Temperature exerted no influence on the soil organic matter $\delta^{13}C$ of surface soil along the 400 mm isopleth of mean annual precipitation in China

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Abstract

Soil organic carbon is the largest pool of terrestrial ecosystem, and its carbon isotope composition is affected by many factors. However, the influence of environmental factors, especially temperature, on soil organic carbon isotope values ($\delta^{13}C_{SOM}$) is poorly constrained. This impedes interpretations and application of variability of organic carbon isotopes in reconstructions of paleoclimate and paleoecology and global carbon cycling. Given then considerable temperature gradient along the 400 mm isohyet (isopleth of mean annual precipitation – MAP) in China, this isohyet provides ideal experimental sites for studying the influence of temperature on soil organic carbon isotopes. In this study, the effect of temperature on surface soil $\delta^{13}C$ was assessed by a comprehensive investigation at 27 sites across a temperature gradient along the isohyet. This work demonstrates that temperature did not play a role in soil $\delta^{13}C$. This suggests that organic carbon isotopes in sediments cannot be used for paleotemperature reconstruction and that the effect of temperature on organic carbon isotopes can be neglected in the reconstruction of paleoclimate and paleovegetation. Multiple regressions with MAT (mean annual temperature), MAP, altitude, latitude, and longitude as independent variables and $\delta^{13}C_{SOM}$ as the dependent variable show that these five environmental factors in total account for only 9% of soil $\delta^{13}C$ variance. However, one-way ANOVA analyses suggest that soil type and vegetation type are significant influential factors on soil $\delta^{13}C$. Multiple regressions in which the five aforementioned environmental factors were taken as quantitative variables and vegetation type, Chinese nomenclature soil type, and WRB soil type were introduced as dummy variables separately show that 36.2, 37.4, and 29.7% of the variability in soil $\delta^{13}C$ are explained, respectively. Compared to the multiple regressions in which only quantitative environmental variables were introduced, the multiple regressions in which soil and vegetation were also introduced explain more variance, suggesting that soil type and vegetation type exerted significant influence on $\delta^{13}C_{SOM}$.

1. Introduction

Global climate change has recently received a great deal of attention, and effective predictions of future climate change depend on the relevant information from climate in the geological past. Over recent decades, stable carbon isotopes in sediments such as loess, paleosol, lacustrine, and marine sediments have been widely used to reconstruct paleo-vegetation and paleo-environments and provided important insights into patterns of past climate and environment changes. For examples, many researchers have used organic carbon isotopes of loess to reconstruct paleo-vegetation and paleo-precipitation. Vidic and Montañez (2004) conducted a reconstruction of paleovegetation at the central Chinese Loess Plateau during the Last Glaciation (LG) and Holocene using the organic carbon isotopes in loess from Jiaodao, Shanxi Province. Hatté and Guiot (2005) carried out a palaeo-precipitation reconstruction by inverse modeling using the organic carbon isotopic signal of the Nuβloch loess sequence (Rhine Valley, Germany). Rao et al. (2013) reconstructed high-resolution summer precipitation variations in the western Chinese Loess Plateau during the LG using a well-dated organic carbon isotopic dataset. Yang et al. (2015) derived a minimum 300 km northwestward migration of the monsoon rain belt from the Last Glacial Maximum to the Mid-Holocene using the organic carbon isotopes from 21 loess sections across the Loess Plateau. However, to our knowledge, no researchers have conducted paleo-temperature reconstructions using organic carbon isotope records of loess and paleosol because it has been argued that temperature exerts slight, or even no influence on soil organic carbon isotope values ($\delta^{13}C_{SOM}$). While this may be likely, it needs to be demonstrated because only few studies have addressed the influence of temperature on organic carbon isotopes of modern surface soil. Lee et al. (2005) and Feng et al. (2008) both reported no relationship between temperature and surface soil $\delta^{13}C$ in central-east Asia. However, Lu et al. (2004) discovered a nonlinear relationship between mean annual temperature (MAT) and $\delta^{13}C_{SOM}$ from the Qinghai-Tibetan Plateau; Sage et al. (1999) compiled the data from Bird and Pousai (1997) and also found a nonlinear trend for the variation in $\delta^{13}C_{SOM}$ along a temperature gradient in Australian grasslands and savannas.

Plant residues are the most important source of soil organic matter. $\delta^{13}C_{SOM}$ is generally close to plant $\delta^{13}C$ value, despite isotopic fractionation during the decomposition of organic matter (Nadelhoffer and Fry, 1988; Balesdent et al., 1993; Ågren et al., 1996; Fernandezet al., 2003; Wynn, 2007). Thus, the influential factors for plant $\delta^{13}C$ might also influence $\delta^{13}C_{SOM}$. $\delta^{13}C$ in plants, especially C_3 plants, is tightly associated with precipitation, so precipitation may affect soil $\delta^{13}C$ (Diefendorf et al., 2010; Kohn, 2010). In addition to the effect of precipitation, many other factors, such as temperature, air pressure, atmospheric CO_2 concentration, altitude, latitude, and longitude may also influence $\delta^{13}C$ in plants (Körner et al., 1991; Hultine and Marshall, 2000; Zhu et al., 2010; Xu et al., 2015). Although patterns of variation in plant $\delta^{13}C$ with respect to temperature are unresolved so far (e.g. Schleser et al., 1999; McCarroll and Loader, 2004; Treydte et al., 2007; Wang et al., 2013), it has been widely accepted that temperature has a slight effect on plant $\delta^{13}C$. As such, if the ^{13}C

enrichment during soil organic matter decomposition is a constant value, we expect a slight or no influence of temperature on soil $\delta^{13}C$. However, this ^{13}C-enrichment is affected by environmental and biotic factors (Wang et al., 2015). Thus, it is difficult to determine whether or how temperature affects soil $\delta^{13}C$, and there should be specific investigations focusing on this issue. Although the relationship between temperature and $\delta^{13}C_{SOM}$ has been investigated in the studies mentioned above, these studies were unable to effectively separate the influence of temperature from the effect of precipitation. Thus, new investigations are necessary. The present study includes an intensive investigation of the variation in $\delta^{13}C_{SOM}$ with respect to temperature across a temperature gradient along the 400 mm isohyet (isopleth of mean annual precipitation; MAP) in China. We sampled surface soil along the specific isohyet to minimize the effect of precipitation changes on $\delta^{13}C_{SOM}$.

In addition, there are no meteorological stations near most of the sampling sites in the previous studies mentioned above; thus, they had to interpolate meteorological data, which can be unrealistic in regions with strong topographical variability. This interpolation could have produced errors in the relationships between temperature and $\delta^{13}C_{SOM}$ that were established in these studies. In the present investigation, we collected samples only at those sites with meteorological stations; thus, the climatic data that we obtained from these stations are probably more reliable compared to the interpolated pseudo-data.

