

Introduction and Overview

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Soil respiration is a crucial piece of the puzzle that is the earth's system. To understand how the earth's system functions, we need to figure out the role that soil respiration plays in regulating atmospheric CO₂ concentration and climate dynamics. Will global warming instigate a positive feedback loop between the global carbon cycle and climate system that would, in turn, aggravate 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, examine how these processes respond to environmental change, and 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 a tedious academic issue. It is also relevant to farmers, foresters, and government officials. 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 signatory countries to 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 measure soil respiration accurately in croplands, forest areas, and other regions. Can the managed carbon sinks last long enough to mitigate greenhouse gas emission effectively in the future? How will soil respiration respond to natural and human-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

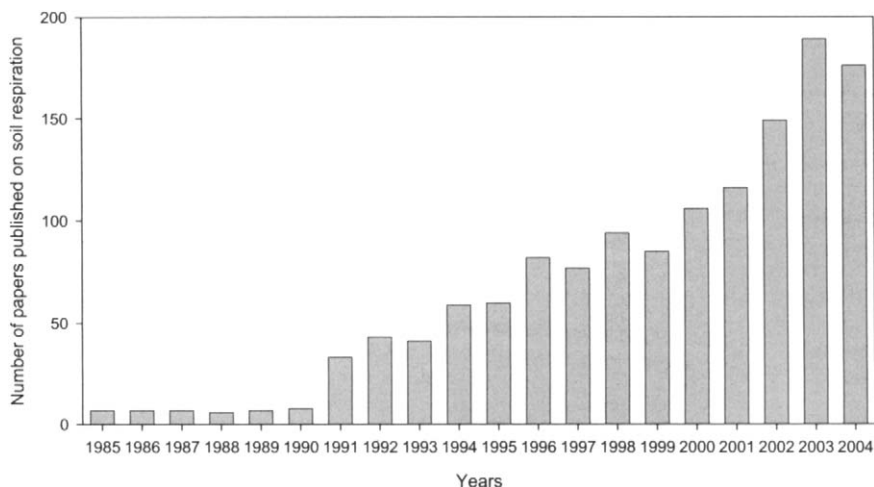


FIGURE 1.1 Number of papers published on soil respiration since 1985. The number was obtained from a search for the key terms “soil respiration,” “soil CO₂ efflux”, and “belowground respiration” in the Web of Science database.

purely academic reasons but also 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 2003–2004, compared with 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 fundamentals of soil respiration while synthesizing the recent literature in this field.

1.1. DEFINITION AND INTRODUCTION

The word respiration, derived from the Latin prefix *re-* (back, again) and root word *spirare* (to breathe), literally means breathing again and again. It is thus 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 micro-organisms 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 the word respiration is used mainly to describe CO_2 production rather than energy supply.

For the purposes of this book, soil respiration 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 (e.g., Killham 1994) also include living organisms in the definition of soil, treating roots, soil microbes, and soil fauna as part of soil. Therefore, it makes 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. The latter refers to respiratory CO_2 production by the plant parts above the soil surface. Although the definition of soil usually does not include dead plant materials at the soil surface 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) cannot 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 4). 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 a 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, and the two terms are thus interchangeable.

However, there are several situations in which CO_2 production may not be at a steady state with CO_2 transport. For example, soil degassing occurs during rainfall or irrigation, driving CO_2 stored in the soil air space out of the soil. After rainfall or irrigation, CO_2 produced by soil organisms is partially stored in the soil to rebuild the CO_2 concentration gradient. Carbonic acid reaction and microbial methanogenesis could each produce or consume

CO₂, depending on conditions that influence reaction equilibria (see Chapter 3). Thus, the CO₂ 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 CO₂ produced by soil living tissues could be absorbed by microbes during methanogenic processes. However, the amount of CO₂ produced and/or consumed by carbonation and methanogenesis is generally trivial in comparison with soil respiration, except in very dry lands. The non-steady-state CO₂ efflux at the soil surface occurs mostly during rainfall or irrigation after long periods of drought (Liu *et al.* 2002a, Xu *et al.* 2004). In absence of major perturbation, the rate of CO₂ production in soil is indistinguishable from the rate of CO₂ efflux at the soil surface on a daily or longer time-scale (Hui and Luo 2004). Thus, the term soil respiration is practically interchangeable with soil surface CO₂ efflux on a long-term scale. However, soil CO₂ efflux rates measured at shorter time-scales may not be equivalent to the rate of soil respiration.

