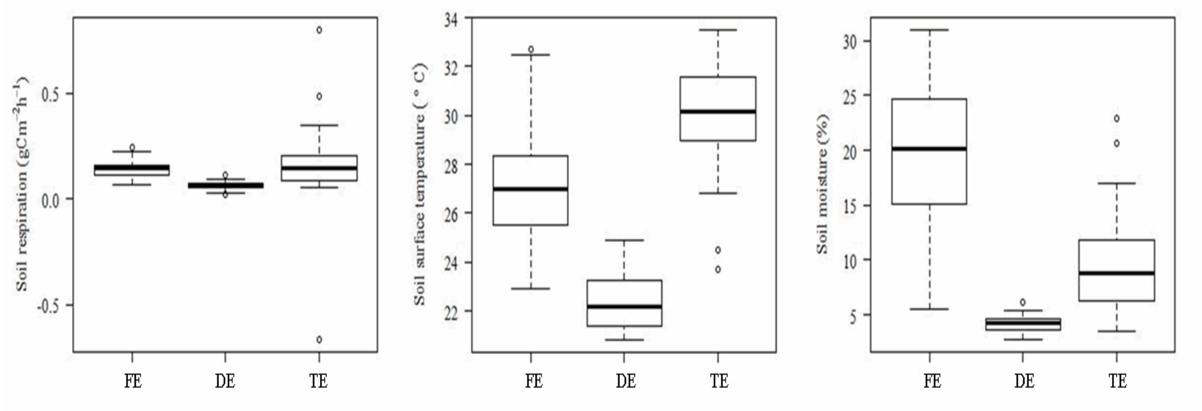

Figure 3-5 Comparison of SR, ST and SM over three different ecosystems. Boxes encompass the 25% and 75% quartiles of the entire dataset. The central solid line represents the median, bars extend to the 95% confidence limits, and the dots represent outliers.

Table 3-2 Summary of SR and controlling factors in each ecosystem.

Variables	Desert Ecosystem (DE) n=36		Transition Ecosystem (TE) n=36		Farmland Ecosystem (FE) n=27	
	Mean ± SD	CV(%)	Mean ± SD	CV(%)	Mean ± SD	CV(%)
Soil Respiration (SR, gC/ m^2/h)	0.061±0.003 ^{a}	29.50	0.160 ± 0.33 ^{b}	57.80	0.147 ± 0.008 ^{a}	27.20
Soil Temperature (ST, ℃)	22.5±0.204 ^{a}	5.40	30±0.369 ^{c}	7.40	27.3± 0.516 ^{b}	10
Soil Moisture (SM, %)	4.18±0.124 ^{a}	17.90	9.70 ± 0.752 ^{b}	46.50	20.1±1.302 ^{c}	33.80
Electrical Conductivity (ECb mS/m)	-	-	6.31±1.638 ^{a}	36.10	13.22 ± 2.168 ^{b}	35.40

Mean ± SD, n = 36, 36 and 27 for DE, TE and FE, different letters indicate significant differences (ANOVA, Tukey's b test, $P < 0.05$). CV: Coefficient of variation.

3.3.2 Correlations between soil respiration and controlling factors

Scatter diagrams between SR and environmental factors of the three ecosystems were presented in Figure 3-6. Correlation analysis (Table 3-3) suggested that in DE, there was no significant correlation between SR and environmental factors, indicating that no single factor could adequately explain the variation of soil respiration. In this area, the soil electrical conductivity value approached zero, indicating rather low salinity content of the soil. Similar situation was also found in TE, with no significant correlations between SR and environmental factors being identified. However, significant negative correlation was found between soil temperature and soil moisture ($P<0.05$), as well as between soil temperature and soil electrical conductivity (ECb) ($P<0.01$) in TE, with values of -0.381 and -0.482, respectively. In addition, the correlations between soil moisture and soil electrical conductivity (ECb) were highly significant in all the cases ($P<0.01$), suggesting the strong correlation between the two parameters.

In FE, the correlation of SR and ST had a negative value of -0.412 ($P<0.05$), indicating that increasing of soil surface temperature may lead to a decline of soil respiration rate in this area. For all three ecosystems, soil respiration had positively correlations with both soil temperature and soil moisture ($P<0.05$), but no significant relationship was found with soil electrical conductivity.

Table 3-3 Correlations between SR and controlling factors of the three ecosystems.

		SR	ST	SM	ECb
Desert Ecosystem	SR	1.000			
	ST	0.016	1.000		
	SM	0.095	0.300	1.000	
	ECb	-	-	-	
Transition Ecosystem	SR	1.000			
	ST	-0.098	1.000		
	SM	0.014	-0.381*	1.000	
	ECb	-0.270	-0.482**	0.886**	1.000
Farmland Ecosystem	SR	1.000			
	ST	-0.412*	1.000		
	SM	0.169	-0.379	1.000	
	ECb	-0.113	-0.224	0.809**	1.000
Total	SR	1.000			
	ST	0.237*	1.000		
	SM	0.211*	0.248*	1.000	
	ECb	0.160	0.140	0.836**	1.000

* and ** indicate significant correlations at $P < 0.05$ and $P < 0.01$, respectively.

SR: soil respiration rate; ST: soil surface temperature; SM: soil moisture; ECb: soil electrical conductivity.

