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A stable carbon isotopic approach for understanding the CO_2 flux at the Haibei Alpine Meadow Ecosystem—A simple model

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Abstract

Although respiration of organisms and biomass as well as fossil fuel burning industrial production are identified as the major sources, the CO_2 flux is still unclear due to the lack of proper measurements. A mass-balance approach that exploits differences in the carbon isotopic signature ($\delta^{13}C$) of CO_2 sources and sinks was introduced and may provide a means of reducing uncertainties in the atmospheric budget. $\delta^{13}C$ measurements of atmospheric CO_2 yielded an average of −10.3‰ relative to the Peedee Belemnite standard; soil and plants had a narrow range from −25.09‰ to −26.51‰ and averaged at −25.80‰. Based on the fact of steady fractionation and enrichment during respiration of mitochondria, we obtained the emission of CO_2 of 35.451 mol m^{-2} a^{-1} and CO_2 flux of 0.2149 μmol m^{-2} s^{-1}. The positive CO_2 flux indicated the Haibei Alpine Meadow Ecosystem a source rather than a sink. The mass-balance model can be applied for other ecosystem even global carbon cycles because it neglects the complicated process of carbon metabolism, however just focuses on stable carbon isotopic compositions in any of compartments of carbon sources and sinks.

Keywords: CO_2 flux; Source; Sink; Stable carbon isotope; Alpine meadow; Qinghai-Xizang (Tibet) Plateau

1. Introduction

Carbon dioxide is the primary gas involved in the exchange for carbon between the atmosphere and the Earth, and is responsible for 50% of all greenhouse forcing (Ross et al., 2001). Atmospheric CO_2 is increasing at the rate of about 1.5% per year from a pre-industrial level of 250–280 ppm to a current ambient level of about 360 ppm (Houghton et al., 1992; Fan et al., 1998). Atmospheric CH_4, which is about 20 times more reactive than CO_2 as a greenhouse gas, is increasing at a rate of 0.8–2.0% per year. The increase in the concentration of these gases has the potential to increase surface temperature and effect climate on a global scale (Houghton et al., 1992). The sinks and sources of carbon dioxide have been generally well

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known, but the atmospheric budget (or flux) of carbon dioxide (CO_2) is still highly uncertain, because of shortage of proper measurements handling carbon flux. To date a series of model were proposed to evaluate carbon budget in certain ecosystems (Fan et al., 1998; Battle et al., 2000; Chen et al., 2000; Ito and Oikawa, 2002). However, some of them engaged in many carbon pools (Ito and Oikawa, 2002), geochemical processes (Chen et al., 2000) and should be taken consideration at a global scale (Ciais et al., 1995) and a long time series (Battle et al., 2000). Still more, a few models were only confined to given ecosystems where the experiments were carried out (Song and Woodcock, 2003). Stable isotopic signatures have been used profitably for studying the budgets of many trace gases in the atmosphere. Model based on stable carbon isotopes of atmospheric CO_2 had been used to evaluated carbon budget in marine ecosystems (Tans et al., 1993; Ciais et al., 1995; Battle et al., 2000) and reached valuable results. The best and most closely related example is that of methane (CH_4) (Schoell, 1980; Whiticar et al., 1986; Whiticar, 1989; Quay et al., 1991). Like CH_4, CO_2 has industrial sources (combustion of fossil fuel), as well as a number of biologically derived sources (respiration). Because CO_2 has a simple chemical structure, we expect its stable isotopes (C, O) to be non-exchangeable with other atmospheric species. Thus, isotopic signatures should act as reliable tracers of the sources and sinks of CO_2 to the atmosphere. We present measurements of $\delta^{13}C$ for CO_2 of respiration, atmosphere and combustion and suggest a modeling framework for exploiting this information to further understanding of the CO_2 budget at the Haibei Alpine Meadow Ecosystem of CAS.

2. Materials and methods

2.1. Study area

The Haibei Alpine Meadow Ecosystem is located in the region of the Qinghai-Tibet Plateau, in a large valley oriented NW-SE surrounded on all sides by the Qilian Mountains with N latitude 37°29′–37°45′ and E longitude 101°12′–101°33′. The average altitude of mountain area is 4000 m above sea level and 3200 m for the valley area. The climate of the Haibei Alpine Meadow Ecosystem is dominated by the Southeast monsoon and the higher-pressure system of Siberia. It has a continental monsoon type climate, with severe and long winters and short cool summers. The average air temperature is −1.7 °C with extreme maximum of 27.6 °C and minimum −37.1 °C. Average annual precipitation ranges from 426 to 860 mm, 80% of which falls in the short summer growing season from May to September. The annual average sunlight is 2462.7 h with 60.1% of total available sunshine. Vegetation is characterized by alpine shrub, alpine meadow, and swamp meadow. The research site is roughly confined in alpine meadow, with *Kobresia humilis* as dominant species and *Polygonum viviparum*, *Carex atro-fusca*, *Saussurea superba*, *Elymus nutans*, and *Gentiana straminea* as sub-dominant species.