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

As a preview, Figure 1.2 shows a typical time course of CO₂ efflux rates from soil. The time course, which was measured at the soil surface in a tall-grass prairie of Oklahoma, displays a distinct seasonal pattern of high soil respiration during summer and low respiration 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 $6\mu\text{mol m}^{-2}\text{s}^{-1}$ in 2002 and is less than $4\mu\text{mol m}^{-2}\text{s}^{-1}$ in 2001. The winter low is nearly $0\mu\text{mol m}^{-2}\text{s}^{-1}$ in 2002 but $0.3\text{--}0.5\mu\text{mol m}^{-2}\text{s}^{-1}$ 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 $0\mu\text{mol m}^{-2}\text{s}^{-1}$ in the winter to about $10\mu\text{mol m}^{-2}\text{s}^{-1}$ 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.

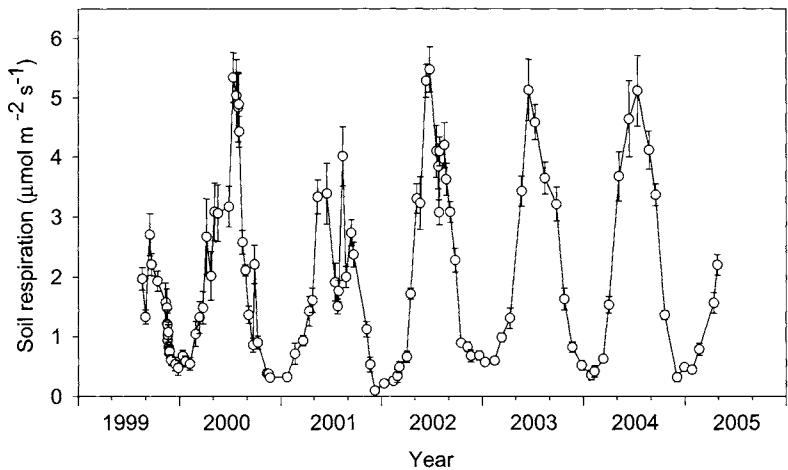


FIGURE 1.2 Measured rate of soil CO₂ efflux in a tallgrass prairie of Oklahoma, USA from 1999 to 2005. Open circles represent data points, and bars indicate the one standard error below and above the data points. Data are only for the measured soil CO₂ efflux in the control treatment in a warming and clipping experiment and adopted from Luo *et al.* (2001), Wan *et al.* (2005), and Zhou *et al.* (2006).

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 another? How can we scale up the plot-level measurements to estimate total carbon losses on 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? This book will address these questions, among others, as it lays down the basic principles of soil respiration. Before turning to these issues, however, let's first review the history of research on soil respiration.

1.2. HISTORY OF RESEARCH

Research on soil respiration has an impressively long history (Fig. 1.3) and can be dated back to papers by Wollny (1831), Boussingault and Levy (1853), and Möller (1879). The earliest studies of soil respiration were intended to characterize soil metabolism. Twentieth-century research on soil respiration

can be divided into roughly four major periods. During the first few decades of the century, research on soil respiration was conducted primarily in the laboratory with agricultural soil. Soil respiration was used to evaluate soil fertility and biological activities in soil. Chemical fertilizers, invented in the late 19th century, were applied to crops to stimulate growth and considerably enhanced agricultural productivity as a result. At that time, researchers emphasized 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 laboratory studies, however, showed that nutrient release was not proportional to the carbon release during mineralization (Waksman and Starkey 1924, Pinck *et al.* 1950).

During that period, some primitive methods for the measurement of soil respiration were developed. Stoklasa and Ernest (1905) passed CO₂-free air over soil samples contained in a flask and measured the amount of CO₂ released from the soil samples using the alkali absorption method. Lundegårdh (1927) recognized that measured CO₂ efflux from soil samples in the laboratory might not be representative of that from intact soils in the field, where, he argued, diffusion was a chief process controlling efflux of CO₂. He was probably the first scientist to make in situ measurements of rates of CO₂ efflux 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 different 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 CO₂-enriched air in an alkali absorption train. The alkali absorption chamber method, first introduced by Lundegårdh (1921), modified by Humfeld (1930) and others, and widely used in the following decades, places static alkali solution within the chamber followed by titration of chloric acid.