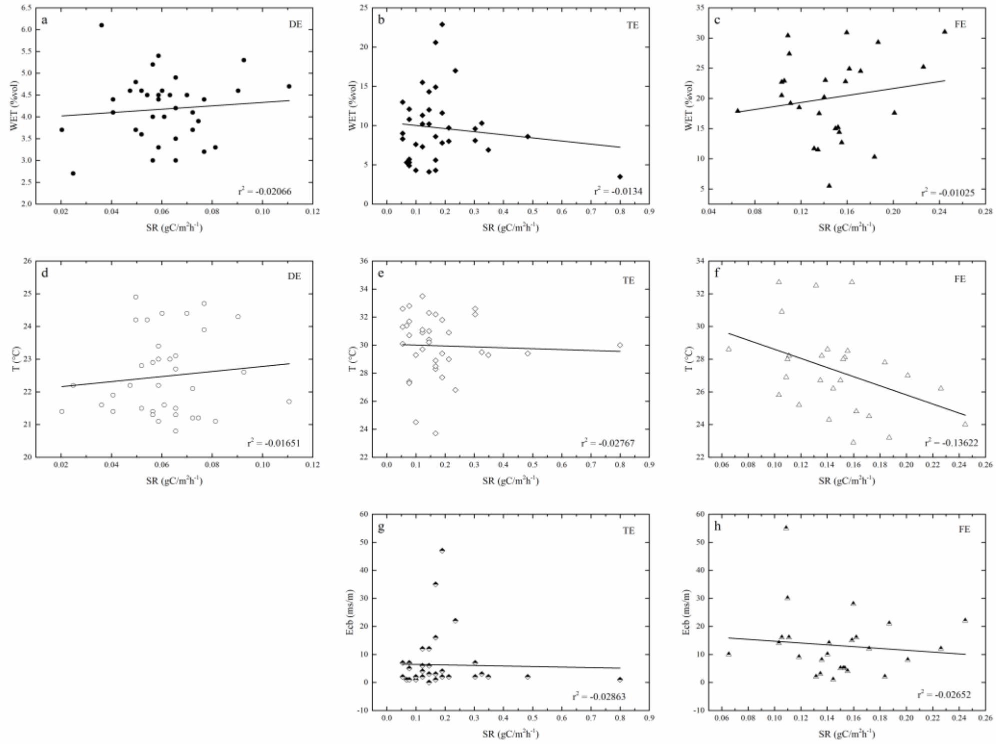

Figure 3-6 Scatter diagrams between SR and environmental factors of the three ecosystems.

3.3.3 Spatial structures of soil respiration and controlling factors

Semivariograms of soil respiration rates, soil temperature, soil moisture and soil ECb of the three ecosystems are given in the Figure 3-7. Furthermore, the key parameters of semivariograms are shown in the Table 3-4. The optimal model of SR semivariogram was found to be a linear model, while Gaussian model for ST and spherical models for both SM and soil ECb fit best. In general, most models had high coefficients of determination, as judged from their R^2 values.

The proportion of nugget to sill was calculated to evaluate the magnitude of the spatial dependence in each site. As a rule of thumb, strong spatial autocorrelation occurs when the proportion is lower than 0.25, and moderate autocorrelation happened when the proportion is within the range of 0.25 and 0.75, and weak autocorrelation with the proportion larger than 0.75 (Cambardella et al. 1994). From the Table 3-4, the value of nugget to sill for SR in DE was 0.907, followed by 0.62 in TE and 0.46 in FE. This suggested that a very weak spatial dependence occurred in the desert ecosystem, indicating a rather homogeneous or random spatial structure in this site, while moderate spatial dependences were found in both TE and FE sites. From DE to TE and FE, the spatial dependence was becoming stronger and the spatial heterogeneity was gradually getting apparent. In both DE and TE, the spatial dependence of SR was mainly affected by random factors, especially in DE because they had relative large nugget values, whereas in FE, the structural factors mainly accounted for the spatial dependence. The ranges of spatial dependence of the three ecosystems were all about 16 m, indicating that the spatial dependence of soil respiration rates occurred almost within the same scale.

Semivariograms of soil moisture had a range of 9.03m, 8.33m and 25.59m in DE, TE and FE, respectively, suggesting that the spatial dependence of soil moisture varied in different scales among different ecosystems. According to the semivariogram of soil moisture in FE, the patchy distribution of soil moisture was seldom appeared, and the heterogeneity was large and smoothly continuous, reflecting a gradual changing structure, which was probably owing to the zonal distribution of cotton plantation. As a comparison, obvious patchy structures and more shapely discontinuity were identified in DE and TE, reflecting hot and cold spots of the measured values (Ettema and Wardle 2002), as showed in the Figure 3-8. This heterogeneity was mainly attributed to the patchy distribution of the plantation of *Haloxylon ammodendron* in DE and *Tamarix ramosissima* in TE. Additionally, the difference of ECb between TE and FE showed similar situations with soil moisture.

Table 3-4 Summaries of semivariogram model parameters for soil respiration and controlling factors.

Variables	Model	Ecosystem	Nugget variance (C)	Sill variance (C_0 + C)	Range A0 (m)	C/(C_0+C)	RSS	R^2
SR	Linear	DE	0.000337	0.000371	16.35	0.907	7.188E-11	0.770
		TE	0.012939	0.020800	16.35	0.622	6.740E-07	0.949
		FE	0.000836	0.001802	16.03	0.464	1.358E-09	0.993
ST	Gaussian	DE	0.038	2.186	15.53	0.017	0.008151	0.989
		TE	0.870	5.708	4.03	0.152	0.463	0.308
		FE	1.290	11.589	12.72	0.111	0.422	0.988
SM	Spherical	DE	0.055	0.613	9.03	0.090	0.004792	0.514
		TE	1.410	21.800	8.33	0.065	5.660	0.379
		FE	0.1	70.2	25.59	0.001	29.100	0.976
ECb	Spherical	DE	-	-	-	-	-	-
		TE	16.3	113	8.44	0.144	94.700	0.479
		FE	11.7	166.5	17.43	0.070	0.119	1