2. Materials and methods

2.1. Study site

In this study, we set up a transect along the 400 mm isohyet from LangKaZi (site 1, 29°3.309′N, 90°23.469′E) on the Qinghai-Tibetan Plateau in southwest China to BeiJiCun (Site27, 53°17.458′N, 122°8.752′E) in Heilongjiang Province in northeast China (Fig. 1, Table 1). The straight-line distance between the above two sites is about 6000 km. Twenty-seven (27) sampling sites were set along the transect. Among these sampling sites, 10 sites were located on the Qinghai-Tibetan Plateau and the others were in north China. BeiJiCun and KuDuEr had the lowest MAT of -5.5 ℃, while ShenMu had the highest MAT of +8.9 ℃. The average MAP of these sites was 402 mm. In north China, rainfall from June to September accounts for approximately 80% of the total annual precipitation, and the dominant control over the amount of precipitation is the strength of the East-Asian monsoon system. In the Qinghai-Tibetan Plateau, however, precipitation is associated with both the Southwest monsoon and the Qinghai-Tibetan Plateau monsoon; approximately 80-90% of rainfall occurs in the summer season (from May to October).

Fig.1

Table 1

2.2 Soil sampling

Soil samples were collected in the summer of 2013 between July 12 and August 30. To avoid disturbance of human activities, sample sites were chosen 5-7 km from the towns where the meteorological stations are located. We set three quadrates (0.5×0.5

m) within 200 m^2 to collect surface mineral soil (0-5 cm) using a ring knife. The O-horizon, including litters, moders, and mors, was removed before collecting mineral soils. About 10 g of air-dried soil was sieved at 2 mm. Plant fragments and the soil fraction coarser than 2 mm were removed. The remainder of the sieved sample was immersed using excessive HCl (1 mol/L) for 24 h. To ensure that all carbonate was cleared, we conducted artificial stirring four times during the immersion. Then, the sample was washed to neutrality using distilled water. Finally it was oven-dried at 50 ℃ and ground. Carbon isotope ratios were determined on a Delta$^{\text{Plus}}$ XP mass spectrometer (Thermo Scientific, Bremen, Germany) coupled with an elemental analyzer (FlashEA 1112; CE Instruments,Wigan, UK) in continuous flow mode. The elemental analyzer combustion temperature was 1020 ℃.

The carbon isotopic ratios are reported in delta notation relative to the V-PDB standard using the equation:

$$\delta^{13}C = (R_{sample}/R_{standard} - 1) \times 1000 \qquad (1)$$

where $\delta^{13}C$ is the carbon isotope ratio of the sample (‰) and R_{sample} and $R_{standard}$ are the $^{13}C/^{12}C$ ratios of the sample and the standard, respectively. For this measurement, we obtained a standard deviation of less than 0.15‰ among replicate measurements of the same soil sample.

3. Results

Except for one $\delta^{13}C_{SOM}$ value (-18.8‰), all other data ranged from -20.4 to -27.1‰ with a mean value of -23.3‰ (n = 80, s.d. = 1.45). Multiple regression with MAT, MAP, altitude, latitude, and longitude as independent variables and $\delta^{13}C_{SOM}$ as the dependent variable shows that only 9% of the variability in soil $\delta^{13}C$ can be explained as a linear combination of all five environmental factors ($p = 0.205$; Table 2). Considering the possibility of correlations among the five explanatory variables, stepwise regression was used to eliminate the potential influence of collinearity among them. Variables were incorporated into the model with *P*-values < 0.05 and excluded with *P*-values > 0.1. Statistical analysis showed that only latitude was included in the stepwise regression model ($R^2 = 0.077$, $p = 0.012$). In order to better constrain the relationship between soil $\delta^{13}C$ and each environmental factor, bivariate correlation analyses of soil $\delta^{13}C$ against some environmental factors were conducted. The bivariate correlation analyses show that $\delta^{13}C_{SOM}$ is not related to MAT ($p = 0.114$) or SMT ($p = 0.697$) along the isohyet (Fig. 2a, b). In addition, in order to further determine the response of $\delta^{13}C_{SOM}$ to temperature, we considered three subsets of our soil samples defined according to the climate, topography, or vegetation type the Qinghai-Tibetan Plateau (mainly alpine meadow, including 10 sites), steppe or grassland (11 sites), and coniferous forest (six sites; Table 1). Bivariate correlation analyses within these subsets also show no relationship between $\delta^{13}C_{SOM}$ and MAT for all categories. The correlation analysis of $\delta^{13}C_{SOM}$ with respect to altitude is shown in Fig. 3, which displays no relationship ($p = 0.132$). Although longitude was not found to influence $\delta^{13}C_{SOM}$ in the above stepwise regression, bivariate correlation analyses showed that latitude and longitude were both negatively related to $\delta^{13}C_{SOM}$ ($p = 0.012$ and 0.034, respectively; Fig. 4a, b).

In addition to the effects of quantifiable environmental factors, qualitative factors such as soil type and vegetation type may influence $\delta^{13}C_{SOM}$. Various concepts have been introduced in soil taxonomy, leaving varied soil nomenclatures in use. In this study we adopted Chinese soil nomenclature and the World Reference Base (WRB) to describe the observed soils. The soil was divided into eight or six types based on the Chinese Soil Taxonomy or WRB, respectively (Table 1). One-way ANOVA analyses suggest that both soil and vegetation type played a significant role in $\delta^{13}C_{SOM}$ ($p = 0.002$ for soil type based on the Chinese Soil Taxonomy, $p = 0.003$ for soil type based on WRB, and $p = 0.001$ for vegetation type; Fig. 5).

To further constrain the effects of soil and vegetation type on $\delta^{13}C_{SOM}$, multiple regressions with soil and vegetation type as dummy variables were conducted. Considering the tight relationship between soil type and vegetation type, especially in Chinese soil taxonomy, the soil variables and the vegetation variables were separately introduced into the statistical analyses. Multiple regression, in which the five aforementioned explanatory environmental factors were taken as quantitative variables and the eight soil types of the Chinese nomenclature as values of a dummy variable, shows that environmental factors and soil types in total account for 37.4% of the soil $\delta^{13}C$ variance ($p < 0.001$; Table 2). Using the six soil types based on WRB rather than the Chinese nomenclature, 29.7% ($p = 0.003$) of the variability is explained (Table 2). Similarly, multiple regression with vegetation types as dummy variables shows that the five environmental factors and vegetation types in total can explain 36.2% of the variability in soil $\delta^{13}C$ ($p = 0.001$; Table 2). Compared to the multiple regressions in which only quantitative environmental variables were introduced, the multiple regressions in which soil and vegetation were also introduced explain more variance, suggesting that soil type and vegetation type played a significant role in $\delta^{13}C_{SOM}$ variability.