By this time the major factors that influence soil respiration had 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 CO₂ efflux from soils was attributable to bacterial decomposition. Lundegårdh (1927) pointed out that soil diffusion was important in controlling the efflux of CO₂. Smith and Brown (1933) indicated that the rate of diffusion of CO₂ through the soil correlated with CO₂ production. Lebedjantzev (1924) observed that air drying of soil samples increased fertility (such as NH₄-N, amide-N, and phosphorus) of a variety of soils and decreased the number of microorganisms in pot experiments.

Few publications on soil respiration can be identified during the relatively inactive research period from the late 1930s to the early 1950s, possibly due to the worldwide social turbulence of that period. From the late 1950s to the 1970s, research activity on soil respiration resumed (Fig. 1.3), mainly from an ecological perspective, as scientists tried to understand heterotrophic processes in the soils of native ecosystems (Lieth and Ouellette 1962, Witkamp 1966, Raguotis 1967, Schulze 1967, Reiners 1968, Kucera and Kirkham 1971). During that period, research advanced the science of soil respiration in many respects, 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 CO₂ efflux. Minderman and Vulto (1973) suggested the use of fine-grained soda lime instead of alkali solution to absorb CO₂.

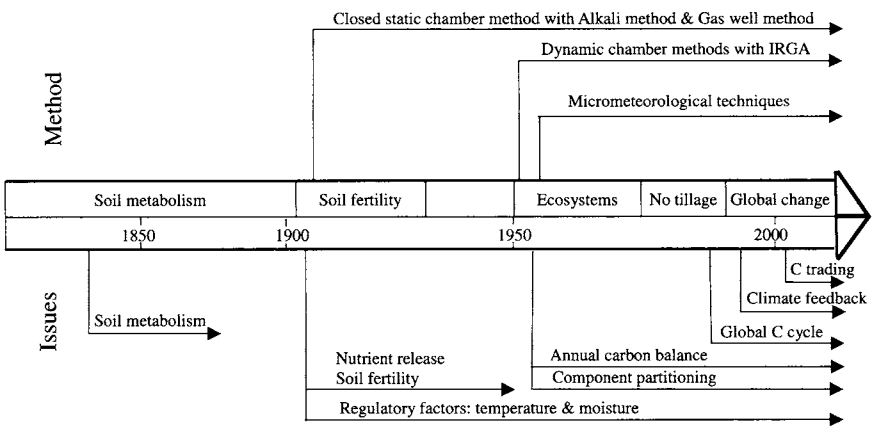


FIGURE 1.3 Schematic illustration of the history of soil respiration research since the 1830s. Within the main axis are major themes in different eras of research. There is little research activity from late 1930s to early 1950s. Above the axis is method development for measurement of soil respiration. Below the axis are major issues that have been addressed by and/or motivate soil respiration research during the different eras.

One major technical advance was made in the 1950s: 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 CO₂ evolution, while Kanemasu *et al.* (1974) studied effects of air “suction” and “pressure” on IRGA measurements of soil respiration. Measured CO₂ efflux with the suction chamber was one order of magnitude higher than with the pressure chamber. The suction chamber drew CO₂ 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 onto 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 CO₂ efflux were then compared with those using the alkali absorption method (Kirita and Hozumi 1966). Many studies found that the alkali method underestimated soil CO₂ efflux compared with 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 first used by Lundegårdh (1927) to estimate soil respiration from a CO₂ concentration gradient along soil profiles was fully developed by de Jong *et al.* (1979). Meanwhile, a variety of micrometeorological methods, such as Bowen ratio and eddy flux, have been developed to measure gas exchanges within and above the plant canopy (Monteith 1962, Monteith *et al.* 1964), from which soil respiration was indirectly estimated.

From the late 1950s to the 1970s, knowledge of factors that regulate soil respiration was greatly enriched. Bunt and Rovira (1954) studied soil respiration in a temperature range of 10 to 70°C. They found that O₂ uptake and CO₂ release increased with temperature up to 50°C, above which it declined. Many studies demonstrated that soil respiration correlated exponentially with temperature (Wiant 1967, Kucera and Kirkhma 1971, Medina and Zelwer 1972). Drobnik (1962) estimated Q_{10} , that is, a quotient indicating the temperature sensitivity of soil respiration (see Chapter 5), to be 1.6 to 2.0 in response to temperatures ranging from 8 to 28°C. Wiant (1967) estimated Q_{10} to be approximately 2 for temperatures from 20 to 40°C. Soil moisture was also identified as 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 the field (Reiners 1968).