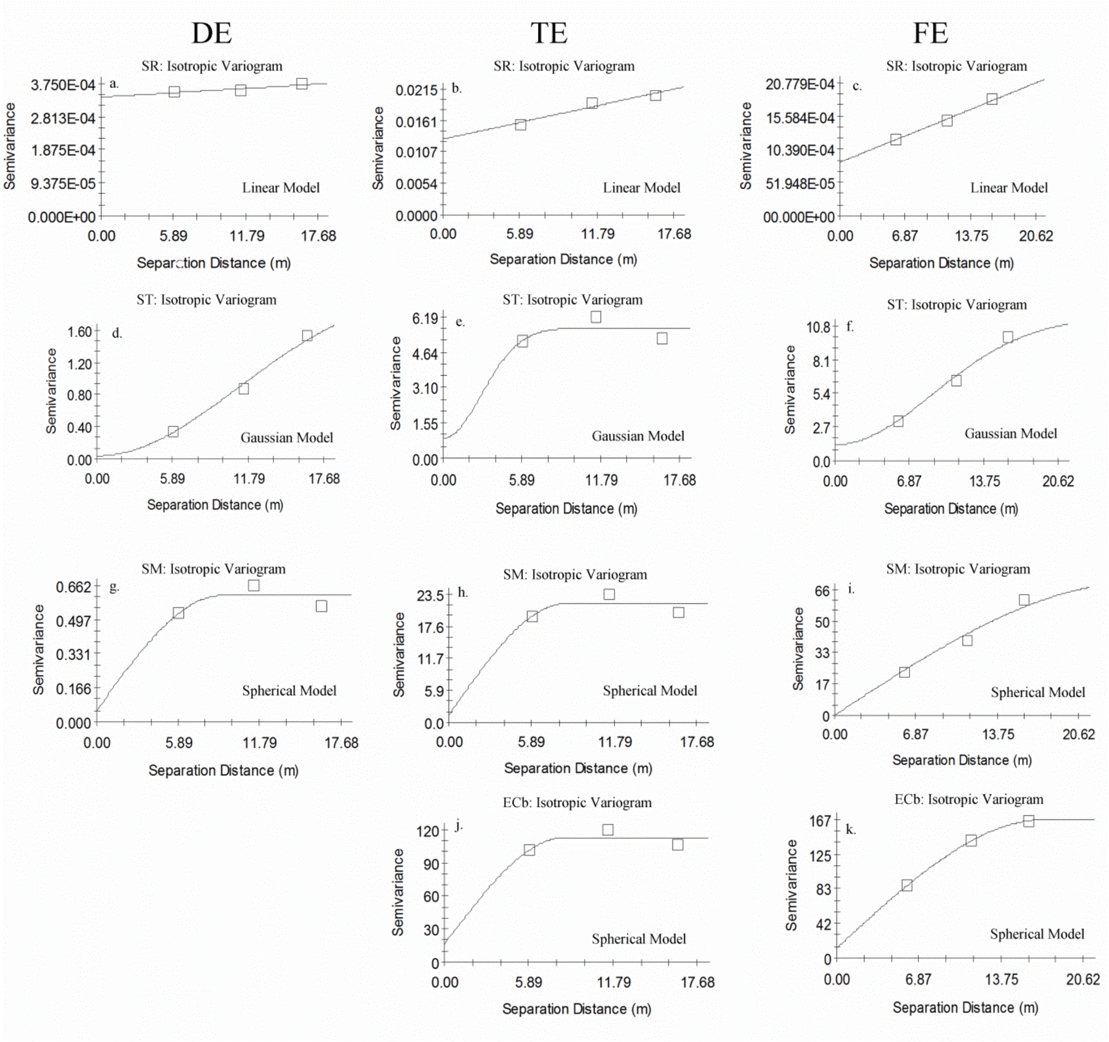

Figure 3-7 Semivarigrams for soil respiration (SR), soil temperature (ST), soil moisture (SM) and soil electrical conductivity (ECb) of the three ecosystems.

3.4 Discussion

3.4.1 Soil respiration and environmental factors

Although the soda lime method, which was used to measure the daily average soil respiration rates over three arid ecosystems in this study, remains disputable about its accuracy, we are relatively confident about our results since a number of similar counterparts were reported. For instance, soil respiration rate of TE was found to be comparable to those reported in similar ecosystems (Sponseller, 2007; Zhang et al., 2010; Ma et al., 2012; Wang et al., 2013a), while the soil respiration in FE was parallel with the results of Zhang et al. (2012) and Bai et al. (2015). Even in DE, soil respiration also had a similar order of magnitude with the data from the review of Raich and Schlesinger (1992) and Cable et al. (2008) and (2011). Although flow-through non-steady-state (FS-NSS) IRGA method are widely used to continuously measure soil respiration rate nowadays, simultaneous measurements of a large number of replicates still require this traditional soda lime absorption method be applied.

Soil temperature and soil moisture are generally considered to be the key controlling factors that account for variations in SR (Tang and Baldocchi, 2005; Fang and Moncriff, 2001; Davidson et al., 2000). Fluctuations of soil temperature and/or soil moisture can well explain the temporal variation of soil respiration, both diurnally and seasonally. Furthermore, a combination of soil temperature and soil water content can usually improve the estimation of soil respiration. For example, the sensitivity of soil respiration to temperature frequently increases as soil water content increases (Xu and Qi, 2001; Borken et al., 2002; Jassal et al., 2008). However, opposite cases were also identified, e.g. high soil temperature suppressed soil respiration which was mainly because of drought stress nearby TE site as found by Naramoto and Wang (2012).

However, it seems that no single factor can explain the spatial variation adequately as compared with the temporal variation (Xu and Qi, 2001; Epron et al., 2004). Spatial variation of soil respiration could occur dramatically even within small distance of centimeters (Ngao et al., 2012), and there tends to be no factor which can be solely responsible for such substantial heterogeneity correspondingly. Similarly, in our case, no significant correlation between soil respiration and controlling environmental factors were found in both DE and TE sites, identical to the results from Panosso's research (2009). Significant relationships were reported for spatial variation of SR and soil moisture (Adachi et al., 2006; Zhang et al., 2010; Wang et al., 2013b), C/N ratio and topsoil bulk density jointly (Ngao et al., 2012), plant root and plant residue patterns (Stoyan et al., 2000) in previous studies, but the correlation between spatial variation of SR with single soil temperature or soil moisture was barely reported, suggesting that when spatial variation is investigated, soil properties and/or vegetation information should be paid more attention to beyond soil temperature and soil moisture.

Sampling size may be another important aspect that having determined the correlations between SR and environmental factors. Larger sampling sizes generally produce more precise estimations, but can be usually limited by labor or time constraints, and also depend on the spatial heterogeneity of SR rates (Adachi et al., 2005). In current study, only 36 or 27 sampling pixels were established in each ecosystem, which may not be sufficient. However, when all the data of the three ecosystems were combined together, correlations between SR and controlling factors emerged, suggesting that sampling size may need to be properly determined.

3.4.2 Spatial variations of soil respiration in three ecosystems

Spatial variation of soil respiration occurs at a variety of different scales, from a few square centimeters up to several hectares and finally the entire globe (Rayment and Jarvis, 2000; Luo and Zhou, 2006). Compared with temporal variation of soil respiration, which can be frequently well explained by environment factors such as soil temperature and soil moisture, the spatial variation of SR tends to be more complicated because of its high spatial variation, especially in semiarid and arid areas (Schlesinger and Pilmanis, 1998; Maestre and Cortina, 2003;). As a result, there are always cases that no evident controlling factor could be detected with significant spatial variations, except that variables related to forest structure may have explained some of the variation of soil respiration (Barba et al., 2013). Generally, different positions apart from a plant have been investigated for spatial heterogeneity of SR in arid ecosystems, in which the existence of vegetation might play an important role in manipulating the spatial heterogeneity (Titus et al., 2002; Schlesinger and Pilmanis, 1998), e.g., Ma et al. (2012) designed an experiment in an adjacent site near TE to measure SR rates along a straight sampling line from the position near the stem of a plant stretch to the interspace in order to detect the spatial variation, and suggested that SR rates decreased with the increase of distance away from the plant stem. In addition, Wang et al. (2013b) also found that the highest values of soil respiration, soil moisture as well as soil microbial biomass carbon were occurred in the locations near the positions of scrubs.