2.2. Measurement of stable carbon isotopes

Atmospheric CO_2 samples were obtained from 2 m above ground for isotopic analysis in 20 August 2003 when the net primary production reached maximum. $\delta^{13}C$ of respiration CO_2 were obtained from plants and soils. Plant leaf and soil samples were collected during the exuberant season (July–August) and were air dried indoors to constant mass in an oven at 70 °C for 48 h, ground finely, and dispatch to Finnigan MAT DELTA^{PLUS}XL isotope ratio spectrometer under EAMS (element-analysis meter and spectrometer) condition. Interface between element-analysis meter and spectrometer is ConF III. Operation condition: oxidizing furnace temperature is 900 °C, reducing furnace is 680 °C, pillar temperature is 40 °C. The resulting CO_2 was purified in a vacuum line and injected in a micromass 602E mass spectrometer (Finnegan Mat, Bremen, Germany) fitted with double inlet and collector systems. Standards were Peedee Belemnite (PDB) formation from South Carolina, USA (Craig, 1957). The results are expressed in $\delta^{13}C$ directly relative to the PDB standard in the conventional δ per mil notation as follows:

$$\delta^{13}C = \left[\frac{(^{13}C/^{12}C)_s}{(^{13}C/^{12}C)_{sta}} - 1\right] \times 1000$$

where $^{13}C/^{12}C$ are the isotopic ratios of sample (s) and PDB standard (sta). The overall (sample preparation plus analysis) analytical precision is ±0.2‰.

2.3. Mass-balance model for determining CO_2 flux

A mass-balance model can be used to understand the effect that various CO_2 sources and sinks will have on the carbon isotope ratio of atmospheric CO_2 and ultimately, to estimate the CO_2 budget of atmosphere. The primary sources are the release of respiration of plants, animals and soils as well as combustion. The primary known sinks are photosynthesis of green plants and other microorganisms, with the latter contributing little. The differential equation that describes the time dependence of the $^{13}C/^{12}C$ ratio (R) of the atmosphere is

$$N\frac{\mathrm{d}R_{\mathrm{atm}}}{\mathrm{d}t} = \sum_{\mathrm{sources}} \Phi_{\mathrm{source}}(R_{\mathrm{source}} - R_{\mathrm{atm}}) - R_{\mathrm{atm}} \sum_{\sin ks} \Phi_{\sin k}(\alpha_{\sin k}^{-1} - 1) \quad (1)$$

where R_{atm} and R_{source} are $^{13}C/^{12}C$ ratios of atmospheric CO_2 and sources and $\alpha_{\sin k}$ is the fractionation factor during recombination into sinks. At steady state, Eq. (1) can be solved for the atmospheric $^{13}C/^{12}C$ ratio of CO_2 and put in the following form:

$$R_{\mathrm{atm}} = \frac{xR_{\mathrm{sources}}}{1 + y(\alpha_{\mathrm{plants}}^{-1} - 1)} \quad (2)$$

where the x in the numerator is the fraction of the total flux to the atmosphere by sources of CO_2 and y in the denominator is the fraction of the removal attributable to photosynthesis of plants and α_{plants} is the fractionation factor during photosynthesis. In this formulation, the sources of CO_2 are combined; this combination assumes that they can be characterized and that a mean value of $^{13}C/^{12}C$ can be established. Recasting this equation in terms of $\delta^{13}C$ the result is

$$\delta^{13}C_{\mathrm{atm}} = x\delta^{13}C_{\mathrm{sources}} - y(\alpha_{\mathrm{plants}}^{-1} - 1) \quad (3)$$

Solve the contribution of total CO_2 sources term x yields:

$$x = \frac{\delta^{13}C_{\mathrm{atm}} + y(\alpha_{\mathrm{plants}}^{-1} - 1)}{\delta^{13}C_{\mathrm{sources}}} \quad (4)$$

Eq. (4) represents the CO_2 source contribution to the atmosphere, based on the $\delta^{13}C$ value of atmospheric CO_2 and the isotopic signature of its sources and sinks.

3. Results and analysis

The measured $\delta^{13}C$ values of atmospheric CO_2 were lower than the reported values (Farquhar, 1987). The measured $\delta^{13}C$ values varied from −10.2‰ to −10.5‰, and the mean was −10.3‰. There were differences in the $\delta^{13}C$ of CO_2 from the plants and soil. Surface soil (0–5 cm) possessed the $\delta^{13}C$ value of −25.09‰, which was a little bit positive than the average $\delta^{13}C$ value of vegetation (102 plants investigated, all showed C_3 photosynthetic pathway and possessed $\delta^{13}C$ values ranged from −28.24‰ to −24.84‰, and averaged at −26.51‰). Most respiration-produced CO_2 have $\delta^{13}C$ values that reflect the biomass source (Whiticar, 1989; Lathja and Michener, 1994) because there is a steady enrichment (or fractionation) during respiration in mitochondrion (Ivlev et al., 1996), so CO_2 evolved by mitochondria is enriched by about 11‰ in ^{13}C (van der Merwe et al., 1988). I tentatively defined $\delta^{13}C$ signature for respiration CO_2 of plants and soil as from −14.09‰ to −15.51‰, with the mean of −14.80‰. Due to the fact of the same substrate for respiration of plants and microorganisms (including animals) as well as small fractionation and enrichment of stable carbon isotope among trophic levels, we combined all the $\delta^{13}C$ signatures of respiration into one.