Table 2

Fig.2a, b

Fig.3

Fig.4a, b

Fig.5

4. Discussion

Soil $\delta^{13}C$ depends on the $\delta^{13}C$ of plants and on carbon isotopic fractionation during organic matter decomposition. $\delta^{13}C$ values of C_3 plants vary between -22 and -34‰ with a mean of -27‰, and C_4 plants range from -9 to -19‰ with a mean of -13‰ (Dienes, 1980). Carbon isotope fractionation occurs during the process of plant litter decomposition into soil organic matter in most environments, especially in non-arid environments, causing ^{13}C-enrichment in soil organic matter compared to the plant sources (Nadelhoffer, 1988; Balesdent et al., 1993; Ågren et al., 1996; Fernandezet al., 2003; Wynn et al., 2005; Wynn, 2007). An intensive investigation of isotope fractionation during organic matter decomposition, which was conducted in Mount Gongga, an area of the Qinghai-Tibetan Plateau dominated by C_3 vegetation with herbs, shrubs, and trees, showed that the mean ^{13}C-enrichment in surface soil (0-5 cm depth) relative to the vegetation was 2.87‰ (Chen et al., 2009). Another investigation of 13 soil profiles from the Tibetan Plateau and north China showed that the $\delta^{13}C$ difference between surface soil (0-5 cm depth) and the original biomass varied from 0.6 to 3.5‰ with a mean of 1.8‰ (Wang et al., 2008). Thus, the $\delta^{13}C_{SOM}$ dataset from this study ($\delta^{13}C_{SOM}$ ranges from -20.4 to -27.1‰) indicates that the modern terrestrial ecosystem along the isohyet is greatly dominated by C_3 plants. This result is consistent with the observations of vegetation along the isohyet completed in our previous study (Wang et al., 2013). We are surprised by such high soil $\delta^{13}C$ values occurring at RiKaZe (Site 2; Fig.3 and Table 1) because only four C_3 plants grew there, and there were no C_4 species. This abnormal observation suggests that very high carbon isotope fractionation with SOM degradation has occurred in the local ecosystem. Previous studies have also observed a similar phenomenon, although the mechanism responsible for the unusually high isotopic fractionation remains unclear. For example, Wynn (2007) reported that the fractionation enriched soil organic carbon ^{13}C up to ~ 6‰ with respect to the original biomass.

The MAT, MAP, altitude, latitude, and longitude combined are responsible for only 9% of the variability in soil $\delta^{13}C$ in the multiple regression model, suggesting that the contribution of these five environmental factors to the soil $\delta^{13}C$ variance is very small. Our previous study conducted along the isohyet resulted in a strong positive relationship between the $\delta^{13}C$ of plants and MAT, with a coefficient of 0.104‰/^{o}C (Wang et al., 2013). The difference between the maximum and minimum temperature along the isohyet is 15 ℃, so the greatest possible effect of temperature on plant $\delta^{13}C$

along the temperature gradient is 1.56‰, which is not very substantial. Because the main source of soil organic matter along the isohyet is C_3 plants, the induced variance in soil $\delta^{13}C$ by plant $\delta^{13}C$ also cannot be very high. On the other hand, although the ^{13}C-enrichment with SOM degradation follows a Rayleigh distillation process (Wynn, 2007), our recent study shows that temperature does not influence carbon isotopic fractionation during decomposition (Wang et al., 2015), which also explains the lack of a relationship between soil $\delta^{13}C$ and temperature. Feng et al. (2008) and Lee et al. (2005) respectively reported no relationships between soil $\delta^{13}C$ and MAT and SMT, which is consistent with our results. Their field campaigns were conducted in central Asia, which is also dominated by C_3 plants, similar to the area along the 400 mm isohyet. This is the reason why the same pattern exists in both central Asia and in the area along the 400 mm isohyet.

The observations in Bird and Pousai (1997) and Sage et al. (1999) appear to be inconsistent with our findings; they found a nonlinear relationship between soil $\delta^{13}C$ and MAT in Australian grasslands. However, if they considered only soil with pure C_3 plants (MAT is below 16 ℃), soil $\delta^{13}C$ and temperature were not related in Australian grasslands, which agrees with our results. Below 15 ℃, the C_4 contribution to productivity in Australian grasslands is negligible, whereas above 23 ℃, C_3 contribution is negligible. Between 14 and 23 ℃, soil $\delta^{13}C$ is positively correlated with MAT, indicating C_4 representation increasing with MAT (Sage et al., 1999). Lu et al. (2004) also reported a nonlinear relationship between soil $\delta^{13}C$ and MAT. Similarly, if the soil data with C_4 plants are excluded from the nonlinear correlation, soil $\delta^{13}C$ is also not related to MAT in Lu et al. (2004) (see Fig.5 b in Lu et al., 2004). Thus, the present study and the previous observations are consistent in showing that in a terrestrial ecosystem in which the vegetation is dominated by C_3 plants, temperature does not influence soil $\delta^{13}C$ variance.

All the soil samples were taken along the 400 mm isohyet; thus, this study shows that the contribution of precipitation to the variability in soil $\delta^{13}C$ is negligible. Although stepwise regression and correlation analysis both show a significant influence of latitude on soil $\delta^{13}C$, the five environmental variables, including latitude, were responsible for only 9% of the variability in soil $\delta^{13}C$ in a multiple regression model (Table 2), suggesting that the contribution of latitude to soil $\delta^{13}C$ was also limited. This study shows a negative correlation between latitude and $\delta^{13}C_{SOM}$ ($p=0.012$). Bird and Pausai (1997) and Tieszen et al. (1979) reported a similar pattern. Latitude is a comprehensive environmental factor, and change in latitude can bring about changes in other environmental factors, such as temperature, irradiation, cloud amount, and moisture. Temperature and irradiation, however, should be most strongly related to latitude and obviously change with latitude. The observed significant relationship between latitude and soil $\delta^{13}C$ (Fig. 4a) suggests that environmental factors other than temperature might contribute more or less to the variance in soil $\delta^{13}C$.

Control of soil $\delta^{13}C$ by vegetation type mainly reflects the effect of life forms on plant $\delta^{13}C$ and the effect of substrate quality on isotope fractionation during organic matter decomposition. Communities in which life forms of dominant plants are similar are generally treated as the same vegetation type. Plant $\delta^{13}C$ is tightly related to life form (Diefendorf et al., 2010; Ehleringerand Cooper, 1988), and this causes $\delta^{13}C$ differences among varying vegetation types, consequently resulting in the observed effect of vegetation type on soil $\delta^{13}C$.

Substrate quality partly quantifies how easily organic carbon is used by soil microbes (Poageand Feng, 2004). It can be related to plant type and is often defined using a C/N ratio, lignin content, cellulose content, and/or lignin content/N ratio (Melilloet al., 1989; Gartern et al., 2000). Our study in Mount Gongga, China, showed that litter quality played a significant role in isotope fractionation during organic matter decomposition, and the carbon isotope fractionation factor α increased with litter quality (Wang et al., 2015). Thus, the isotope fractionation factor should differ among sites because litter quality is dependent on vegetation, and this makes soil change its $\delta^{13}C$ with vegetation type.

