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Chapter 1. Introduction and overview

Soil respiration is a crucial piece of the puzzle that is the earth system. To understand how the earth system functions, we need to figure out the role that soil respiration plays in regulating atmospheric CO_2 concentration and climate dynamics. Will global warming instigate a positive feedback loop between the global carbon cycle and climate system that would, in turn, aggravates climatic warming? How critical is soil respiration in regulating this positive feedback? To answer these questions, we have to understand the processes involved in soil respiration, to examine how these processes respond to environmental change, and to account for their spatial and temporal variability.

Since climate change is one of the main challenges facing humanity, quantification of soil respiration is no longer just an arduous academic issue. It is also relevant to farmers, foresters, and government officers. Can respiratory carbon emission and/or photosynthetic carbon uptake be manipulated to maximize carbon storage so that farmers and foresters can earn cash awards in global carbon-trading markets? To effectively manipulate respiratory carbon emission from terrestrial ecosystems we need to identify the major factors that control soil respiration. Even if we can manipulate respiratory processes, how could participant countries in the Kyoto treaty verify carbon sinks in the biosphere to claim their credits during the intergovernmental negotiations? All these issues make it necessary for us to invent reliable methods to accurately measure soil respiration in croplands, forest areas, and other regions. Can the managed carbon sinks last long enough to effectively mitigate greenhouse gas emission in future? How will soil respiration respond to natural and man-made perturbations? To answer all these questions, it is necessary to develop a predictive understanding of soil respiration, aiming toward a mechanistic modeling of soil respiration. It is evident from all these examples that studying soil respiration is not only desirable for purely academic reasons but also is crucial in the commercial and political arenas.

Due to the recent societal need to mitigate climate change and the scientific aspiration to understand soil respiration itself, the research community has been very active in studying soil respiration. During the past 15 years, the number of papers published on soil respiration has linearly increased and reached nearly 200 papers in 2003 and 2004 from about 10 papers in 1985-1990 (Fig. 1.1). The active research also partially reflects the fact that soil respiration remains least understood among ecosystem carbon processes despite its central role in the global carbon cycle and climate change. This book lays down the various aspects pf the fundamentals of soil respiration while synthesizing all the recent literature in this field.

1.1. Definition and Introduction

The word respiration comes from Latin prefix *re-* (i.e., back, again) and root word *spirate* (i.e., to breathe). It literally means breathing again and again and thus is used to describe the process of gas exchange between organism and environment. Physiologically, respiration is a series of metabolic processes that break down (or catabolize) organic molecules to liberate energy, water, and carbon dioxide (CO_2) in a cell. All living organisms - plants, animals, and microorganisms alike – share similar pathways of respiration to obtain the energy that fuels life while releasing CO_2. Respiration is often studied in relation to energy supply at the biochemical and cellular levels as a major component of bioenergetics. However, bioenergetics in soils is not well developed (Dilly 2005), and soil respiration is studied predominantly in relation to CO_2 and O_2 exchanges. In this book, we use the word respiration mainly to describe CO_2 production rather than energy supply.

Soil respiration, the subject of this book, is defined as the production of carbon dioxide by organisms and the plant parts in soil. These organisms are soil microbes and fauna, and the plant parts are roots and rhizomes in the soil. Additionally, soil is often defined as a mixture of dead organic matter, air, water, and weathered rock that supports plant growth (Buscot 2005). Some authors also include living organisms in the definition of soil (e.g., Killham 1994) so that roots, soil microbes, and soil fauna become part of soil. Therefore, it would make a sense to talk about soil that can breathe. Soil respiration means that the living biomass of soil respire CO_2 while soil organisms gain energy from catabolizing organic matter to support life.

Soil respiration is sometimes called belowground respiration in contrast with aboveground respiration, which is referred to respiratory CO_2 production by the plant parts above the soil surface. Although the definition of soil usually does not include plant materials that have not been well decomposed, CO_2 production via litter decomposition in the litter layers is generally included in soil respiration (or belowground respiration) in many publications and, for the sake of simplicity, in this book as well.

Technically, the rate of CO_2 production in the soil (i.e., the soil respiration rate) can not be directly measured in the field. Measurements are often made at the soil surface to quantify a rate of CO_2 efflux from the soil to the atmosphere. The instantaneous rate of soil CO_2 efflux is controlled not only by the rate of soil respiration but also by the transport of CO_2 along the soil profile and at the soil surface (see Chapter 5). The CO_2 transport is influenced by the strength of the CO_2 concentration gradient between the soil and the atmosphere, soil porosity, wind speed, and other factors. At steady state, the CO_2 efflux rate at the soil surface equals the rate of CO_2 production in soil. In this case, soil CO_2 efflux is practically equivalent to soil respiration. Thus the two terms are inter-changeable.

