Agriculture, Ecosystems and Environment 216 (2016) 177–187

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

The factors related to carbon dioxide effluxes and production in the soil profiles of rain-fed maize fields

Weige Nan[a,c], Shanchao Yue[a,b], Shiqing Li[a,b,*], Haizhou Huang[b], Yufang Shen[a,b]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China
[b] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
[c] University of Chinese Academy of Sciences, Beijing, 100049, China

ARTICLE INFO

Article history:
Received 21 April 2015
Received in revised form 25 September 2015
Accepted 27 September 2015
Available online 19 October 2015

Keywords:
Carbon dioxide
Concentration gradient
Fertilization
Season
Cumulative amount

ABSTRACT

We assessed soil carbon dioxide (CO_2) production and transport in high-yield fields and confirmed the main sources and main driving factors of CO_2 at different soil depths. Our experiments were performed at the Changwu ecological station, and we utilized a 3-year-old fertility experiment to study the production and effluxes of CO_2 within soil profiles. Soil CO_2 efflux rates were computed by the concentration gradient method, where CO_2 concentrations were measured using flame ionization detector (FID) from situ gas samplers. The results showed that the cumulative production and effluxes of CO_2 in the soil decreased with depth; most of CO_2 soil production and effluxes occurred in the surface soil (0–15 cm), where the cumulative production and effluxes of CO_2 accounted for 72.3% and 76.3% of the total amounts in the soil profile (0–100 cm), respectively. Higher efflux rates were observed with high production rates from the sixth-leaf stage (V6) to the silking stage (R1), which is a period of rapid maize growth and soil water stress. During that period, mean cumulative effluxes accounted for 52–57% of the annual effluxes. The application of nitrogen fertilizer strongly improved plant growth and grain yield and slightly promoted CO_2 production and effluxes. However, nitrogen fertilizer application did not affect the productive contribution rate, i.e., the contribution rate of CO_2 production in each soil layer to the entire profile (% of total), which revealed that the production and effluxes of CO_2 responded weakly to nitrogen fertilizer. The integrated application of manure and nitrogen fertilizer significantly increased the production and effluxes of CO_2 within the soil profiles and significantly improved the productive contribution rates of CO_2 in the topsoil. In addition, manure application promoted much greater soil CO_2 production throughout the observation period, so the contribution from manure was greater than that from nitrogen fertilizer.

1. Introduction

Soils are a major source of atmospheric carbon dioxide (CO_2), contributing 60–70 Pg CO_2–C yr^{-1} (Allen et al., 2009; Schlesinger and Andrews, 2000), and minor changes in the balance between belowground carbon storage and release can have major impacts on CO_2 emissions. Vast quantities of carbon in the form of roots and decomposed organic matter are stored in the soil, and carbon is released into the atmosphere as CO_2 through physical, chemical, and biological processes, which result in a balance between the storage of organic carbon compounds and their emission (Johnston et al., 2004). Soil CO_2 emission is often referred to as soil respiration, which is typically classified as autotrophic (from plant roots and the rhizosphere) or heterotrophic (from soil organisms ranging in size from bacteria to fungi, small insects, and small mammals) (Trumbore, 1993). Crops directly affect autotrophic respiration, and crop residues affect heterotrophic respiration (Hassan et al., 2014; Schulz et al., 2011; Vargas et al., 2014). However, environmental factors, such as soil temperature, moisture, and organic matter, can also affect soil respiration (Bond-Lamberty and Thomson, 2010; Cook et al., 1998; Davidson et al., 1998, 2000, 2006; Davidson and Janssens, 2006; Liu et al., 2012; Fang et al., 2009; Fang and Moncrieff, 2001; Gaumont-Guay et al., 2006; Jassal et al., 2004; Kirschbaum, 1995), and manures support rich microbial communities (Elhottová et al., 2012) and provide many different types of organic matter (Šimek et al., 2014),

---

[*] Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China. Fax: +86 29 87016171.
E-mail address: sqli@ms.iswc.ac.cn (S. Li).

http://dx.doi.org/10.1016/j.agee.2015.09.032
0167-8809/

which is an important source of CO_2 (Hynšt et al., 2007; Xu et al., 2011). Fertilizer inputs increase soil N availability, which can affect crop growth and the microbial community and accelerate the decomposition of soil organic matter, thereby affecting soil respiration (Ramirez et al., 2010; Xu et al., 2011). Thus, we conceived an experiment to identify and measure the major factors that affect CO_2 production, including plant growth, soil temperature and water content, from the application of organic fertilizer and N fertilizer.

Net soil surface gas fluxes result from the production and transportation of gases through the underlying soil (Bowden and Bormann, 1986), and soil CO_2 is produced at all depths and transported to the soil surface. To understand when and how soil CO_2 is produced at different depths, it is necessary to determine both the soil CO_2 concentration and the CO_2 efflux of the soil profile (Fierer et al., 2005; Jassal et al., 2005; Kusa et al., 2010; Novak, 2007; Risk et al., 2002a,b; Shrestha et al., 2004). Some studies have undertaken field observations to highlight the importance of the vertical distribution of CO_2 concentrations and their flux, which is generally derived from Fick's first law, on soil CO_2 efflux. Hendry et al. (1999) simulated soil CO_2 concentration and soil-surface CO_2 flux and quantified the CO_2 production rate at each depth using parameterization and sensitivity analysis. Some studies have also investigated the relative contribution of different soil depths to the total CO_2 production of a soil profile (Hashimoto et al., 2007). For example, Davidson and Trumbore (1995) found that approximately 70–80% of the CO_2 production in forests and pasture in the Amazon basin occurs within the top 100 cm of soil, and Gaudinski et al. (2000) found that 63% of soil respiration occurs in the top 15 cm of the soil in a temperate forest. Davidson et al. (2006) estimated that the O horizon (the organic horizon, which is 3–8 cm thick) contributes 40–48% of the total annual soil CO_2 efflux in a mixed hardwood stand in Massachusetts, and Fierer et al. (2005) revealed that the CO_2 production in the subsurface (soil below 40 cm in depth) at a California grassland site equals half of the CO_2 flux when surface conditions are water-limited. However, few studies have investigated CO_2 production and effluxes in the soil profiles in an agro-ecosystem. Supplemental fertilizer can enhance agricultural production, but its impact on CO_2 effluxes and production remains unclear. Thus, it is necessary to investigate the CO_2 production from soil profiles under different fertilization regimes.