The effect of soil type on soil $\delta^{13}C$ may be associated with the effect of soil type on isotope fractionation during organic matter decomposition, which involves at least two mechanisms (Wang et al. [2008] has discussed the mechanisms in detail). First, properties and compositions of microbial decomposer communities are dependent on soil type (Gelsominoet al., 1999). Different microbes can have different metabolic pathways even when they decompose the same organic compound (Mackoand Estep, 1984), and the extent of isotope fractionation during decomposition may be tightly related to the metabolic pathways of microbes (Macko and Estep, 1984). Second, physical and chemical properties such as pH, particle size fraction, and water-holding capacity display considerable differences among soil types, and this causes organic compounds to decay at different rates in different soil environments. The magnitude of isotope fractionation during decomposition is linked to the degree of organic matter decomposition (Feng, 2002). Thus, soil type plays a significant role in fractionation.

5. Conclusions

The present study measured organic carbon isotopes in surface soil along a 400 mm isohyet of mean annual precipitation in China and observed that soil type and vegetation type both significantly influenced soil organic carbon isotopes. However, temperature was found to have no observable impact on $\delta^{13}C_{SOM}$, suggesting that $\delta^{13}C$ signals in sediments cannot be used for the reconstruction of temperature and that the effect of temperature on $\delta^{13}C_{SOM}$ should be neglected in reconstructions of paleo-climate and paleo-vegetation that use carbon isotopes of soil organic matter.

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References

Ågren, G.I., Bosatta, E., andBalesdent. J.: Isotope discrimination during decomposition of organic matter: A theoretical analysis. Soil Sci. Soc. Am. J., 60, 11211126, 1996.

Balesdent. J., Girardin, C., and Mariotti, A.: Site-related $\delta^{13}C$ of tree leaves and sol organic matter in a temperate forest. Ecology, 74, 1713–1721, 1993.

Bird, M.I., and Pousai, P.: Variations of delta C-13 in the surface soil organic carbon pool. Global Biogeochemical Cycles, 11, 313–322,1997.

Chen, P.N., Wang, G.A., Han, J.M., Liu, X.J., and Liu, M.: $\delta^{13}C$ difference between plants and soil organic matteralong the eastern slope of Mount Gongga. Chinese Science Bulletin,dio:10.1007/s11434-009-0405-y, 2009.

Deines, P. The isotopic composition of reduced organic carbon.Handbook of environmental isotope geochemistry I, The terrestrial environment(eds. by P. Fritz & J.C. Fontes), pp. 329 –406. Elsevier, Amsterdam ,1980.

Diefendorf, A.F., Mueller, K.E., Wing, S.L., Koch, P.L., Freeman, K.H.: Global patternsin leaf ^{13}C discrimination and implications for studies of past and future climate.Proceedings of the National Academy of the Sciences of the United States of America, 107,5738–5743, 2010.

Ehleringer, J. R., and Cooper, T. A.: Correlations between carbon isotope ratio and microhabitat in desert plants. Oecologia, 76, 62–66, 1988.

Feng, X.H.: A theoretical analysis of carbon isotope evolution of decomposing plant litters and soil organic matter.Global Biogeochemical Cycles, 16, 4–1119.dio: 10. 1029/2002GB001867, 2002.

Feng, Z.D., Wang, L.X., Ji, Y.H., Guo, L.L., Lee, X.Q.,andDworkin, S. I.: Climatic dependency of soil organic carbon isotopic composition along the S-N Transect from 34^{o}N to 52^{o}N in central-east Asia. PalaeogeographyPalaeoclimatologyPalaeoecology, 257, 335–343, 2008.

Fernandez, I., Mahieu, N.,andCadisch, G.: Carbon isotopic fractionation during decomposition of plant materials of different quality. Glo.Biogeochem.Cyc.,17, 1075, doi: 10. 1029/2001GB001834, 2003.

Gartern, C.T.Jr., Cooper, L.W., Post, W.M., and Hanson, P.J.: Climate controls on forest soil C isotope ratios in the Southern Appalachian Mountains. Ecology, 81,1108–1119,2000.

Gelsomino, A., Keijzer-Wolters, A.C., Cacco, G., and van Elsasb, J.D.: Assessment of bacterial community structure in soil by polymerase chain reaction and denaturing gradient gel electrophoresis. Journal of Microbiological Methods, 38,1–15, 1999.

Hatté, C., and Guiot, J.: Palaeoprecipitation reconstruction by inverse modelling using the isotopic signal of loess organic matter: application to the Nuβloch loess sequence (Rhine Valley, Germany). Climate Dynamics, 25, 315-327, doi:10.1007/s00382-005-0034-3, 2005.

Hultine, K.R., and Marshall, J.D.: Altitude trends in conifer leaf morphology and stable carbon isotope composition. Oecologia, 123, 32–40, 2000.

Kohn, M.J.: Carbon isotope compositions of terrestrial C_3plantsas indicators of (paleo)ecology and (paleo)climate. Proceedings of the National Academy of Sciences of the United States of America, 107: 19691–19695, 2010.

Körner, C., Farquhar, G.D., and Wong, S.C.: Carbon isotope discrimination by plants follows latitudinal and altitude trends. Oecologia, 88,30-40,1991.

Lee, X.Q., Feng, Z.D., Guo, L.L., Wang, L.X., Jin, L.Y., Huang, Y.S., Chopping, M., Huang, D.K., Jiang, W., and Jiang, Q.: Carbon isotope of bulk organic matter: A proxy for precipitation in the arid and semiarid central East Asia. Global Biogeochemical cycles: 19, GB4010, dio: 10.1029/2004GB002303, 2005.

Lu, H.Y., Wu, N.Q., Gu, Z.Y., Guo, Z.T., Wang, L., Wu, H.B.,Wang, G.,Zhou, L.P., Han, J.M. andLiu, T.S.:Distribution of carbon isotope composition of modern soils on the Qinghai-Tibetan Plateau.Biogeochemistry, 70, 273–297.2004.

Macko, S.A.,and Estep, M.L.F.: Microbial alteration of stable nitrogen and carbon isotopic composition of organic matter. Organic Geochemistry,6, 787–790,1984.

McCaroll, D., Loader, N. J.: Stable isotopes in tree rings.Quaternary Science Reviews 23,771–801, 2004.

Melillo, J.M., Aber, J.D., Kinkins, A.E., Ricca, A., Fry, B., andNadelhoffer, K.J. Carbon and nitrogen dynamics along the decay continuum: Plant litter to soil organic matter. Plant and Soil, 115, 189–198,1989.