However, there are several situations in which CO_2 production may not be at steady state with CO_2 transport. For example, soil degassing occurs during rainfall or irrigation so that stored CO_2 in the soil air space is driven out of the soil. After rainfall or irrigation, produced CO_2 by soil organisms is partially stored in the soil to rebuild the CO_2 concentration gradient. Carbonic acid reaction and microbial methanogensis each could produce or consume CO_2, depending on conditions that influence reaction equilibriums (see Chapter 3). Thus, the CO_2 released at the soil surface could be generated by carbonic acid reactions during rock weathering, particularly in arid-lands where carbonic reaction is very strong. On the other hand, the CO_2 produced by soil living tissues could be absorbed by microbes during methonogenic processes. However, the amount of CO_2 produced and/or consumed by carbonation and methanogensis is generally trivial in comparison to soil respiration except in very dry lands. The non-steady-state CO_2 efflux at the soil surface occurs mostly during rainfall or irrigation after long period of drought (Liu et al. 2002, Xu et al. 2004). In absence of major perturbation, the rate of CO_2 production in soil is indistinguishable from the rate of CO_2 efflux at the soil surface on a daily or longer time scale (Hui and Luo 2004). Thus, the term soil respiration is practically inter-changeable with soil surface CO_2 efflux on a long-term scale. However, measured soil CO_2 efflux rates at shorter time scales may not be equivalent to the rate of soil respiration.

As a preview, Fig. 1.2 shows a typical time course of CO_2 efflux rates. The time course, which was measured at the soil surface in a tallgrass prairie of Oklahoma, USA, displays a distinct seasonal pattern that soil respiration is high during summer and low in winter. The seasonal pattern is roughly repeated in subsequent years. Nonetheless, there are observable variations from year to year. For example, the summer peak of soil respiration reaches nearly 6 μmol m^{-2} s^{-1} in 2002 and is less than 4 μmol m^{-2} s^{-1} in 2001. The winter low is nearly 0 μmol m^{-2} s^{-1} in 2002 but 0.3 - 0.5 μmol m^{-2} s^{-1} in other years. In most years, there are dips in the measured soil respiration during the late summer and early autumn but in 2004, the seasonal pattern is relatively smooth. This kind of year-to-year variation exemplifies the term “interannual variability”.

Similar seasonal patterns have also been observed in northern semiarid grasslands (Frank et al., 2002), forests (Salvage and Davidson 2001, Epron et al. 2004, King et al. 2004), and croplands (Beyer 1991). For example, soil respiration varies from nearly 0 μmol m^{-2} s^{-1} in the winter to about 10 μmol m^{-2} s^{-1} in the summer over one year in the Duke Forest, North Carolina (King et al. 2004). This seasonal pattern repeats from 1997 to 2002, and interannual variation is apparent with different peaks in summer and valleys in winter.

From the observed soil respiration patterns, we can ask many questions. For example, what causes such seasonal and interannual variations? Why does soil respiration vary from one site to the other? How can we scale up the plot-level measurements to estimate total carbon losses at regional and global scales? Can we derive general mechanisms from the observed patterns and then predict future changes in soil respiration? What percentage of the lost carbon is from root respiration? How much is the carbon released by soil respiration directly from the recent photosynthesis? These issues, among others, will be addressed in this book while laying down the basic principles of soil respiration. First, we review the history of research on soil respiration.

1.2. History of research

Research on soil respiration has a long history (Fig. 3) and can be dated back to papers by Wollny (1831), Boussingault and Levy (1853), and Mőller (1879). The earliest studies of soil respiration were intended to characterize soil metabolism. In the last century, research on soil respiration can be roughly divided into four major periods. During the first few decades of the 20th century, research on soil respiration was primarily conducted in the laboratory with agricultural soil. Soil respiration was used to evaluate soil fertility and biological activities in soil. Chemical fertilizers were invented in late 19th century and applied crops to stimulate growth. As a consequence, agricultural productivity was considerably enhanced. At that time, research emphasis was placed on understanding the soil properties that influence crop production. Soil respiration was used as an index of soil fertility for agricultural production (Russell and Appleyard 1915) because in a field study, fertilization of agricultural crops generally increases soil respiration rates (Lundegårdh 1927). Some of the laboratory studies, however, showed that nutrient release was not proportional to the carbon release during mineralization (Waksman and Starkey 1924, Pinck et al. 1950, Schlesinger 1977).