Alternatively, we aimed to provide a meaningful reference considering the larger plot scale heterogeneity of soil respiration. In this study, we compared the spatial variation of soil respiration under three different ecosystems and found distinctly different degree of spatial variation among them. Soil respiration in the TE had a great variance with the CV of 57.8%, much larger than those of DE (29.5%) and FE (27.2%). Compared to DE and FE, the soil surface of TE may exhibit a more “patchy” structure feature (Titus et al., 2002; Wang et al., 2013b). In this site, the predominant plantations of *Tamarix ramosissima* were sturdy with larger diameter at breast height (DBH) and basal area (BA), which were scattered to develop “islands of fertility” phenomenon. Besides soil respiration rate, the CV of soil temperature, soil moisture and soil electrical conductivity in TE were all larger than in DE and FE, indicating the most significant heterogeneity among the three ecosystems. In DE, *Haloxylon* *ammodendron* was relatively scarce with lower productivity. Soil respiration was weak and less influenced by the distribution pattern compared with TE.

Although the descriptive statistics (SD and CV) are the first indicators of spatial variation, they cannot reveal the real situation of spatial heterogeneity because of the absence of the information about the points of the spatial distribution (Fang et al., 1998; Panosso et al., 2009). Hence, geostatistics were employed in this study to figure out their spatially structured phenomena which may provide a means for defining the magnitude of spatial dependence as well as the scale of spatial autocorrelation (Kosugi et al., 2007; Robertson, 1987). As a central tool in geostatistics, the semivariance statistic is extensively applied to evaluate the spatial heterogeneity of SR in forest ecosystems (Stoyan et al., 2000; Kosugi et al., 2007; Rayment and Jarvis, 2000) or farmland ecosystems (Panosso et al., 2009; Zhang et al., 2010), but there are few reports that clarify the spatial structure of soil respiration in the arid desert ecosystems using geostatistical analysis. Wang et al. (2013b) conducted an experiment in an area adjacent to the our TE site which contained 42 sampling points with 2m grids and found a moderate spatial autocorrelation of SR with the nugget to sill value of 0.49 and a range of 4.78m, compared with our more homogeneous distribution as deduced from larger nugget/sill value of 0.62 and range of 16.35m. It is reported that the range of spatial variation models of SR changed temporally (Stoyan et al., 2000; Ohashi and Gyokusen, 2007) and could also be affected by the plot size (Konda et al., 2008), which might account for the discrepancy.

Previous research has found that vegetation and topographic status in the monoculture plantations were considered to be relatively homogeneous (Adachi et al., 2005). However, in our case, based on geostatistic method rather than CV values, the spatial heterogeneity of the cotton field (FE) exhibited most significantly, probably due to the different irrigation management within this site. Our sampling points spread on the site which was characterized by two different irrigation methods, including drip irrigation and flood irrigation, and flood irrigation was conducted in the middle part of this sampling site about 20 days before the experiment, which could dramatically change the soil properties and generate inhomogeneity of SR rates in this area. As the Figure 3-8 showed, soil moisture and soil respiration were significantly larger in the middle area where irrigation was conducted. Compared to DE and TE, which presented the patchy structure of soil respiration and soil moisture, FE tended to show zonal distribution (Figure 3-8) mainly owing to the vegetation and irrigation characteristics. In summary, although CV values showed that TE had the largest variation, we believe that the more reliable geostatistic method provided the real spatial heterogeneity status, with the order of significance as FE>TE>DE.

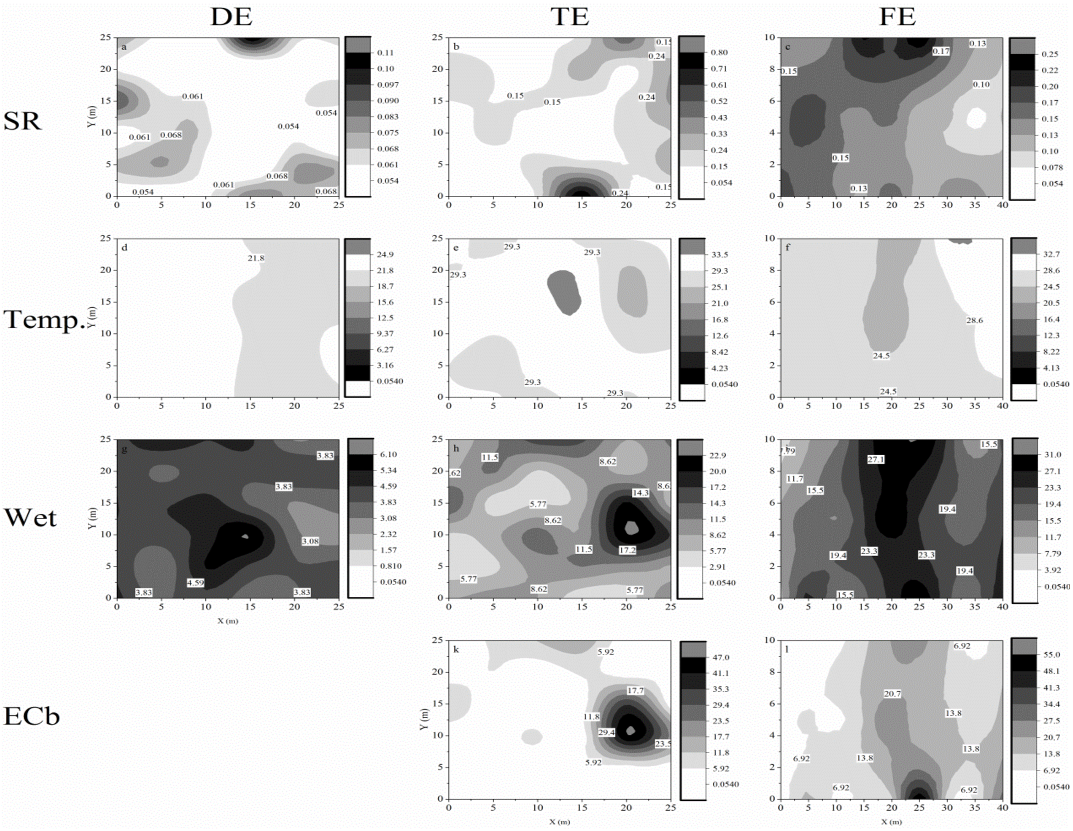

Figure 3-8 Isopleths for the soil respiration (SR), the soil temperature (ST), the soil moisture (SM) and the soil electrical conductivity (ECb) of the three ecosystems.