The Loess Plateau covers an area of 623,800 km^2 in northwest China suffers from serious soil erosion and low productivity (Li and Xiao, 1992), so the land must be enhanced through fertilization and reduced CO_2 efflux (Chen et al., 2014; Rustad et al., 2000; Tilman et al., 2002). We had previously constructed a high-yield and high-efficiency hybrid maize production system and found that the grain yield in the area increased with increasing rates of N application. Higher N application (i.e., 380 kg N ha^{-1}, N380) practices could achieve high yields but might pose environmental risks, such as nitrogen surpluses, nitrate leaching, ammonia volatilization and N_2O emissions (Liu et al., 2014a). Nevertheless, grain yield peaked as a result of the integrated application of manure and N (250 kg N ha^{-1}, MN250), in which the N input was nearly equivalent to the N uptake by the maize, which resulted in lower N_2O emissions (Liu et al., 2014b). Using the two treatments in the high-N and high-efficiency plot, we investigated the influence of fertilizer application on the soil effluxes and production of CO_2 to further understand the main controlling factors by analyzing plant growth, soil temperature, soil water-filled pore space (WFPS) and water-soluble organic carbon (WSOC). Based on changes in the CO_2 concentrations in the profile soil with depth and over time, we calculated the CO_2 efflux by Fick's first law and determined CO_2 production to enhance our understanding of the net carbon flux at the interface of the soil and atmosphere. This information could enable the development of measures to abate CO_2 effluxes.

2. Experiments

2.1. Site description

The experiment was performed between 2012 and 2013 at the Changwu Agro-ecological Station on the Loess Plateau (35.28°N, 107.88°E and approximately 1200 m ASL). The station is located in a typical semiarid farming area with an average annual precipitation of 582 mm and an average annual temperature of 9.2 °C; the frost-free period is 171 days. One crop is planted per year (wheat or maize), and according to the Chinese soil taxonomy, the soils at the study site are Cumuli-Ustic Isohumosols (Gong et al., 2007). The annual precipitation was 480.8 mm in 2012 and 577.3 mm in 2013 with 75.6% and 71.3%, respectively, falling during the maize growing season. The daily average air temperature changed from approximately −5.0 °C in January to approximately 23 °C in August (air temperature data were missing from May 7th to June 6th in 2013, due to equipment failure). The experimental soil was identified before planting in 2009 and found to contain 4% sand, 59% silt and 37% clay. The soil in the top 20 cm had a bulk density of 1.3 g cm^{-3}, a pH of 8.4, an organic matter content of 16.4 g kg^{-1}, a total N content of 1.05 g kg^{-1}, an Olsen-P content of 20.7 mg kg^{-1}, an NH_4OAc-extractable K content of 133.1 mg kg^{-1}, and a mineral N content of 28.8 mg kg^{-1}.

2.2. Experimental design and crop management

The field experiment was situated within 50 m of the experimental site and composed of the following three treatments: no N applied (N0); N fertilizer applied at a rate of 380 kg N ha^{-1} (N380); and manure (cattle dung) applied at rate of 30 t ha^{-1} (C/N ratio of 20, nitrogen content of 0.28%, and a 25 kg N ha^{-1} seasonal increase in use) in addition to N fertilizer applied at a rate of 225 kg N ha^{-1} (MN250). These treatments were maintained throughout the entire year with three replications in 9 plots, which measured 8.0 m × 7.0 m each (with a buffer zone of 1.0 m between the plots), distributed in a completely randomized block design. After ridging the treatment plots, chemical fertilizer was applied to the soil in the form of 40% N (as urea: 46% N), 40 kg P ha^{-1} (as calcium super phosphate: 12% P_2O_5), and 80 kg K ha^{-1} (as potassium sulfate; 45% K_2O). Next, the soil was plowed to distribute the fertilizer into the subsurface, and prior to planting, manure was broadcast throughout the plots and buried in the soil with hoes. Using a hole-sowing machine in the furrows, 30% of the N fertilizer was applied at the jointing stage (June 21st, 2012 and June 30th, 2013), and the remaining 30% was applied at the silking stage (July 14th, 2012 and July 16th, 2013). In April of both years, the maize was sown at a depth of 5 cm and a density of 85,000 plants ha^{-1}, and it was harvested on September 8th, 2012 and September 12th, 2013. The soil water supply depended solely on natural rainfall.

2.3. Sample collection and measurements

2.3.1. Soil gases

The soil-air samplers used in each plot were multiport gas wells composed of poly-vinyl chloride (PVC) tubes with an inner diameter of 44 mm (Cates and Keeney, 1987; Wang et al., 2013). These sampling wells were composed of six gas chambers and were installed at depths of 7, 15, 30, 50, 70 and 90 cm (for more details, see Nan et al., 2015). Each gas chamber was connected to the soil surface via a tubule (4 mm in diameter), and twelve air holes were then drilled in the lower part of the chamber wall