During that period, some primitive methods for the measurement of soil respiration were developed. Stoklasa and Ernest (1905) passed CO_2-free air over soil samples contained in a flask and measured the amount of CO_2 evolved from the soil samples by using the method of alkali absorption. Lundegårdh (1927) recognized that measured CO_2 evolution from soil samples in the laboratory may not be representative of that from intact soils in the field, where, he argued, diffusion was a chief process controlling evolution of CO_2. He was probably the first scientist to make *in situ* measurements of rates of CO_2 evolution from field soil by covering the soil surface with a chamber for a period of time. Then he took air samples with brass tubes from the chamber as well as from air spaces in the soil at three depths. The air samples were passed through alkali solutions for measurements of soil respiration. Humfeld (1930) modified Lundegårdh's method and passed air through the chamber with inlet and outlet ports to collect the CO_2-enriched air in an alkali absorption train. The alkali absorption chamber method, first introduced by Lundegårdh (1921) and modified by Humfeld (1930) and others, which places static alkali solution within the chamber followed by titration of chloric acid, has been widely used in the following decades.

By then, the major factors that influence soil respiration have been identified. Greaves and Carter (1920) were among the first to document a consistent relationship between soil water content and microbial activity. Turpin (1920) reviewed soil respiration and concluded that the primary source of CO_2 efflux from soils was attributable to decomposition by bacteria. Lundegårdh (1927) pointed out that soil diffusion was important in controlling the evolution of CO_2. Smith and Brown (1933) indicated that rate of diffusion of CO_2 through the soil was correlated with CO_2 production.

A relatively inactive research period occurred from the late 1930s to the early 1950s when few publications can be identified on soil respiration, possibly due to the worldwide social turbulence. During the period from the late 1950s to the 1970s, research activity on soil respiration was resumed (Fig. 1.3), mainly from an ecological perspective to understand heterotrophic processes in the soils of native ecosystems (Leith and Ouellette, 1962; Witkamp 1966; Raguotis 1967; Schultze 1967; Reiners 1968; and Kucera and Kirkham 1971). During that period, research advanced the science of soil respiration in many aspects, including (1) methods of measurement, (2) controlling factors, (3) partitioning into components, (4) relationships with other ecosystem carbon processes, and (5) synthesis and scaling to global estimation.

Many studies were devoted to careful evaluation of the various factors that affect the accuracy of the alkali absorption method (Walter 1952, Howard 1966, Kirita and Hozumi 1966, Kirita 1971, Chapman 1971, 1979; Anderson 1973, Gupta and Singh 1977). The accuracy of the method was found to vary with factors such as the amount and strength of alkali used, the area of covered soil, the chamber height above the ground, the depth of the chamber inserted into soil, the surface area and the height of the alkali container within the chamber, the duration of measurement, and the rates of soil CO_2 evolution. Minderman and Vulto (1973) suggested the use of fine-grained soda lime instead of alkali solution to absorb CO_2.

One major technical advance was made in the 1950s that infrared gas analyzer (IRGA) was used for the measurement of soil respiration. Haber (1958) first used IRGA to calibrate the alkali absorption method. Golley et al. (1962) were among the first to make field measurements of soil respiration on the peat floor of a mangrove forest using IRGA. Reiners (1968) examined how gas flow rates influenced IRGA measurement of CO_2 evolution. Kanemasu et al. (1974) studied effects of air "suction" and "pressure" on IRGA measurements of soil respiration. Measured CO_2 efflux with the suction chamber was one order of magnitude higher than that with the pressure chamber. The suction chamber drew CO_2 from the soil outside the chamber and/or in deep layers via mass flow. Edwards and Solins (1973) designed an open flow system with the chamber linked to IRGA to measure soil respiration continuously. Edwards (1974) used movable chambers that were lowered on to the forest floor during measurements and lifted between measurements. The movable chambers allowed natural drying of the soil and litterfall onto the measurement surface. The IRGA measurements of soil CO_2 efflux were compared with those using the alkali absorption method (Kirita and Hozumi 1966). Many studies found that the alkali method underestimated soil CO_2 efflux in comparison to the IRGA measurements (Haber 1958, Witkamp 1966, Kucera and Kirkham 1971). Other studies did not detect any significant differences between the two methods (e.g., Ino and Monsi 1969).

The gas-well method that was first used by Lundegårdh (1927) to estimate soil respiration from a CO_2 concentration gradient along soil profiles was fully developed by de Jong et al. (1979). Meanwhile, a variety of micrometerological methods, such as Bowen Ratio and Eddy flux, have been developed to measure gas exchanges within and above the plant canopy (Monteith 1962, Montieth et al. 1964), from which soil respiration was indirectly estimated.

From the late 1950s to the 1970s, knowledge on factors that regulate soil respiration had been greatly enriched. Bunt and Rovira (1954) studied soil respiration in a temperature range from 10 to 70°C. They found that O_2 uptake and CO_2 release increased with temperature until 50 °C followed by a decline. Many studies demonstrated that soil respiration was exponentially correlated with temperature (Wiant 1967, Kucera and Kirkhma 1971, Medina and Zelwer 1972). Drobnik (1962) estimated Q_{10} (i.e., a quotient indicating the temperature sensitivity of soil respiration, see Chapter 5) to be 1.6 to 2.0 in response to temperature over a range from 8 to 28 °C. Wiant (1967) estimated Q_{10} of approximately 2 within a temperature range from 20 to 40°C. Soil moisture had also been identified to be important in influencing soil respiration. A laboratory study suggested that microbial respiration decreased when soil moisture was below 40% or above 80% of the field holding capacity (Ino and Monsi 1969). Soil temperature and moisture combined could account for up to 90% of the variation of soil respiration measured in field (Reiners 1968).