Nadelhoffer, K.J., and Fry, B.: Controls on natural nitrogen-15 and carbon-13 abundances in forest soil organic matter. Soil Science Society of American Journal, 52,1633–1640,1988.

Poage, M.A., and Feng, X.H.: Atheoretical analysis of steady state $\delta^{13}C$ profiles of soil organic matter. Global Biogeochimcal Cycles, 18, GB2016, dio: 10. 1029/2003GB002195, 2004.

Rao, Z.G.,Chen, F.H., Cheng, H., Liu, W.G., Wang, G.A., Lai, Z.P., and Bloemendal, J.: High-resolution summer precipitation variations in the western Chinese Loess Plateau during the last glacial. Scientific Reports, 3, 2785,doi: 10.1038/srep02785, 2013.

Saga, R.F., Wedin, D.A., and Li, M.: The biogeography of C_4 photosynthesis: patterns and controlling factors (pp. 313-373.).In: Saga, R.F., Monson, R.K. (Eds.), C_4 Plants Biology. Academic Press, San Diego, California, 1999.

Schleser, G. H., Helle, G., Lucke, A., and Vos, H.: Isotope signals as climate proxies: the role of transfer functions in the study of terrestrial archives. Quaternary Science Reviews, 18, 927–943, 1999.

Tieszeen, L.L., Senyimba, M.M., Imbamba, S.K., Troughton, J.H.: Distritribution of C_3 and C_4 gasses and carbon isotope discrimination along an altitudinal and Moisture Gradient in Kenya. Oecologia, 37, 337–350,1979.

Treydte, K., Frank, D.; Esper, J., Andreu, L., Bednarz, Z., Berninger, F., Boettger, T., D'Alessandro, C. M., Etien, N., Filot, M., Grabner, M., Guillemin, M. T., Gutierrez, E., Haupt, M., Helle, G., Hilasvuori, E., Jungner, H., Kalela-Brundin, M., Krapiec, M., Leuenberger, M., Loader, N. J., Masson-Delmotte, V., Pazdur, A., Pawelczyk, S., Pierre, M., Planells, O., Pukiene, R., Reynolds-Henne, C. E., Rinne, K. T., Saracino, A., Saurer, M., Sonninen, E., Stievenard, M., Switsur, V. R., Szczepanek, M., Szychowska-Krapiec, E., Todaro, L., Waterhouse, J. S., Weigl, M., and Schleser, G. H.: Signal strength and climate calibration of a European tree-ring isotope network.Geophysiccal Research Letters34: L24302, doi:10.1029/2007GL031106, 2007.

Vidic, N.J., and Montanez, I.P.: Climatically driven glacial-interglacial variations in C-3 and C-4 plant proportions on the Chinese Loess Plateau. Geology, 32,337–340, 2004.

Wang, G.A., Feng, X.H., Han, J.M., Zhou, L.P., Tan, W.B., and Su, F.:Paleovegetation reconstruction using δ^{13}C of Soil organic matter. Biogeosciences, 5, 1325–1337, 2008.

Wang, G.A., Li, J.Z., Liu, X.Z., and Li, X.Y.: Variations in carbon isotope ratios of plants across a temperature gradient along the 400 mm isoline of mean annual precipitation in north China and their relevance to paleovegetation reconstruction. Quaternary Science Reviews, 63, 83–90, 2013.

Wang, G.A.,Jia, Y.F., and Li, W.:Effects of environmental and biotic factors on carbon isotopic fractionation during decomposition of soil organic matter. Scientific Reports,5, 11043,doi: 10.1038/srep11043, 2015.

Wynn, J.G., Bird, M.I., Wong, V.N.L.: Rayleigh distillation and the depth profile of ^{13}C/^{12}C ratios of soil organic carbon from soils of disparate texture in Iron Range National Park, Far North Queensland, Australia. GeochimicaetCosmochimicaActa, 69, 1961-1973, 2005.

Wynn, J.G.: Carbon isotope fractionation during decomposition of organic matter in soils and paleosols: Implications for paleoecological interpretations of paleosols. Palaeogeography, Palaeoclimatology, Palaeoecology, 251, 437-448, 2007.

Xu, M., Wang, G.A., Li, X.L., Cai, X.B., Li, X.L., Christie, P., Zhang, J.L.: The key factor limiting plant growth in cold and humid alpine areas also plays a dominant role in plant carbon isotope discrimination. Frontiers in Plant Science, 6, doi:10.3389/fpls.2015.00961,2015.

Yang, S.L., Ding, Z.L., Li, Y.Y., Wang, X., Jiang, W.Y., Huang, X.F.:Warming-induced northwestward migrationof the East Asian monsoon rain belt from theLast Glacial Maximum to the mid-Holocene.Proceedings of the National Academy of Sciences of the United States of America, www.pnas.org/cgi/doi/10.1073/pnas.1504688112

Zhu, Y., Siegwolf, R. T. W., Durka, W., and Körner, C.:Phylogenetically balanced evidence for structural and carbon isotope responses in plants along elevational gradients. Oecologia, 162, 853-863,2010.