In Eq. (4), α_{plants} is equal to 1.01665 and calculated from $\alpha_{\mathrm{plants}} = \Delta + 1 = (\delta^{13}C_{\mathrm{atm}} - \delta^{13}C_{\mathrm{plants}})/(\delta^{13}C_{\mathrm{plants}} + 1) + 1$, y is the maximum net primary production (aboveground and belowground) and is defined as $1120\,\mathrm{g\,m^{-2}\,a^{-1}}$, e.g., $32.6656\,\mathrm{mol\,m^{-2}\,a^{-1}}$ (the carbon content of alpine meadow community was about 35% (Zhou, 2001), the aboveground maximum net primary production is $350\,\mathrm{g\,m^{-2}\,a^{-1}}$ (Yi, 2000; Yi et al., 2000) and the belowground maximum net primary production is 2.2 times as the aboveground (Yang et al., 1985)). Based on the above information, x is calculated as $35.451\,\mathrm{mol\,m^{-2}\,a^{-1}}$ and CO_2 flux as $2.7854\,\mathrm{mol\,m^{-2}\,a^{-1}}$ or $0.2149\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ (here the growth season at the Haibei Alpine Meadow Ecosystem is defined as 150 days correspondent with plant photosynthesis duration).

4. Discussion

The results reported here are significant, because they inform us that the $\delta^{13}C$ value of atmospheric CO_2 is a very useful and important indicator for carbon budget. The $\delta^{13}C$ value of atmospheric CO_2 could provide an indication of the relative strength of the CO_2 sources (Eq. (4)). The results showed that carbon source contributed to atmosphere and CO_2 flux were $2.7854\,mol\,m^{-2}\,a^{-1}$ or $0.2149\,\mu mol\,m^{-2}\,s^{-1}$, which clearly indicated the Haibei Alpine Meadow Ecosystem a source rather than a sink of CO_2. These results were consistent with the previous research carried out at the same areas, where Zhang et al. (2003) found the ecosystem appeared to be a CO_2 source by direct measurement of C content in several compartments, however, CO_2 flux in this study is a little bit less than the result of Zhang et al. (2003). CO_2 samples were collected at the height of 2 m, which somewhat did not meet the demand of National Oceanic and Atmospheric Administration (NOAA). But it is reasonable to assume that the concentration and isotopic value of CO_2 will approach steady state. And the most positive value of $\delta^{13}C$ of atmospheric CO_2 is reported as −8.8‰ (Ehleringer, 1993) (provided in this condition, the CO_2 flux is $0.2167\,\mu mol\,m^{-2}\,s^{-1}$), which means that sampling diversity causes acceptable differences (0.84%). Variations in the $\delta^{13}C$ of atmospheric CO_2 with time, latitude as well as altitude should provide additional information about the factors controlling the atmospheric CO_2 budget. Differences in the $\delta^{13}C$ of atmospheric CO_2 would indicate differences in the source and sink fluxes providing new constraints on the global budget. Temporal variations in the $\delta^{13}C$ of atmospheric CO_2 could provide information on seasonality of the various sources and sinks.

5. Conclusion

The mass-balance model has three specific characters: i.e. (1) it is a two-compartment model, dividing carbon sinks and sources into two main compartments and isotopic measurements of CO_2 sources and sinks serve as the main topics; (2) it is a process-based model, which estimates carbon budget based on mass-balance theory of stable isotopes; (3) it is a prognostic model to predict carbon flux under changing environments because $\delta^{13}C$ of atmospheric CO_2 is dynamic and very easy to measure. The measurements presented here indicate that the Haibei Alpine Meadow Ecosystem maybe remain a carbon source based on $\delta^{13}C$ value of atmospheric CO_2, and its sinks as well as sources. Despite the coarseness of the balance model, in which all types of respiration were taken as a whole, isotopic measurements of CO_2 sources and sinks as well as the atmospheric reservoir could therefore greatly improve our understanding of the biogeochemical processes controlling the atmospheric CO_2 budget. And stable carbon isotope-based approach is a time-integrated and reflects a long-term pattern of carbon dioxide flux rather than daily or monthly budget. This approach could also provide an independent tool for assessing the effectiveness long-term carbon flux observation at the Haibei Alpine Meadow Ecosystem.

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