A study that was done by Birch and his colleague (Birch and Friend 1956, Birch 1958) is worth mentioned. They demonstrated that when a soil was dried and rewetted, decomposition of soil organic matter was enhanced, leading a flush of CO_2 production. They explained that the drying-wetting effect was not related to microbial stimulation or microbial death but was caused by liberation of rapidly decomposable material from the clay. The organic materials were protected by the clay from microbial attacks under steady moist conditions.

During that period, components of soil respiration have been clearly identified into two major categories: autotrophic and heterotrophic respiration. The autotrophic components are the metabolic respiration of live root, associated mycorrhiza, and symbiotic N fixing nodules. The heterotrophic respiration is from microbial decomposition of root exudates in rhizosphere, aboveground and belowground litter, and soil organic matter. Coleman (1973b) measured total respiration of intact soil cores and individual components of roots, litter, and soil. Contribution to the total soil respiration was 8 - 17% from roots, 6 - 16% from litter, and 67 – 80% from soil microbes in a successional grassland. Edwards and Sollins (1973) partitioned total soil respiration from a forest into 35% from roots, 48% from litter and 17% from soil. Richards (1974) found it difficult to partition soil respiration among different soil fauna, fungi, and bacteria.

Field measurements over whole growing seasons made it possible to scale up individual measurements to estimate annual carbon efflux. Kucera and Kirkham (1971) estimated annual soil CO_2 efflux to be 452 g C m^{-2} in a tallgrass prairie by applying a temperature-respiration regression to continuous temperature records. Coleman (1973a) scaled up monthly averages of soil respiration and estimated annual soil CO_2 efflux of 357 – 421 g C m^{-2} in a grassland. Estimated annual soil CO_2 releases were about 1000 g C m^{-2} in many forests (Edwards and Sollins 1973, Garrett and Cox 1973).

Estimated annual efflux from soil respiration was often compared with annual carbon influx via aboveground litterfall although the two processes are not completely comparable. Reiners (1968) showed that total soil respiratory C release was three times higher than litter C input. Edwards and Sollins (1973) found that litter decomposition only accounted for one-fifth of annual soil respiration. Anderson (1973) showed that annual soil respiration released 2.5 times C in annual litter fall. However, several studies demonstrated that C released by soil respiration was equivalent to that input from litterfall (Colemen 1973a, Witkap and Frank 1969).

Accumulation of studies during that period offered opportunities of synthesis to compile results from many ecosystems. Singh and Gupta (1977) linked soil respiration to litter decomposition. They made a comprehensive synthesis on C processes of litter decomposition, soil respiration, root respiration, microbial respiration, faunal respiration, and soil organic matter dynamics. Schlesinger (1977) reviewed many studies on soil respiration in the literature to synthesize latitudinal patterns and environmental factors that influenced soil respiration worldwide and offered an estimate of global soil respiration.

Bunnell et al. (1977) and Minderman (1968) suggested that decomposition could be represented best by summation of the exponential decay curves for all major chemical constituents including sugars, cellulose, hemicellulose, lignin, waxes and phenols. Henin et al. (1959) appears to have been the first to propose a model to relate explicitly the two exponential rates to fresh plant C and “humified”C.

Long-term no-till plots were first established at the International Institute of Tropical Agriculture, Ibadan, in 1971 and continued through 1987 (Lal 2004). In 1980s, agricultural practice of no-tillage stimulated research on soil properties. Soil respiration was often used to indicate biological activities in soil with different tillage treatments (Anderson 1982). For example, Linn and Doran (1984) studied how no tillage affected soil water-filled pore space and its relationships with CO_2 and N_2O production. The level of soil aeration using microbial respiration rates of aerobic heterotrophs was also examined for compaction problems in no-tillage management system (Linn and Doran 1984, Wilson et al. 1985, Neilson and Pepper 1990).

Since the 1990s, research on soil respiration has been primarily driven by global change. While climate research has its own long history (Weart 2003), ecologists, stimulated by a US National Research Council (NRC) report (NRC 1986) and a variety of publications by the International Geosphere Biosphere Program, have been involved in the global change research only in the past two decades and have studied ecosystem-level responses to climate change since early 1990s (Mooney et al. 1991). In particular, the paper by Tan et al. (1990) plays a critical role in attraction of research attention to the land biosphere. Their analysis of atmospheric CO_2 data suggests that land biosphere may absorb a large portion of the emitted carbon from anthropogenic sources. The three reports by Intergovermental Panel on Climate Change (IPCC, 1990, 1995, 2001) and the paper by Schimel (1995) provide a global perspective of the carbon cycle in terrestrial ecosystems. Cox et al. (2000) linked a carbon cycle model with a global circulation model and highlighted the importance of temperature sensitivity of respiration for the future climate prediction. That study stimulates great research interests in the temperature sensitivity of soil respiration.