Figures

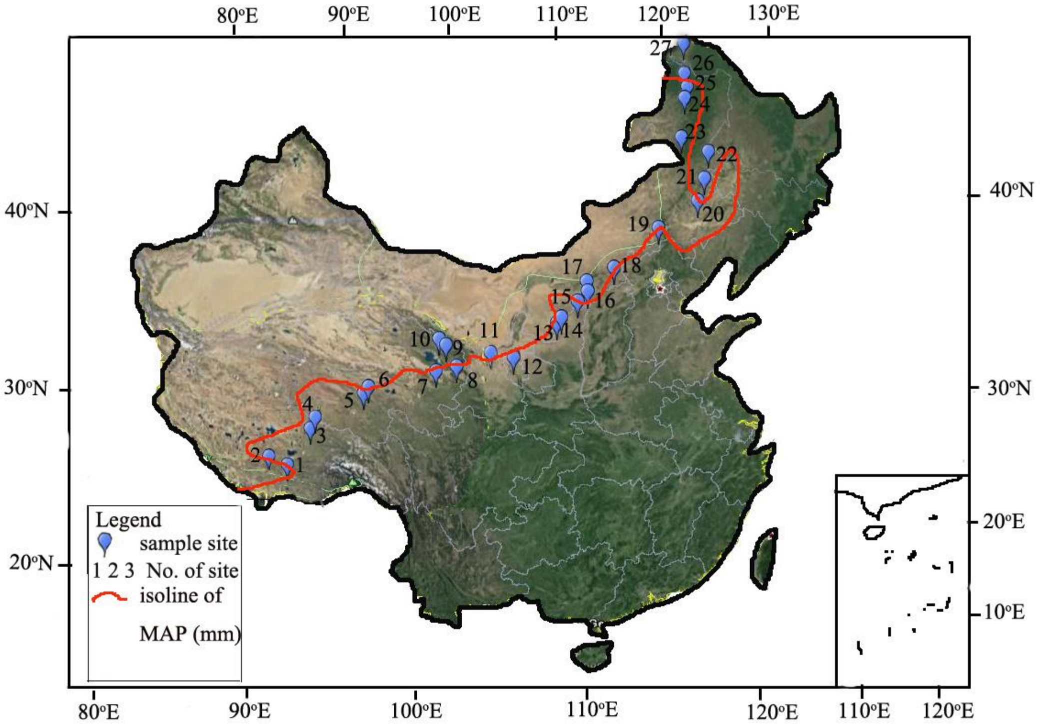

Fig.1. Sketch of sampled region. Sample sites are indicated with numbers. 1, LangKaZi; 2,RiKaZe; 3,NaQu; 4,NieRong; 5,ZhiDuo; 6,QuMaLai; 7,TongDe; 8,TongRen; 9,HuangYuan; 10,HaiYan; 11,YuZhong; 12,XiJi; 13,JingBian; 14,HengShan; 15,ShenMu; 16,HeQu; 17,ZhunGeErQi; 18,FengZhen; 19,DuoLun; 20,LinXi; 21,ZhaLuTeQi; 22,WuLanHaoTe; 23,AErShan; 24,YaKeShi; 25,KuDuEr; 26,GenHe; 27,BeiJiCun. Detailed information of sites is shown in Table 1.

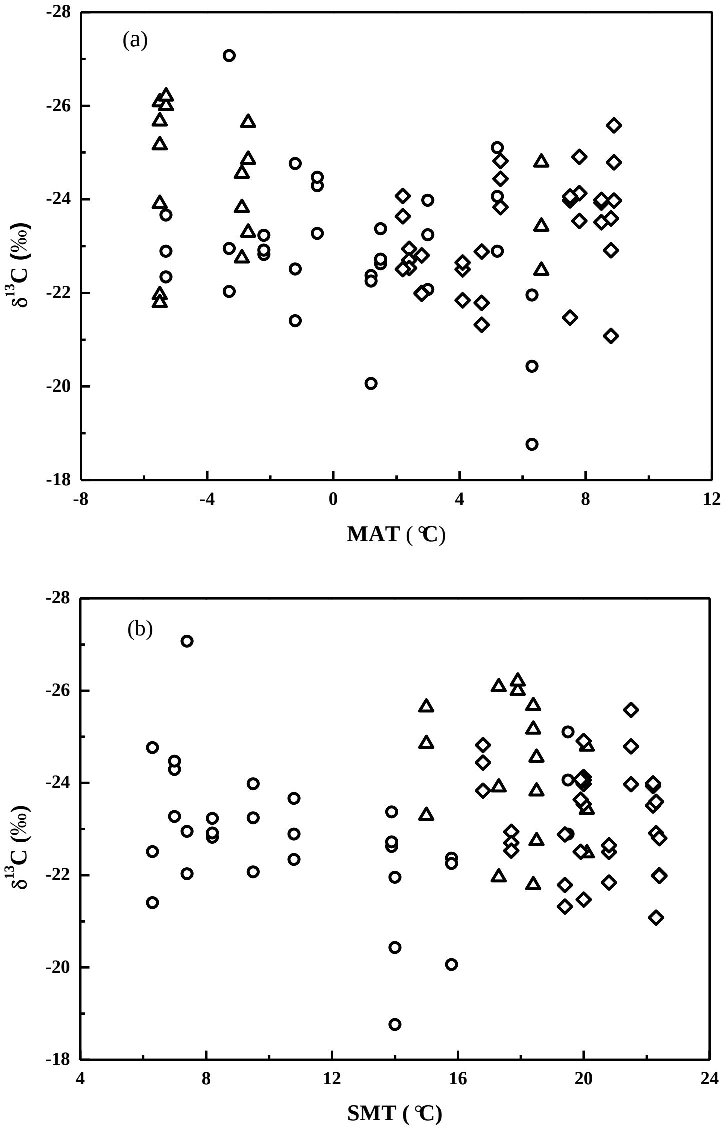

Fig.2 shows the variance in surface soil $\delta^{13}C$ with MAT (a) and SMT (b) along the 400 mm isoline in China. Circle represents alpine and subalpine; diamond indicates temperate steppe and grassland; triangle is coniferous forest.

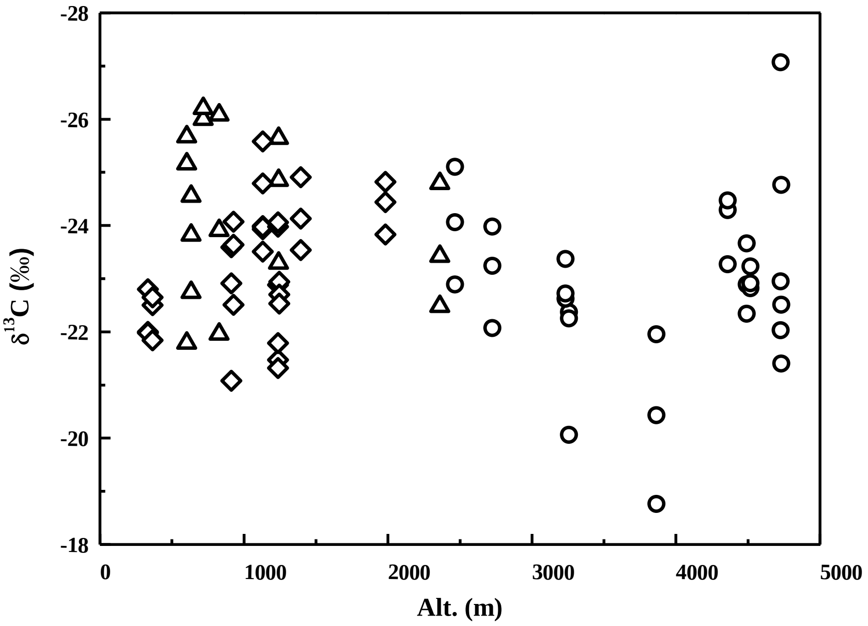

Fig.3 shows the variance in surface soil $\delta^{13}C$ with altitude.