3.5 Summary

Geostatistical analysis offers a reliable method to investigate the spatial variation of soil respiration. Soil respiration in desert ecosystem tends to show relatively small spatial variation owing to the homogeneous structure of soil properties. While in transition area, larger xerophytes may play a more important role in controlling the spatial pattern of soil surface properties including soil respiration. In arid region, irrigation is necessary for agriculture production, which can result in significant change in soil respiration. Soil moisture may be the decisive factor in many occasions in this drought area, but different from temporal variation, multiple factors are needed to verify the spatial variation of soil respiration.

Chapter 4 Soil respiration as influenced by salinization in arid ecosystem: a laboratory approach

4.1 Introduction

Soil salinity, which degrades land by increasing soil salt concentration, especially in unirrigated landscapes, is considered to be an emergent threat to agricultural productions in arid and semiarid areas (Keren, 2000; Liang et al., 2005; Bossio et al., 2007; Yuan et al., 2007; Wong et al., 2008; Wang and Li, 2013). Saline soils usually have an EC > 4 dS m^{-1}, which is unfavorable to the growth of most crop species (Bui et al., 2013).

Salt accumulation generally occurs where precipitation is relatively lower than evaporation (e.g. in our study site, annual precipitation was around 200 mm but the evapotranspiration was larger than 2000 mm, ten times more than the rainfall) and leaching is insufficient to move salts out of soil profiles. Due to the increasing agriculture irrigation and tree cutting, second salinization occurs more frequently and further enlarges such salt-affected area (Pannell and Ewing, 2006; Mavi et al., 2012). According to the statistics from UNESCO and FAO (2006), the area of saline soils in the world was estimated at about 397 million ha (Wang, 2015), and this area is likely to increase in the future due to the secondary salinization. It has been proved that salinity has negative effects on plant growth and microorganism metabolism because of the osmotic potential of the soil solution is low and ion uptake is imbalanced (Yan and Marschner, 2013). As a result, SR is hence projected to be affected by soil salinity.

Although the effects of soil salinity on SR have been investigated somehow, such studies mainly take agriculture ecosystems and wetland ecosystems into consideration, and the results are quite inconsistent among different studies. Furthermore, information on the response of SR to soil salinity in desert ecosystem is still limited. In China, the salt-affected soil area is estimated at 99.13 million hm^2, about 1/9 of the world's total, and is wide spread in northwest China (Zhang, 2010). Xinjiang is the largest salt-affected soil region, which takes up 1/3 of the total salt soil area of China. Arid and semiarid regions are so expansive that they cannot be neglected in the global ecosystem studies (Wang, 2015). Consequently, SR research in such typical regions is considered to be an important topic and is able to provide valuable part in the carbon cycling system.

Previous studies have indicated that SR can be regulated by various environmental factors, including abiotic factors (e.g. soil temperature, soil moisture, substrate concentration) and biotic factors (e.g. microbial community, microbial biomass, root density) (Boone et al., 1998; Jiang et al., 2013; Karhu et al., 2014; Whitaker et al., 2014). As a result, SR deploys strong spatial-temporal heterogeneity and can be easily changed by these factors under field conditions (Moyano et al., 2013; Song et al., 2013; Zhang et al., 2013). Furthermore, field works may only sample salt concentrations within a certain range, and the components of salt are too complex to figure out the response of SR to a specific salt type (Mavi et al., 2012). It is therefore hard to isolate the controlling effects of salt types or contents on SR under field conditions solely. In arid areas, soil salinity is expected to increase since the low soil moisture can always favor the secondary salinization (Bui, 2013). Therefore, conducting controlling experiment under laboratory condition is a possible way to not only clarify the effects of salt type and contents on SR, but also to explore the likely mechanisms that affect SR under severe salinity environment (Mavi et al., 2012).

To investigate the effects of salt types and contents on SR from desert soils in arid areas, soils of F site and D site were collected and three salt types (NaCl, Na_2CO_3 and Na_2SO_4) were added into the two soils at 0% (control, CK), 2%, 5% and 10% (w/w). It was hypothesized that SR of both two soils would show different responses to different salt types, and SR would decrease with the increase of salt contents.

4.2 Materials and methods

Salinity gradient controlling experiment in the laboratory was carried out in October of 2011. Previous studies revealed that soils in desert ecosystems of Gurbantungut desert are generally full with sodium type of salts (Wang, 2015). Therefore, in this laboratory controlled experiments, three types of typical salts in this region-NaCl, Na_2CO_3, Na_2SO_4 were selected and four gradients of salt contents-0%, 2%, 5%, 10% (w/w) were set, which 0% meant soil samples were treated without salt addition and kept initial salt content. Soil samples from both F site and D site were collected in late September of 2011, which were mainly composed of soil from the depth between 20cm to 1m below the soil surface. Three types of salts, four levels of salt contents and three repetitions were designed, and soils were divided into 36 samplings evenly (3 kg in weight for each sampling) after the process of mix up for both the two soil sources (Figure 4-1). After the addition of salt solution into the soil samplings, SR were measured using Li-cor 840 and small chamber four times on the day 4, 7, 12 and 18 for F site soil and on the day 3, 6, 11 and 17 for D site soil. During the intervals of measurement, slight watering was conducted for all the soil samples evenly.