The modern active research on soil respiration has also been stimulated by advance in measurement techniques. Portable infrared gas analyzers (IRGA) are widely used for the measurements of soil surface CO_2 fluxes since the early 1990s (Norman et al. 1992). The IRGA method relatively requires less technique training but provides more accurate measurements of soil respiration than the traditional alkali or soda lime absorption methods. Meanwhile, many companies have retooled IRGA sensors and developed various chambers specifically for the measurement of soil CO_2 effluxes (Chapter 8).

The rest of the book summarizes results from the modern research and lays down the fundamentals of soil respiration.

1.3. Overview of the book:

This book is dedicated to the understanding of various aspects of soil respiration and is divided into four parts. The first part provides a context of soil respiration science in Chapters 1 and 2. The second part describes fundamental processes of CO_2 production and CO_2 transport in Chapters 3 and 4. The third part presents regulatory mechanisms of soil respiration, including controlling factors, spatial and temporal variations, and responses to natural and human-made perturbations in Chapters 5 - 7. The last part is about research approaches to measurement of soil respiration, partitioning to various components, and modeling in Chapters 8 - 10.

After an introduction and a brief history of research on soil respiration in this chapter, Chapter 2 places it in context of ecosystem productivity, nutrient relationships, regional and global carbon cycling, climate change, and carbon trading. The section of ecosystem productivity discusses the relationships between soil respiration and various components of ecosystem production, such as net primary productivity and net ecosystem productivity. We also briefly discuss relationships between soil respiration and nutrient dynamics. The section on regional and global carbon cycling describes components of the global carbon cycle, quantifies the relative magnitude of soil respiration, and discusses the role that temperature sensitivity of soil respiration plays in regulating future global carbon balance. The section on climate change primarily examines the relationship between soil respiration and climate change. We also discuss global carbon trading markets, relevant carbon sinks in terrestrial ecosystems, and their relationships with soil respiration.

Chapter 3 focuses on the processes of CO_2 production, including the fundamental biochemistry of respiratory processes, root respiration, microbial respiration in rhizosphere, and microbial decomposition of litter and soil organic matter (SOM). The primary biochemical process of CO_2 production is the tricarboxylic acid (TCA) cycle. Root respiration in an ecosystem is determined by root biomass growth and the specific rates of root respiration. Microbial respiration occurs in rihzosphere with root exudates, during litter decomposition, and SOM oxidation. We briefly describe a variety of microorganisms that use root exudates, litter, and SOM as substrates. In each section, we point out major environmental and biological factors that regulate root and microbial respiration.

Chapter 4 describes processes of CO_2 transport along vertical profiles within the soil, at the soil surface, within the canopy, and above the canopy. Soil CO_2 transport is primarily driven by gradients of CO_2 concentration along soil vertical profiles and determined by diffusion and mass flow processes. The CO_2 release at the soil surface depends on CO_2 gradients and is strongly affected by wind gusts and turbulences. The CO_2 transport within and above the canopy may not be directly related to soil respiration. But CO_2 profiles within and above the canopy are influenced by soil respiration and are often used to indirectly estimate soil respiration.

Chapter 5 focuses on controls of soil respiration by substrate, temperature, moisture, oxygen, nitrogen, soil texture, and pH value. Soil respiration consumes various sources of substrate, ranging from simple sugars from root exudation to complex humic acids in SOM. We discuss how the quantity and quality of substrates affect soil respiration. In general, soil respiration increases with temperature exponentially. Mechanistically, temperature affects almost all aspects of soil respiration, including biochemical reactions, substrate transport in soil aggregates, and substrate supply from plants through changes in phenology. We also introduce the concept of Q_{10} that describes temperature effects on soil respiration. In general, soil respiration is low when soil is very dry or water logged and high at intermediate levels of soil moisture. Soil respiration usually displays complex patterns during a drying cycle between two rain events. This chapter also discusses effects of the other factors on soil respiration.

Chapter 6 presents spatial and temporal patterns of soil respiration. We discuss temporal variations in soil respiration at various time scales from diurnal and weekly, to seasonal, interannual, and decadal and millennial. Spatial patterns emerge at the stand level, landscape and regional scales, and across biomes. We comparatively present soil respiration among ecosystem types and examine general relationships of soil respiration with ecosystem productivities, prevailing environmental variables, and soil characteristics.