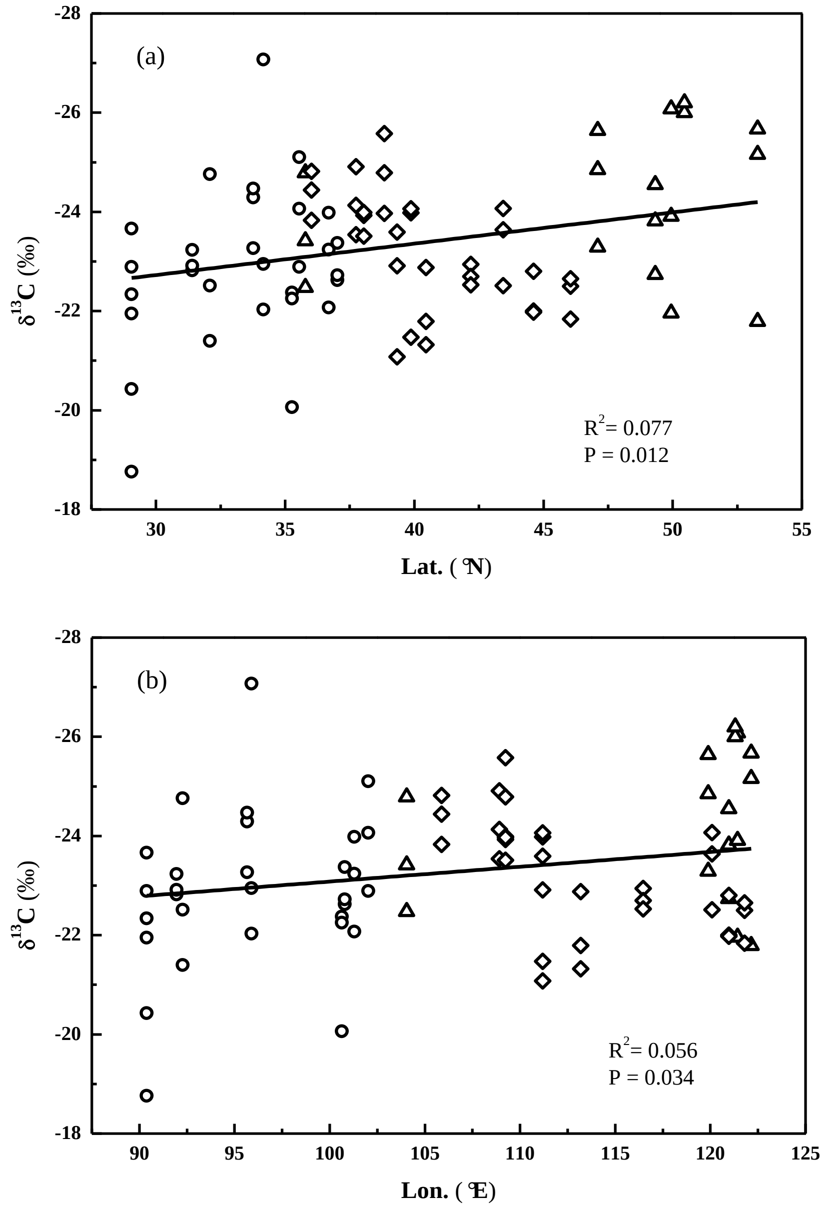

Fig.4 shows the relationships between the soil $\delta^{13}C$ and latitude (a) and longitude (b).

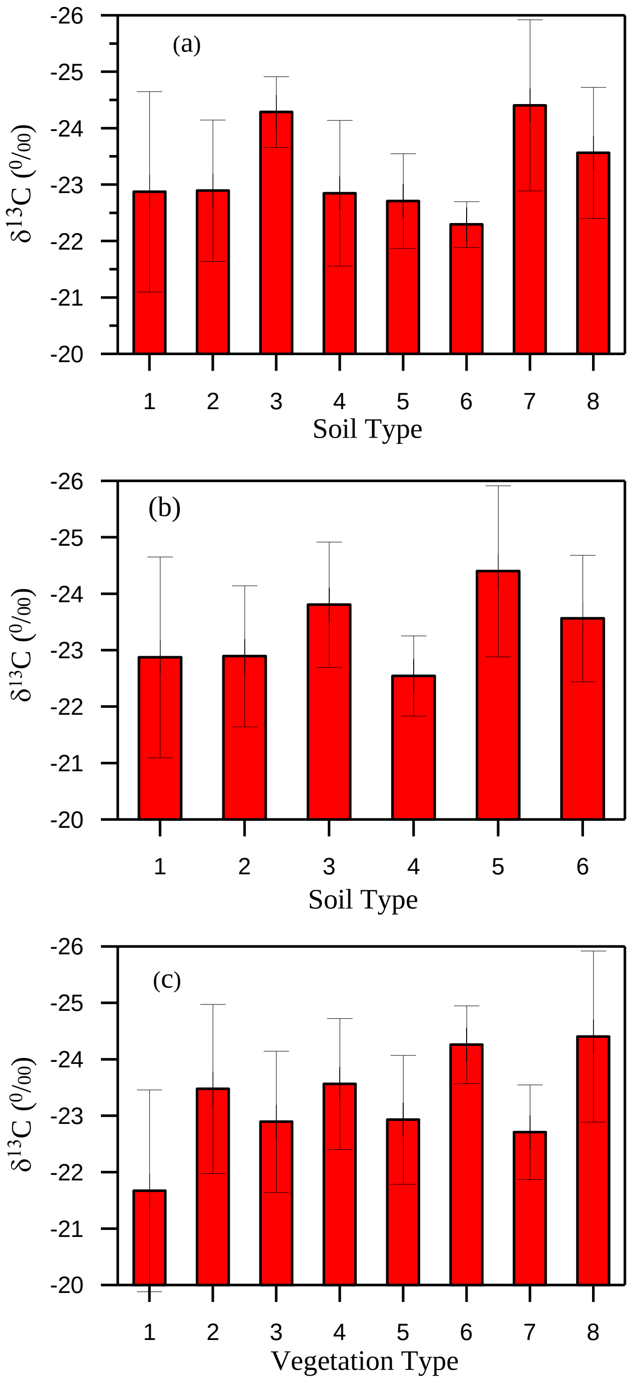

Fig.5 shows the effects of soil types and vegetation types on the soil δ^{13}C. (a.) soil types based on Chinese soil taxonomy. 1. Matti-GelicCambosols; 2. Hapli- CryicAridosolsl; 3.Calci-OrthicAridosols; 4.MottlicCalci-OrthicAridosols; 5.TypicCalci-UsticIsohumosols; 6.Pachi-UsticIsohumosols; 7.Umbri-GelicCambosols; 8.Hapli-UsticArgosols. (b.) soil types based on WRB. 1.Cambisols; 2. Leptosols; 3.Calcisols; 4.Chernozems; 5.Umbrisols; 6.Luvisols. (c.) vegetation type. 1. Alpine grassland; 2. Alpine meadow; 3.Subalpine grassland; 4.Temperate coniferous and broad-leaved mixed forests; 5.Temperate meadow steppe; 6.Semi-desert grasslands; 7.Temperate typical steppe; 8.Frigid temperate coniferous forest. The bar in Fig.5 indicates ±1SD.