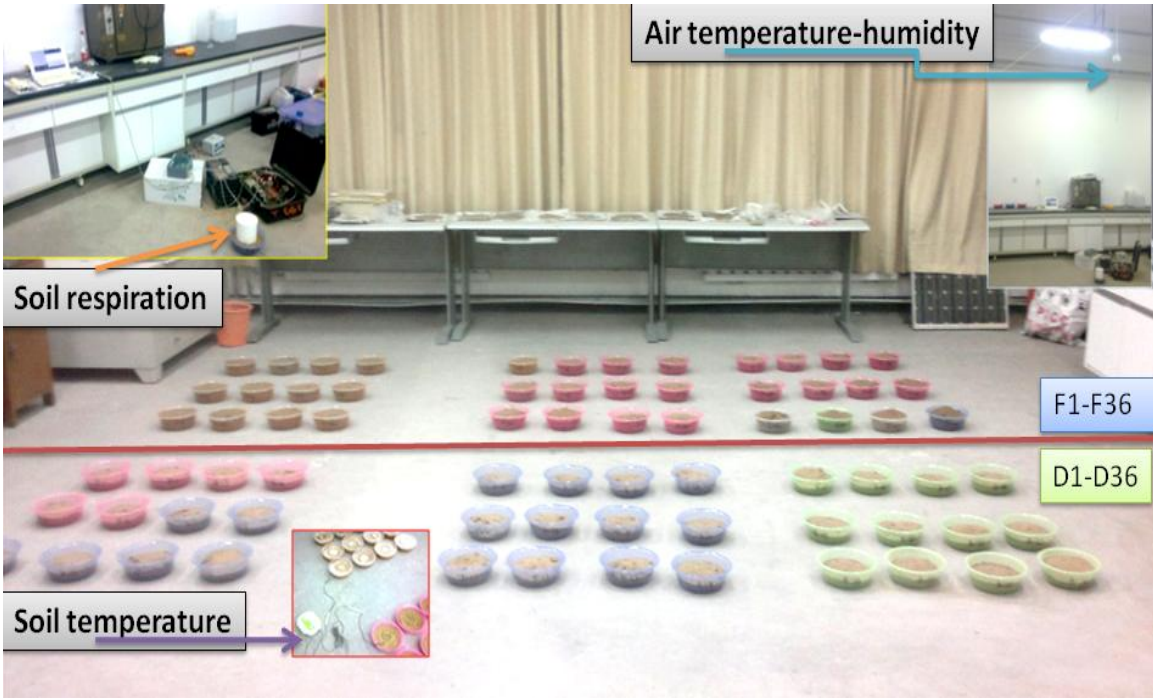

Figure 4-1 photograph of the soil samplings of the saline controlling experiment in the laboratory (F: F site soil sample; D: D site soil sample).

4.3 Results

4.3.1 Effects of different salt gradients on soil respiration

As shown in Figure 4-2, salt gradients had considerable effects on SR for both two sites soils. As compared to 0%, 2% salt content generally had no effects on SR in soils of F site, while had increasing effects on SR in soils of D site. By contrast, salt content at 5% had relatively complex effects on SR. Under NaCl and Na_2CO_3 treatments, the SR from soils of F site at 0% and 5% salt contents showed no significant differences. However, SR was significantly lower at 5% salt content than at 0% salt content when Na_2SO_4 was added. For soils of D site, addition of NaCl and Na_2CO_3 at salt content of 5% could increase SR in comparison with those of 0% salt content. Furthermore, 10% of salt contents decreased SR for most of the treatments compared to 0% salt content (except for NaCl treatments on soils of F site). On the other hand, SR with different salt contents also varied with the increase of incubation time. Under 0% salt content, SR of each treatment generally showed decreasing tendencies during incubation period. In contrast, under 2%, 5% and 10% salt contents, SR from soils of both two sites increased over incubation time at first, and then decreased in the rest of incubation time.

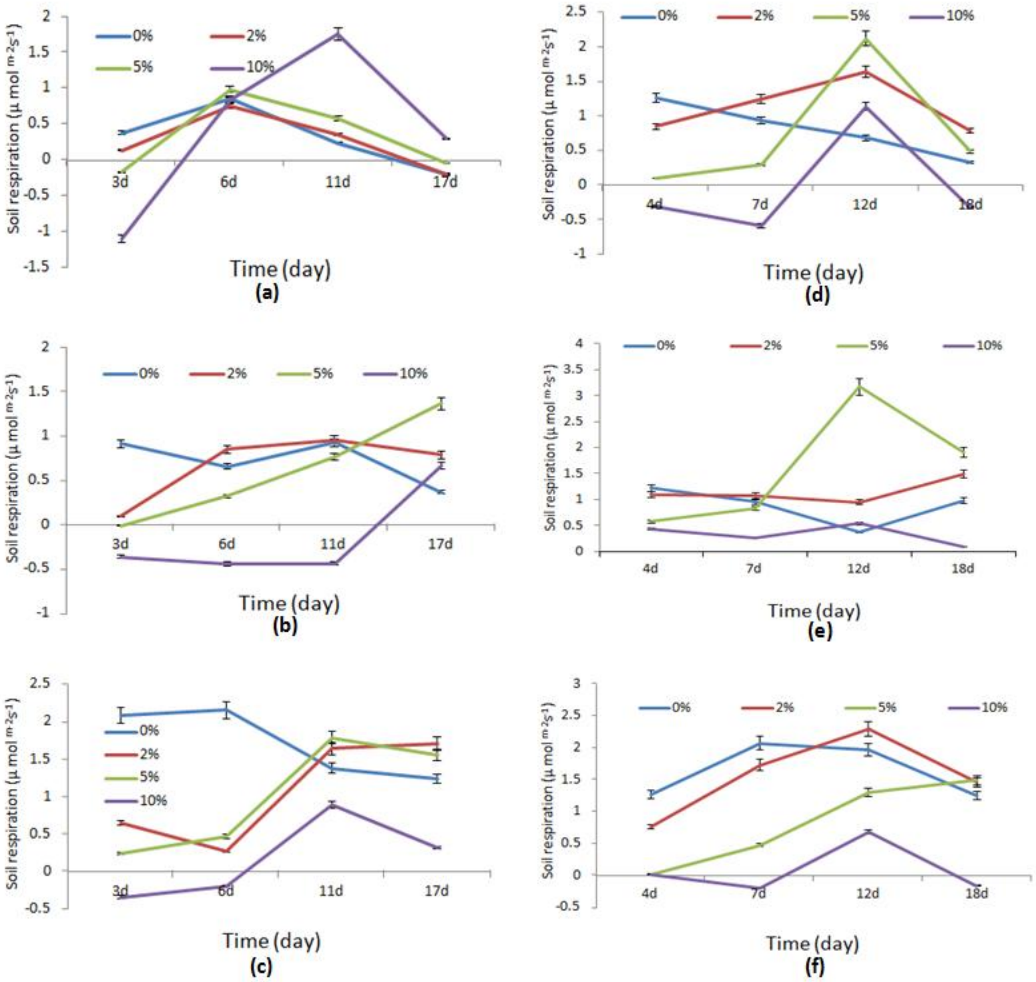

Figure 4-2 Soil respiration under different NaCl, Na_2CO_3, Na_2SO_4 concentration gradient in F site soil(a, b, c); Soil respiration under different NaCl, Na_2CO_3, Na_2SO_4 concentration gradient in D site soil(d, e, f).