Chapter 7 describes changes in soil respiration caused by perturbations such as elevated CO_2, climatic warming, changes in precipitation frequency and intensity, substrate supply/depletion (through biomass removal, shading, fire, grazing, clear-cutting, addition of saw dust), N deposition/fertilization, and agricultural disturbance. Elevated CO_2 usually stimulates substrate supply to rhizosphere and results in increases in soil respiration. Climatic warming not only directly affects processes of soil respiration but also causes soil drying and substrate supply. The section on warming-induced changes in soil respiration synthesizes experimental results and underlying mechanisms, particularly from warming experiments in intact natural ecosystems. It is a common phenomenon that soil respiration shows dynamic changes within a raining cycle, usually being low right after rainfall when soil moisture is saturated, reaching a maximum, and then declining as soil is drying. We present results from experiments with water manipulation, studies of soil respiration during natural cycles of precipitation, and from transect studies along precipitation gradients. The section on substrate supply/depletion discusses effects of various substrate treatments on soil respiration. In general, soil respiration decreases with substrate depletion and vice versa. We also present results of studies on effects of N deposition/fertilization on soil respiration.

Chapter 8 introduces a variety of methods for the measurement of soil respiration, including methods using dynamic and static chambers, the gas well method, micrometeorological methods, and the mass balance method. Chamber methods, which directly measure rates of CO_2 efflux at the soil surface, are most commonly used. The chamber methods can be, depending on the presence or absence of air circulation and detecting agents, divided into (1) closed dynamic chamber that operates in a fully enclosed mode on soil surface; (2) open dynamic chamber that operates in a continuously ventilated, quasi-steady-state mode; and (3) closed static chamber that isolates an amount of atmosphere from the environment. This chapter describes basic principles behind the chamber methods, discusses chamber designs and deployment, and assesses their accuracy and potential pitfalls of those methods. The gas-well method measures gradients of CO_2 concentration along a vertical soil profile and then estimates the rate of soil respiration. In addition to those methods for direct measurements, soil respiration can be estimated from the mass balance on an annual time scale and estimated from micrometeorological measurements through eddy-flux, Bowen-ratio, and CO_2 gradients in the nocturnal stable boundary layer. This chapter also briefly describes those indirect methods and evaluates their advantages and disadvantages.

The partitioning of soil respiration is critical for developing predictive understanding of soil respiration. Chapter 9 introduces several methods using experimental manipulations, isotopes, and indirect inference analysis for partitioning. The experimental methods manipulate substrate supply to different pathways of soil respiration and separate components of soil respiration. The manipulative methods include direct component measurements and integration, root exclusion, severing root C sources through trenching, girding, clear-cutting, and shading, and litter removal. The isotope methods take advantage of land use and land cover changes that shift C_3 and C_4 plant vegetation, CO_2 experiments that fumigate CO_2 with different isotope values, bomb ^{14}C

that enriched ^{14}C in the atmosphere in 1950s and 1960s, and labeling experiments. The inference methods are to estimate component contributions through regression extrapolation, carbon kinetics analysis, and inverse analysis. This chapter also offers estimates of contributions to the total soil respiration from each component.

Chapter 10 provides a general description of models and modeling studies of soil respiration. In general, the modeling studies can be divided into three categories: empirical models, CO_2 production models, and CO_2 production and transport models. The empirical models are primarily based on empirical relationships of soil respiration with temperature, moisture, and some quantities of substrate availability. The production models account for ecosystem carbon balances by considering photosynthetic carbon influxes, carbon partitioning into different plant and soil carbon pools, and carbon releases from each pools via respiratory processes. In addition to CO_2 production, the production-transport models consider transport processes of soil CO_2 along a soil profile from the production sites to soil surface. This chapter also critiques each of the model types and discusses different issues in the scaling of soil respiration measurements from plots to landscapes, regional and global scales.

Soil respiration usually accounts for the majority of ecosystem respiration, which is the sum of soil respiration and respiration of aboveground parts of plants (Chapter 2). Some of the measurement methods can directly measure ecosystem respiration, from which soil respiration is indirectly estimated (Chapter 8). Thus the soil and ecosystem respirations are closely related. This book focuses on soil respiration and often describes ecosystem respiration as well.

There are two broad types of soil in terrestrial ecosystems: mineral and organic. The majority of the world's soils are mineral soil in upland ecosystems (>99%) and the rest are organic soils, which are largely formed in wetlands. The organic soils contain at least 20% organic carbon (Miller and Donahue 1995). The latter is potentially released to the atmosphere through decomposition in response to climate change. While this book mainly focuses on soil respiration from non-wetland ecosystems, we briefly describe respiratory processes in wetlands in Chapter 6.

Figure legends

Figure 1. Number of papers published on soil respiration since 1985. The number was obtained from search for key words soil or belowground respiration in the Web of Science database.