Table 1 Information of the sampling sites

No.	Site name	MAT/℃	SMT/℃	MAP/mm	Alt./m	Lat./N°	Lon./E°	Mean $\delta^{13}C$ (‰)	Vegetation type	Dominate species	Soil types
1	LangKaZi	-5.3	10.8	376	4492	29.06	90.39	-23	Alpine grassland	*Stipa*、*Festuca* and *Carex*	Matti-GelicCambosols (Cambisols)
2	RiKaZe	6.3	14	420	3865	29.33	88.98	-20.4	Alpine grassland	*Stipa*、*Festuca* and *Carex*	Matti-GelicCambosols (Cambisols)
3	NaQu	-2.2	8.2	406	4519	31.41	91.96	-23	Alpine meadow	*Kobresia*	Matti-GelicCambosols (Cambisols)
4	NieRong	-1.2	6.3	400	4731	32.09	92.27	-22.9	Alpine meadow	*Kobresia*	Matti-GelicCambosols (Cambisols)
5	ZhiDuo	-0.5	7	394	4360	33.77	95.66	-24	Alpine meadow	*Kobresia*	Matti-GelicCambosols (Cambisols)
6	QuMaLai	-3.3	7.4	391.7	4727	34.16	95.9	-24	Alpine meadow	*Kobresia*	Matti-GelicCambosols (Cambisols)
7	TongDe	1.2	15.8	371	3258	35.27	100.64	-21.6	Subalpine grassland	*Stipa* and *Hippolytia*	Hapli- CryicAridosolsl (Leptosols)
8	TongRen	5.2	19.5	425.7	2467	35.55	102.03	-24	Subalpine grassland	*Stipa* and *Hippolytia*	Hapli- CryicAridosolsl (Leptosols)
9	HuangYuan	3	13.9	408.9	2725	37.02	100.8	-22.9	Subalpine grassland	*Stipa* and *Hippolytia*	Hapli- CryicAridosolsl (Leptosols)
10	HaiYan	1.5	9.5	400	3233	36.69	101.3	-23.1	Subalpine grassland	*Stipa* and *Hippolytia*	Hapli- CryicAridosolsl (Leptosols)
11	YuZhong	6.6	20.1	403	2361	35.78	104.05	-23.6	Temperate coniferous and broad-leaved mixed forests	*Pinustabulaeformis*	Hapli-UsticArgosols (Luvisols)
12	XiJi	5.3	16.8	400	1982	36.02	105.88	-24.4	Temperate meadow steppe	*Stipa* and *Hippolytia*	Calci-OrthicAridosols(Calcisols)
13	JingBian	7.8	20	395.4	1394	37.74	108.91	-24.2	Semi-desert grasslands	*Stipa*、*Hippolytia* and *Ajania*	Calci-OrthicAridosols(Calcisols)
14	HengShan	8.5	22.2	397	1131	38.04	109.24	-23.8	Semi-desert grasslands	*Stipa*、*Hippolytia* and *Ajania*	Calci-OrthicAridosols(Calcisols)
15	ShenMu	8.9	21.5	393	1131	38.84	110.44	-24.8	Semi-desert grasslands	*Stipa*、*Hippolytia* and *Ajania*	Calci-OrthicAridosols(Calcisols)
16	HeQu	8.8	22.3	426	912	39.33	111.19	-22.5	Temperate meadow steppe	*Bothriochloa* and *Pennisetum*	MottlicCalci-OrthicAridosols(Calcisols)
17	ZhunGeErQi	7.5	20	400	1236	39.87	111.18	-23.2	Temperate meadow steppe	*Stipa*and *Aneuralepidium*	MottlicCalci-OrthicAridosols(Calcisols)
18	FengZhen	4.7	19.4	413	1236	40.45	113.19	-22	Temperate typical steppe	*Stipa* and *Aneuralepidium*	TypicCalci-UsticIsohumosols (Chernozems)
19	DuoLun	2.4	17.7	407	1245	42.18	116.47	-22.7	Temperate typical steppe	*Stipa* and *Aneuralepidium*	TypicCalci-UsticIsohumosols (Chernozems)
20	LinXi	2.2	19.9	370	928	43.44	120.08	-23.4	Temperate typical steppe	*Stipa* and *Aneuralepidium*	TypicCalci-UsticIsohumosols (Chernozems)
21	ZhaLuTeQi	2.8	22.4	387	332	44.61	120.97	-22.3	Temperate meadow steppe	*Stipa*、*Aneuralepidium and*	Pachi-UsticIsohumosols (Chernozems)

22	WuLanHaoTe	4.1	20.8	416	366	46.05	121.79	-22.3	Temperate meadow steppe	*Filifolium Stipa*、*Aneuralepidium and Filifolium*	Pachi-UsticIsohumosols (Chernozems)
23	AErShan	-2.7	15	391	1240	47.1	119.89	-24.6	Frigid temperate coniferous forest	*Larixgmelinii* and*Betulaplatyphylla Suk*	Umbri-GelicCambosols (Umbrisols)
24	YaKeShi	-2.9	18.5	379	634	49.33	120.97	-23.7	Frigid temperate coniferous forest	*Larixgmelinii*	Umbri-GelicCambosols (Umbrisols)
25	KuDuEr	-5.5	17.3	402	829	49.94	121.43	-24	Frigid temperate coniferous forest	*Larixgmelinii* and*Betulaplatyphylla Suk*	Umbri-GelicCambosols (Umbrisols)
26	GenHe	-5.3	17.9	424	718	50.46	121.31	-26.1	Frigid temperate coniferous forest	*Betulaplatyphylla Suk*	Umbri-GelicCambosols (Umbrisols)
27	BeiJicun	-5.5	18.4	450.8	603	53.29	122.15	-24.2	Frigid temperate coniferous forest	*Larixgmelinii and Pinussylvestnisvar*	Umbri-GelicCambosols (Umbrisols)

Note: MAT, SMT, MAP, Alt, Lat. and Lon. are the abbreviations of mean annual temperature, summer mean temperature, mean annual precipitation, altitude, latitude, longitude, respectively. Longitude, latitude and altitude of each site were from the portable GPS; MAT and MAP represent the average values of more than 30 years, SMT presents the average value of June, July and August for more than 30 years. All climatic data were from the local meteorological stations and the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/shishi/climate.jsp); The soil types are based on Chinese soil taxonomy and WRB (in the brackets).

Table 2 shows the results from multiple regressions.

Model	R^2	Adjusted R^2	F	p-value
1	0.091	0.030	1.484	0.205
2	0.374	0.273	3.690	<0.001
3	0.297	0.195	2.911	0.004
4	0.362	0.247	3.164	0.001

Note: Model-1 is the multiple regression of soil $\delta^{13}C$ against MAT, MAP, altitude, latitude and longitude; For Model-2, Model-3 and Model-4, in addition to taking these five environmental factors as independent variables, the soil types based on Chinese nomenclature and WRB, and the vegetation types as dummy variables were separately introduced in the multiple regressions.