4.3.2 Effects of different salt types on soil respiration

Similar to salt gradients, salt types could change SR as well. For soils of F site (Figure 4-3), different salt types had no significant effects on SR when the salt content was 2%. When the salt content increased to 5%, SR from soils under NaCl treatments increased at first and then decreased with incubation time went on, while SR under other two salt treatments gradually increased over incubation period. SR from soils under 10% salt contents differed significantly among salt types. For NaCl and Na_2SO_4 treatments, SR increased from 0 d to 11 d and then decreased, while the increases were more significant under NaCl treatment than those of Na_2SO_4 treatment. In contrast, SR from Na_2CO_3 treatment showed opposite tendencies, and the SR was generally negative during most of the incubation period. On the other hand, for soils of D site, SR under NaCl and Na_2SO_4 treatments were higher than those of Na_2CO_3 treatment when the salt content was 2%. Nevertheless, SR of Na_2CO_3 treatment was significantly higher than those of other two treatments at 5% salt content. When the salt content was 10%, SR from different salt types differed not significantly, and the variation tendencies were also similar.

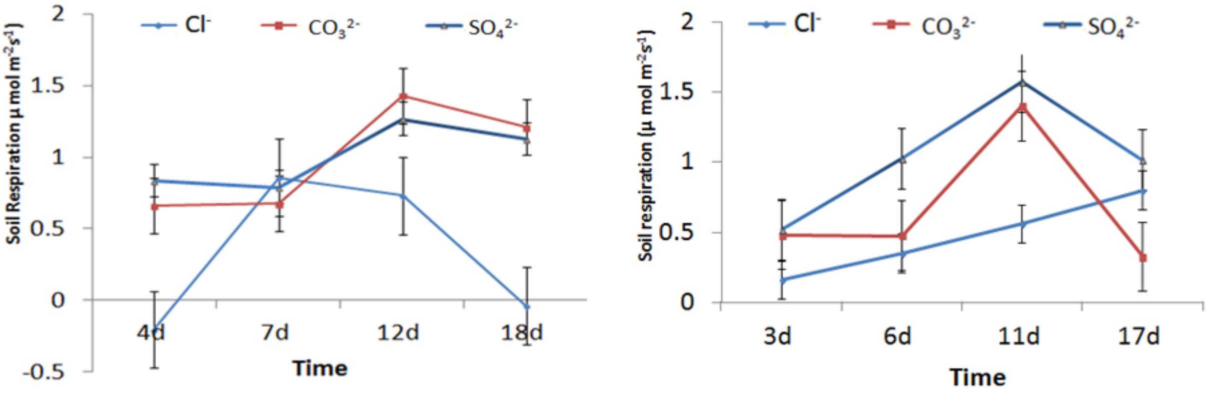

Figure 4-3 Variation of soil respiration affected by different types of salt (left: F site; right: D site).

4.4 Discussion

The results of the present study indicated that when soil salinity ranged from 0% to 5%, SR might not be influenced by soil salinity in both two desert soils. However, high salt content (10%) significantly decreased SR from both two soils, which was in agreement with previous observations in various ecosystems. For example, in an ephemeral wetland, Drake et al. (2014) reported that high soil salinity will lead decreases in SR. Similarly, Krauss et al. (2012) pointed out that SR could be reduced by increasing salinity in coastal swamps. Wong et al. (2008) pointed out that SR was highest in low salinity treatments and lowest in mid-salinity treatments. Previous studies also suggested that high soil salinity may reduce SR through decreasing the magnitude of microbial biomass. Moreover, Chowdhury et al. (2011) compared the effects of soil water content and salinity on microbial activity, and indicated that soil moisture played more detrimental effects on soil microorganisms rather than soil salinity. They also pointed out that low soil water content is the major factor that affects microbial activity in arid and semi-arid regions due to its soil salinization prone-characteristic.

Similarly, low soil moisture and high soil salinity were also observed in our study area. As all the roots were removed from the soil samplings before the laboratory treatments, microbial respiration should be the dominant source of total SR in our study. Guan (2015) pointed out that SR was significantly correlated with soil microbial biomass carbon in a desert ecosystem, suggesting that the restrain on microbial activity by the increase of soil salinity was the most likely reason for the SR reductions. Although there were some limitations in this study, the results still demonstrated that soil salinity plays an important role on influencing SR in the desert ecosystem. The effects of salinity on SR, soil microbial biomass, soil microbial community as well as their relationships under filed conditions will be investigated in our future studies.

4.5 Summary

The results of this study suggested that high soil salinity (10%) could decrease SR in these desert soils, and the responses of SR to soil salinity were different when different salts were added. The decreased microbial activity caused by high soil salinities was the most likely reason for the SR reductions. Therefore, in desert ecosystems, soil salinization, which caused by the low soil moisture and high evaporation, may play an important role in affecting SR. Future studies will be focused on the effects of salinity on SR especially heterotrophic respiration.

Chapter 5 General discussion and future developments

5.1 General discussion

Although the temporal variation of SR has been widely investigated, relatively little information is available about the diurnal and seasonal variations of SR in desert ecosystems. In the present study, it is found that SR showed obvious diurnal variations, which was consistent with previous observations in other researches (Han et al., 2014; Liu et al., 2016). Diurnal variation of SR rate generally deployed a single peak curve in this desert ecosystem. The variation characteristics were in agreement with previous studies. For example, in an oak–birch forest, Mo et al. (2005) reported that SR exhibited diurnal change which keep close pace with the diurnal variation of soil temperature, and the mean value of daily SR varied from 1.8-6.0 g C^{-1} m^{-2} d^{-1} between May and August. Liu et al. (2006) found that diurnal variation of SR rate showed a single peak curve in a temperate deciduous forest, and the daily minimum SR rates and maximum SR rates were detected between 4:00 to 6:00 and 14:00 to 16:00, respectively. These all indicated that such diurnal variations of SR owned largely to the diurnal variations of soil temperature (Song et al., 2015; Huang et al. 2016). Since vegetation cover is sparse in this desert ecosystem, soil temperature can be easily affected by the strong solar radiation.

On the other hand, apparent seasonal SR variations were also observed in these desert ecosystems. In F site, SR rates during summer times were higher than those of spring and autumn, which were in agreement with most common concepts. Since there are large amounts of *Tamarix ramosissima* distributed in F site, the summer time favors growth of vegetation and then the root respiration are also accelerated. By contrary, SR in D site was lower in summer than those of other seasons. This was possibly due to the inhibition on microbial respiration by extreme high temperature and low moisture during summer.