Figure 2. Measured rate of soil CO_2 efflux in a tallgrass prairie in Oklahoma from 1999 to 2005. Open circles represent data points and bars indicate the one standard error below and above the data points. Data are adopted from Luo et al. (2001), Wan et al. (2005), and Zhou et al. (2006) and only for the measured soil respiration in the control treatment in a warming and clipping experiment.

Figure 3. Schematic illustration of history of soil respiration research since 1830s. The major research activities have been focused on method development for measurement of soil respiration, identification of major regulatory factors, partitioning of measured soil respiration to various components, and scaling up to estimate ecosystem, regional and global carbon budgets.

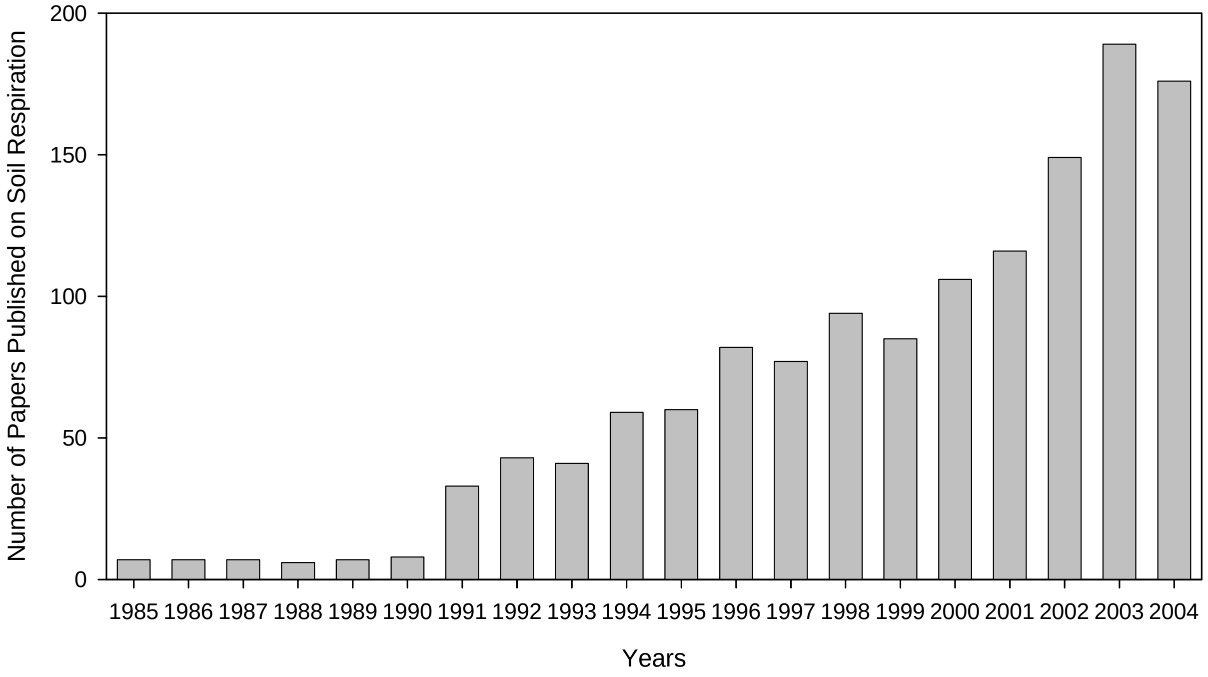
Number of Papers Published on Soil Respiration
0
50
100
150
200
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Years