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

During that period, components of soil respiration were 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 (SOM). 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 to 17% from roots, 6 to 16% from litter, and 67 to 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 the 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 $452 \text{ g C m}^{-2} \text{ yr}^{-1}$ in a tallgrass prairie by applying a temperature-respiration regression to continuous temperature records. Coleman (1973a) scaled up monthly averages of soil respiration in a grassland and estimated annual soil CO_2 efflux to be 357 to $421 \text{ g C m}^{-2} \text{ yr}^{-1}$. Estimated annual soil CO_2 releases were about $1000 \text{ g C m}^{-2} \text{ yr}^{-1}$ 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 carbon release was three times higher than litter carbon input. Edwards and Sollins (1973) found that litter decomposition accounted for only one-fifth of annual soil respiration. Anderson (1973) showed that annual soil respiration released 2.5 times as much carbon in annual litterfall. However, several studies demonstrated that carbon released by soil respiration was equivalent to that input from litterfall (Coleman 1973a, Witkamp and Frank 1969).

The accumulation of studies during that period offered opportunities to synthesize and compile results from many ecosystems. Singh and Gupta (1977) produced a major synthesis on the carbon processes of litter decomposition, soil respiration, root respiration, microbial respiration, faunal

respiration, and SOM dynamics. Schlesinger (1977) reviewed many studies on soil respiration in the literature in order to develop latitudinal patterns of soil respiration worldwide and estimate a global total of carbon released via soil respiration.

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

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 the 1980s the 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 CO₂ and N₂O production. The level of soil aeration using microbial respiration rates of aerobic heterotrophs was also examined for compaction problems in a 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 driven primarily by global change. While climate research has its own long history (Weart 2003), the ecology research community, stimulated by the International Geosphere Biosphere Program (IGBP) and by a U.S. National Research Council (NRC) report (NRC 1986), has been involved in global change research in the past two decades and has studied ecosystem-level responses to climate change since the early 1990s (Mooney *et al.* 1991). In particular, the paper by Tan *et al.* (1990) played a critical role in attracting researchers' attention to the land biosphere. Their analysis of atmospheric CO₂ data suggested that land biosphere may absorb a large portion of the emitted carbon from anthropogenic sources. Three reports by the Intergovernmental Panel on Climate Change (IPCC, 1990, 1995, 2001) and Schimel (1995) provided a global perspective on 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 the temperature sensitivity of respiration in future climatic predictions. That study continues to stimulate great interest in the temperature sensitivity of soil respiration among the research community.

Advances in measurement techniques have also stimulated modern, active research on soil respiration. Portable IRGAs have been widely used to measure soil surface CO₂ fluxes since the early 1990s (Norman *et al.* 1992). The IRGA method requires relatively less technique training than the traditional alkali or soda-lime absorption methods, but it provides quicker

measurements of soil surface CO₂ effluxes. Meanwhile, many companies have retooled IRGA sensors and developed various chambers specifically for the measurement of soil CO₂ effluxes (see Chapter 8 and Appendix) facilitating research on soil respiration.

1.3. OVERVIEW OF THE BOOK

This book, which comprises 10 chapters, is dedicated to providing an understanding of various aspects of soil respiration. Chapters 1 and 2 provide a context of soil respiration science. Chapters 3 and 4 describe fundamental processes of CO₂ production and CO₂ transport. Chapters 5 through 7 present regulatory mechanisms of soil respiration, including controlling factors, spatial and temporal variations, and responses to natural and human-made perturbations. Chapters 8 through 10 discuss research approaches to measurement of soil respiration, partitioning to various components, and modeling.

Following the introduction and brief history of research on soil respiration covered in this chapter, Chapter 2 places soil respiration in the context of ecosystem carbon balance, nutrient cycling, regional and global carbon cycling, climate change, and carbon storage and trading. Soil respiration releases a large portion of carbon fixed by photosynthesis and strongly regulates net ecosystem productivity. Carbon dioxide released via microbial decomposition of litter and SOM is accompanied by either immobilization or mineralization of nutrients and is thus related to soil nutrient dynamics. Soil respiration plays a critical role in regulating global and regional carbon cycles. Its temperature sensitivity is a key issue in modeling feedback between global carbon cycling and climate change in response to anthropogenic warming. Although it is not the direct mechanism underlying land carbon storage, soil respiration is relevant to understanding carbon sequestration and global carbon trading markets.