In the present study, spatial variations of SR in three arid ecosystems (DE, TE and FE) were investigated. The results showed that the spatial heterogeneity of SR in DE was not significant. On the contrary, SR in TE and FE showed higher spatial heterogeneity. Different vegetation covers and soil water contents might be the possible reasons for this discrepancy. In general, vegetation in DE was sparse, and less rainfall events as well as high air temperature made the soil moisture stayed at a low level consistently. As a result, SM in DE showed a low spatial heterogeneity. However, there were large sized *Tamarix ramosissima* patchy-distributed in TE site, and soils of FE site could be frequently affected by human interference, such as tillage or irrigation. As a result, spatial heterogeneity of SR in TE and FE were higher than that of DE. Moreover, the relationship between SR and soil temperature was not significant in our study, suggesting that soil temperature might has tiny effects on SR when spatial variation is referred. Similarly, Mitra et al. (2014) also found that spatial variations of SR were influenced by vegetation covers in a sagebrush shrubland of Wyoming. Another studies also suggested that the spatial pattern of SR related to the spatial variation of soil microorganisms (Saetre and Bååth, 2000). Therefore, the respective spatial patterns of root respiration and microbial respiration in desert ecosystems should be also analyzed in spatial variation studies.

It has been proved that soil salinity is high in arid areas where salinization is a common process (Mavi et al., 2012). In the present study, the effects of salt type and salinity content on SR of two site soils were investigated. The results showed that 2-5% soil salinity had no significant effects on SR as compared to those of 0%. However, 10% salinity content significantly decreased SR from both two soils, which was in agreement with previous observations in various ecosystems (Wong et al. 2008; Krauss et al. 2012; Drake et al. 2014). Previous study also suggested that high soil salinity may reduce SR through decreasing the magnitude of microbial biomass (Tripathi et al. 2006). Since all roots were removed before the laboratory experiment, microbial respiration should be the dominant source of SR in our study. A previous study also stated that SR was significantly correlated to soil microbial biomass carbon in the desert ecosystem (Guan, 2015), suggesting that decreased microbial activity with the increase of soil salinity was the most likely reason for the SR reductions. In our future studies, the further effects of soil salinity on SR, soil microbial biomass, soil microbial community as well as their relationships under field conditions will be investigated.

5.2 Inadequacies and future developments

1) Improvement of the stability and accuracy of the chamber system

For the existing experimental conditions, there are several limits and unsolved subjects need to be addressed for the future developments. For instance, extreme weather conditions, especially extreme high temperature, became the main cause for the breakdown of the chamber system. During the daytime of summer, the highest desert soil surface temperature could surpass 50^{o}C, and some metallic parts of the equipment even more burned, which consequently lower the efficiency and indeed paralyzed the operation of the system. Therefore, it remains difficult to fulfill continuous measurement inside the desert completely. Moreover, long time sustaining power supply was still somewhat impractical at present. Thus, improvements on the stability of the equipment and accuracy of the measurement are essential for this study. Additionally, the disturbance on the soil environment was inevitably involved during the measurement period when the chamber was closed and covered onto the ground, causing unnatural condition and errors, which should be eliminated as far as possible in the future consideration.

2) More abiotic and biotic factor should be incorporated

As already known, SR contains different aspects of physical, chemical, and biological processes. Although temperature and water content frequently dominated almost every aspect of respiration processes, another factors, including soil substrate supply, oxygen, soil nitrogen (C:N ratio), soil texture and so on, are also supposed to influence SR somehow. Generally, developing a quantitative relationship which directly links them is a difficult task (Luo and Zhou, 2006), and SR is interactively affected by multiple factors that are hard to be separated. In the desert ecosystems, where the primary productivity is low owing to the scarcity of the vegetation, meanwhile, roots of the plants tend to penetrate into the deep soil layer, root respiration is assumed to be weak, while the respiration from soil microorganism takes considerable proportion. Therefore, the dynamic of the soil microbe activities, as well as its influential effects, should also be investigated in the future work.

3) Modeling and up-scaling

Ecologists measure SR on the scales of plots or ecosystems, but the ultimate goal is to clarify its role in larger scales of carbon cycling such as regional and global scales. In this present study, only small-scaled carbon effluxes were evaluated, and thus further modeling or up-scaling work are desired. Since arid and semiarid desert ecosystems constitute the typical landscapes of the northwest China, as well as occupy a great proportion of global terrestrial ecosystems, it is necessary to seek some common mechanism from our investigation which could be promoted to larger area or similar situations, and incorporated into regional and global carbon flux models. Finally, the ultimate goal is always to develop a mechanistic and simple model which is able to predict SR in different ecosystems more accurately.

Chapter 6 Conclusions

1) For diurnal variation of soil respiration, unimodal curves were displayed daily during the entire measurement period. Inverted U and inverted V curves for diurnal soil respiration variation was detected, which was also consistent with the diurnal variation of soil temperature, and inverted U curves tended to appear in the hot summer days. For seasonal variation, there were different tendencies between the two study sites. In F site, the predominant part of soil respiration in summer was assumed to be root respiration, while heterotrophic respiration prevailed in the D site. Root respiration tended to be intensified in summer owing to the thriving *Tamarix ramosissima* growth, while soil microbial respiration in D site was suppressed by extremely high temperature and low moisture in the hottest summer days. In this drought-stressed arid ecosystems, soil respiration rates were closely related to soil temperature but also modified by soil moisture, and altered greatly by the dramatic change of soil moisture owing to the infrequent precipitation pulse.

2) Geostatistical analysis revealed soil respiration in desert ecosystem tends to show relatively small spatial variation owing to the homogeneous structure of soil properties. While in transition area, larger xerophytes may play a more important role in controlling the spatial pattern of soil surface properties including soil respiration. In arid region, irrigation is necessary for agriculture production, which can result in significant change in soil respiration. Soil moisture may be the decisive factor in many occasions in this drought area, but different from temporal variation, multiple factors are needed to verify the spatial variation of soil respiration.

3) Different salt types and salinity gradients all exert different influences on soil respiration. Salinity controlling experiments in the laboratory suggested that for arid

desert soil, although salt addition might stimulate short term rising trend of soil respiration, but long term effect of salt on soil respiration as well as soil microbial activity is supposed to be adverse. Salinization constitutes another important affecting factor in such arid land ecosystems and should also be incorporated in SR processes.

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