Fig. 1

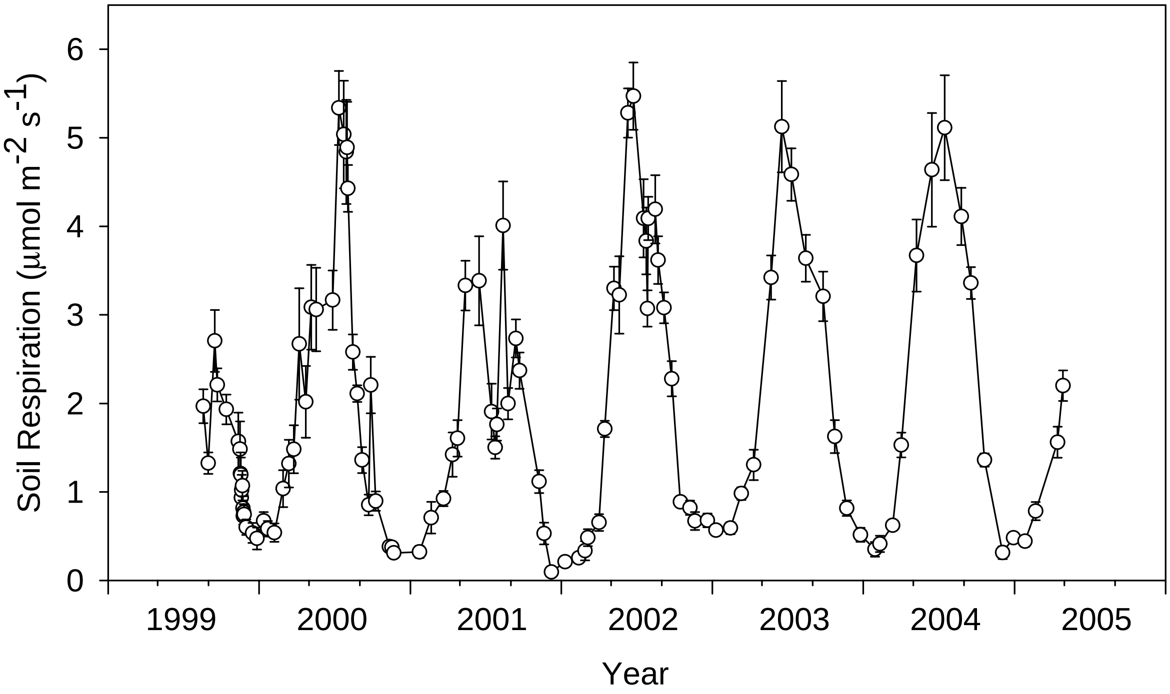
Soil Respiration (μmol m^{-2} s^{-1})
6
5
4
3
2
1
0
1999
2000
2001
2002
2003
2004
2005
Year

Fig. 2

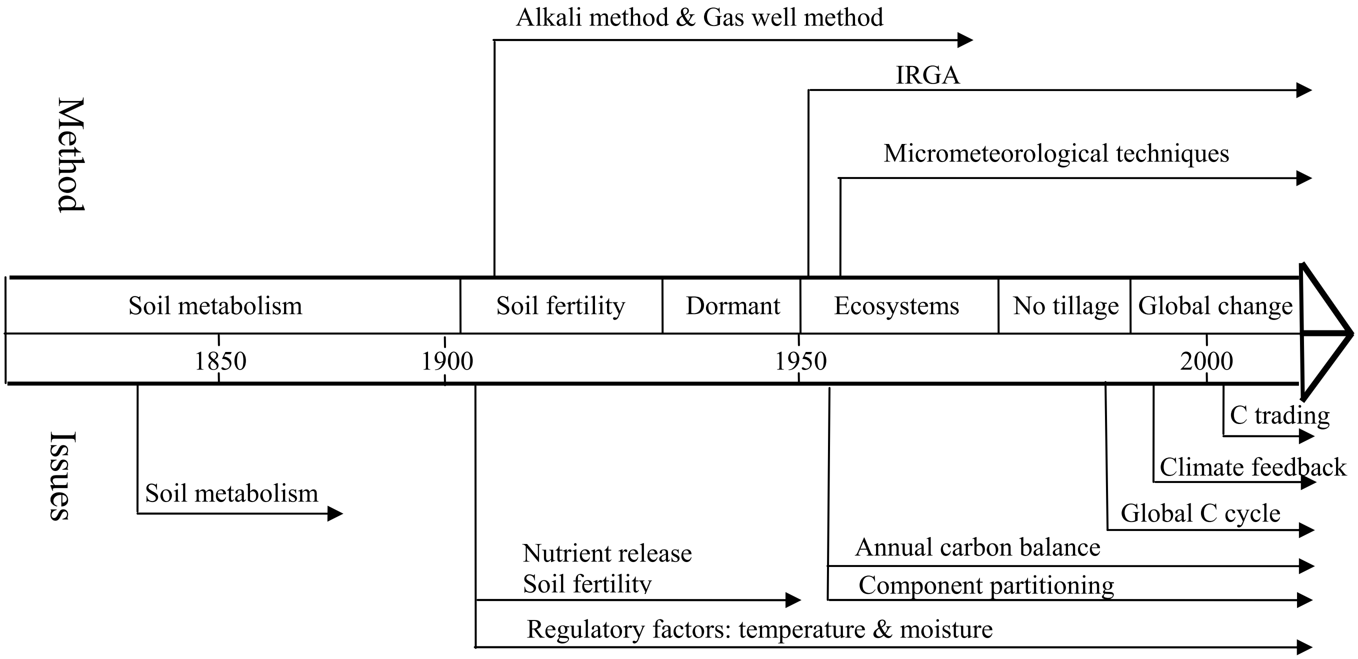
Method
Alkali method & Gas well method
IRGA
Micrometeorological techniques
Soil metabolism
Soil fertility
Dormant
Ecosystems
No tillage
Global change
1850
1900
1950
2000
Issues
Soil metabolism
Nutrient release
Soil fertility
Regulatory factors: temperature & moisture
Annual carbon balance
Component partitioning
Global C cycle
Climate feedback
C trading

Fig. 3