Chapter 3 focuses on the processes of CO₂ production, including the fundamental biochemistry of respiratory processes, root respiration, microbial respiration in rhizosphere, and microbial decomposition of litter and SOM. The primary biochemical process of CO₂ 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 while root exudates are broken down, litter is decomposed, and SOM oxidized. Microorganism communities that use root exudates, litter, and SOM as substrates differ greatly and are briefly described in this chapter.

Chapter 4 describes processes of CO₂ transport along vertical profiles within the soil, at the soil surface, in the canopy, and in the planetary boundary layer. Soil CO₂ transport is driven primarily by gradients of CO₂

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, turbulences, and atmospheric pressure fluctuation. The CO_2 transport in the canopy and planetary boundary layer may not be directly relevant to soil respiration per se but is influenced by and often used to estimate soil respiration indirectly.

Soil respiration is affected by many factors, such as substrate supply, temperature, moisture, oxygen, nitrogen, soil texture, and pH value. Chapter 5 focuses on how individual factors regulate component processes of soil respiration and attempts to show that many of the factors influence multiple processes in various magnitudes and at different directions, leading to variable responses and complex patterns of soil respiration. The interactive effects of multiple factors on soil respiration are very complex and poorly understood.

Chapter 6 presents spatial and temporal patterns of soil respiration. It discusses temporal variations in soil respiration at multiple time-scales—from diurnal and weekly to seasonal, interannual, and decadal and centennial. Spatial patterns emerge at the stand level, landscape and regional scales, and across biomes. The chapter comparatively presents soil respiration among ecosystem types and examines general relationships of soil respiration to ecosystem productivities, prevailing environmental variables, and soil characteristics. This chapter also examines how soil respiration varies along latitudinal, altitudinal, and topographical gradients.

Chapter 7 describes changes in soil respiration in response to a variety of perturbations, such as elevated CO_2 , global warming, changes in precipitation frequency and intensity, disturbances and manipulation of substrate supply, nitrogen deposition and fertilization, and agricultural cultivation. Generally speaking, soil respiration increases when substrate availability increases, such as under elevated CO_2 and litter addition. Soil respiration decreases if substrate supply is reduced under disturbances of fire, burning, forest cutting, cutting and grazing in grasslands, and litter removal. Agricultural cultivation usually stimulates soil respiration in the short term because of soil disturbances but results in a long-term decrease in soil carbon content. Climatic warming also causes short-term stimulation of soil respiration and may induce long-term acclimation. Responses of soil respiration to changes in precipitation and nitrogen addition are highly variable.

Chapter 8 introduces a variety of methods for measurement of soil respiration. The most commonly used are chamber methods, which include the closed dynamic-chamber method, the open dynamic-chamber method, and the closed static-chamber method. Soil respiration can also be estimated from air samples from different depths of soil using the gas-well method. This chapter describes the basic principles behind those methods, discusses

chamber designs and deployment, and assesses the accuracy and potential issues of those methods. It also briefly describes a few indirect methods for estimation of soil respiration.

The partitioning of soil respiration is critical for developing predictive understanding of soil respiration. Chapter 9 introduces three groups of methods—experimental manipulations, isotope tracers, and indirect inference analysis—for partitioning. The experimental methods manipulate the substrate supply to different pathways of soil respiration and separate components of soil respiration. The isotope methods take advantages of isotope signals of C_3 and C_4 plants and soils, 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 and deconvolution analysis. This chapter summarizes estimates of contributions of each source component to the total soil respiration.

Chapter 10 provides a general description of models and modeling studies of soil respiration. In general, the modeling studies are based on three types of models: empirical models, CO_2 production models, and CO_2 production and transport models. The empirical models are derived primarily from regression analysis of soil respiration with temperature, moisture, and some surrogate quantities of substrate availability. The production models usually incorporate carbon processes of photosynthesis, partitioning, and decomposition of litter and SOM. The production-transport models consider transport processes of soil CO_2 along a soil profile from the production sites to soil surface. This chapter examines modeling studies according to different spatial and temporal scales and discusses model development and evaluation.